

Micropaleontological parameters as proxies of late Miocene surface water properties and paleoclimate in Gavdos Island, eastern Mediterranean

Assimina ANTONARAKOU
Hara DRINIA
Nikolaos TSAPARAS
Michael D. DERMITZAKIS

National and Kapodistrian University of Athens, Faculty of Geology,
Department of Historical Geology and Paleontology,
Panepistimiopolis, GR-157 84 Athens (Greece)
aantonar@geol.uoa.gr, cntrinia@geol.uoa.gr
ntsapar@geol.uoa.gr, mderm@geol.uoa.gr

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ABSTRACT

The present study describes the early late Miocene paleoenvironmental evolution and the main paleoclimatic trends of Gavdos Island (eastern Mediterranean) reconstructed using planktonic foraminifera. The three stratigraphic sections studied in this area are characterized by whitish to greyish marls and sands (Potamos and Ag. Giannis sections) and by grey-bluish marls and reefal limestones (Bo Section). Based on the distributional pattern of neogloboquadrinids in the three sections, we attribute a lower Tortonian age to studied sediments, corresponding to the interval ranging between 11.21 to 10.01 Ma. Four distinct assemblages of planktonic foraminifera were identified by Q-mode cluster analysis. The succession of assemblages allows dividing each section into four paleoceanographic stages: 1) a warm-oligotrophic stage characterized by the prevalence of *Globigerinoides obliquus*-*Globoturborotalita apertura*; 2) a cool-eutrophic stage characterized by *Neogloboquadrina acostaensis*; 3) upwelling conditions dominated by *Globigerina bulloides*; and 4) a relatively warm with seasonal high productivity stage characterized by the *N. acostaensis* and *Globigerinoides trilobus*. On the basis of planktonic foraminifera paleoclimatic indices, paleoclimatic curves were constructed for each section. Our data suggest that, although adjacent, the areas where the three sections are located underwent different paleoclimatic and paleoenvironmental evolution during early late Miocene: Bo shelf is characterized by warmer, nearly oligotrophic conditions compared to cooler and eutrophic conditions on the adjacent Potamos and Ag. Giannis shelves. This difference is probably related to the presence of an island between Bo shelf and the open sea which acted as a local oceanographic and biogeographic barrier.

KEY WORDS

Planktonic Foraminifera,
paleoclimate,
paleobiogeography,
early late Miocene,
Gavdos Island,
Greece.

RÉSUMÉ

Paramètres micropaléontologiques comme «proxies» des propriétés des eaux de surface et des paléoclimats dans l'île de Gavdos (Méditerranée orientale) au début du Miocène supérieur.

En se basant sur l'étude des foraminifères planctoniques, cette note décrit l'évolution du milieu et les principales tendances paléoclimatiques de l'île de Gavdos (Méditerranée orientale) au début du Miocène supérieur. Les trois coupes stratigraphiques étudiées sont constituées de marnes blanchâtres à grisâtres et de sables (coupes de Potamos et d'Ag. Giannis) et de marnes gris-bleu et de calcaires récifaux (coupe de Bo). En nous basant sur la distribution des néogloboquadrinides dans les trois coupes, nous attribuons un âge Tortonien inférieur aux sédiments étudiés qui correspondent à l'intervalle entre 11,21 et 10,01 millions d'années. Quatre assemblages de foraminifères planctoniques ont été identifiés en réalisant une analyse «Q-mode cluster». La succession des assemblages permet de diviser chacune des coupes en quatre épisodes paléo-océanographiques: 1) un épisode chaud oligotrophique caractérisé par la prédominance de *Globigerinoides obliquus-G. apertura*; 2) un épisode froid eutrophique caractérisé par *N. acostaensis*; 3) un régime d'upwelling dominé par *G. bulloides*; et 4) un épisode relativement chaud présentant une forte productivité saisonnière, caractérisé par *Neogloboquadrina acostaensis* et *G. trilobus*. Des courbes paléoclimatiques ont été construites pour chaque coupe en utilisant la signification paléoclimatique des foraminifères planctoniques. Nos données suggèrent que, bien qu'elles soient voisines, les régions où sont situées les trois coupes ont subi des évolutions paléoclimatiques et paléoenvironnementales différentes au début du Miocène supérieur. À Bo, le plateau continental est caractérisé par des conditions pratiquement oligotrophiques, plus chaudes que celles, fraîches et eutrophiques, des littoraux voisins de Potamos et d'Ag. Giannis. Cette différence est probablement liée à l'existence d'une île qui jouait le rôle de barrière océanographique et biogéographique entre le littoral de Bo et la mer ouverte.

MOTS CLÉS

Foraminifères
planctoniques,
paléoclimat,
paléobiogéographie,
base du Miocène
supérieur,
île de Gavdos,
Grèce.

INTRODUCTION

The Miocene represents a time of exceptional interest for deciphering the impact of global climatic and paleoceanographic changes in the Mediterranean Sea. The global climate underwent rapid cooling with increased production of cold Antarctic deep waters and major growth of East Antarctic ice sheet (e.g., Miller *et al.* 1991; Flower & Kennett 1994). The global climate deterioration was interrupted by a pronounced reversal from 17 to 14.5 Ma which has been named "The Miocene Climatic Optimum" (Flower 1999). Moreover, this timespan experienced an extreme warm climate accompa-

nied by major changes in the deep ocean benthic foraminiferal fauna.

The late middle to early late Miocene is a period of relatively stable climatic conditions following the global climate cooling with increased zonality from 15 to 12 Ma (Flower & Kennett 1994; Zachos *et al.* 2001). This period is characterized by two short-term increases in benthic foraminiferal $\delta^{18}\text{O}$ (Mi5 and Mi6 events) which supposedly reflect continental ice growth and/or bottom water cooling (Miller *et al.* 1991).

Even though the middle to the early late Miocene is a crucial period in the Cenozoic evolution of ocean-climate system, a complete picture concerning

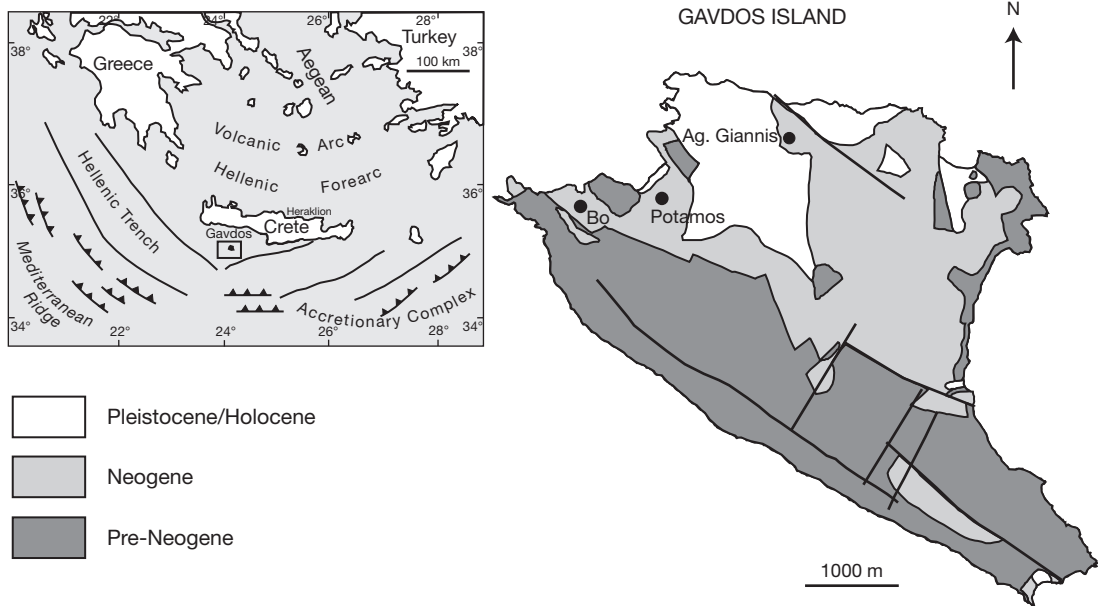


Fig. 1. — Simplified geological map of Gavdos Island indicating the study area. After Tsaparas (2005), modified.

the Mediterranean Basin is still lacking. The knowledge of the paleoceanography and paleoclimate is incomplete and the processes which interacted are still poorly understood. The poor time control of the various events which punctuated the climatic history of the Cenozoic is one of the main reasons for this. Recent detailed analyses on cyclostratigraphy (based on lithologic, micropaleontologic and isotopic evidence) of the middle-late Miocene demonstrated that the integrated magneto-bio-chronologic scale is constantly improved in accuracy and precision by the contribution of Milankovitch-based astrochronological studies.

Currently, the sedimentary cycles recognized in pelagic-hemipelagic sediments of the middle-late Miocene intervals were astronomically tuned to insolation/precession curves (Hilgen *et al.* 2000, 2003; Caruso *et al.* 2002; Lirer *et al.* 2004; Iaccarino *et al.* 2004). The astronomical calibration of sedimentary cycles has permitted to calibrate the bioevents to astronomical curves obtaining astronomical ages for bioevents and climate changes (Hilgen *et al.* 2000, 2003; Caruso *et al.* 2002; Di Stefano *et al.* 2002; Foresi *et al.* 2002; Turco *et al.*

2002; Lirer *et al.* 2004; Iaccarino *et al.* 2004; Lirer & Iaccarino 2005).

Besides, during that time the Mediterranean Basin was characterized by a succession of rapid and profound changes in climate and sea level, and a radical reorganization of oceanic circulation.

The study of planktonic foraminifera is useful for the interpretation of these paleoenvironmental features. The results refer to both aspects of local significance and global processes. Good examples of the successful application of this fossil group can be seen in several studies of climate change and circulation of oceanic water mass (e.g., Cifelli 1976; Ruddiman 1985; Flower & Kennett 1994; Bicchi *et al.* 2003). Ecological studies show that temperature is of primary importance in controlling the distribution of the modern planktonic foraminifera (Bé 1977; Bé & Hutson 1977). This environmental relationship is therefore applied to reconstructions of the paleotemperature of oceans.

The purpose of this research is to identify and describe the distribution patterns of early late Miocene planktonic foraminifera from three sections in Gavdos Island, eastern Mediterranean, and to

speculate on their relations to paleoceanographic and paleoclimatic conditions. The parameters discussed include faunal composition, percent abundance of planktonic foraminiferal and the paleoclimatic indices, as proposed by Cita *et al.* (1977) to estimate the paleotemperatures.

GEOLOGICAL SETTING

The island of Gavdos is located approximately 38 km south of Crete and represents the southernmost emerged part of the Hellenic arc system (Fig. 1). Gavdos and Crete are situated between a volcanic arc in the north and a northward subduction Zone (the Ionian Trench) to the south. The Hellenic Arc and the Ionian Trench are associated with the northward subduction of the oceanic lithosphere of the African plate under the Aegean continental plate (e.g., McKenzie 1978; Angelier *et al.* 1982). Subduction probably started in the late Oligocene/early Miocene (cf. Meulenkamp *et al.* 1988) and is still active today.

The early late Miocene of Gavdos Island is well represented in three sections (the Ag. Giannis, the Potamos and the Bo sections) located in the NNW side of the island.

The Ag. Giannis and Potamos sections (75 m and 110 m thick respectively, Fig. 2) are characterized by similar lithology. Sediments are mainly composed of whitish to greyish-bluish marls and sands of turbiditic origin. In the upper part of the Ag. Giannis Section, there are remnants of a fractured reef with significant presence of corals, molluscs like *Chlamys latissima*, *Ostrea lamelosa*, *Ostrea edulis* and gastropods, whereas in Potamos Section there are shale and sand alternations with significant presence of mollusks such as *Chlamys latissima* and *Gryphaea (Crassostrea) gryphoides crassissima* exposed in a distinct bed. Both sections are topped by *Heterostegina* sands with abundant gastropods, bivalves, *Clypeaster* and coral fragments.

Combined results of benthic foraminiferal and sedimentological analyses indicate that both sedimentary successions were part of a broad shelf of outer neritic to upper bathyal marine depths (Drinia *et al.* 2004).

The Bo Section (Fig. 2) is located in the north-west part of the island. It is 25 m thick and sediments are mainly composed of grey-bluish marls in its lower part and reefal limestones in its upper part. The marly deposits of the Bo Section are very rich in benthic fauna (Tsaparas 2005). This fauna, especially sponges, bryozoans and foraminifera, is interpreted as typical of an outer shelf setting.

MATERIAL AND METHODS

Detailed quantitative micropaleontological analyses have been performed on 101 samples from the studied sections (32 from the Ag. Giannis Section, 58 from the Potamos Section and 11 from the Bo Section). After washing and drying, the samples were sieved through 125 and 63 μm mesh. The > 125 μm size fraction was split into aliquots, from which 300-500 specimens of planktonic foraminifera were randomly picked. Each fraction was analyzed for planktonic foraminifera at species level according to Dermitzakis (1978), Kennett & Srinivasan (1983), Iaccarino (1985) and Hilgen *et al.* (2000). The preservation of planktonic foraminifera is generally good, rarely poor.

Raw data of microfossils were transformed into percentages over the total abundance and percentage abundance curves were plotted. Species with phylogenetic affinities and similar environmental significance were also grouped to better interpret distribution patterns.

For paleoenvironmental reconstructions, Q-mode cluster and R-mode factor analyses have been performed on the data set, after exclusion of rare species (< 2%) and grouping of species that have a discontinuous, scattered distribution at generic level. Q-mode cluster analysis was used to determine the overall statistical similarity between samples. The Q-mode clustering of the reduced data set was carried out using PAST (1.19) statistical software package of Hammer *et al.* (2000), and the results were reported as Euclidean distances and arranged in hierarchical dendrograms. R-mode factor analysis was performed in order to obtain a more accurate differentiation of the planktonic foraminiferal assem-

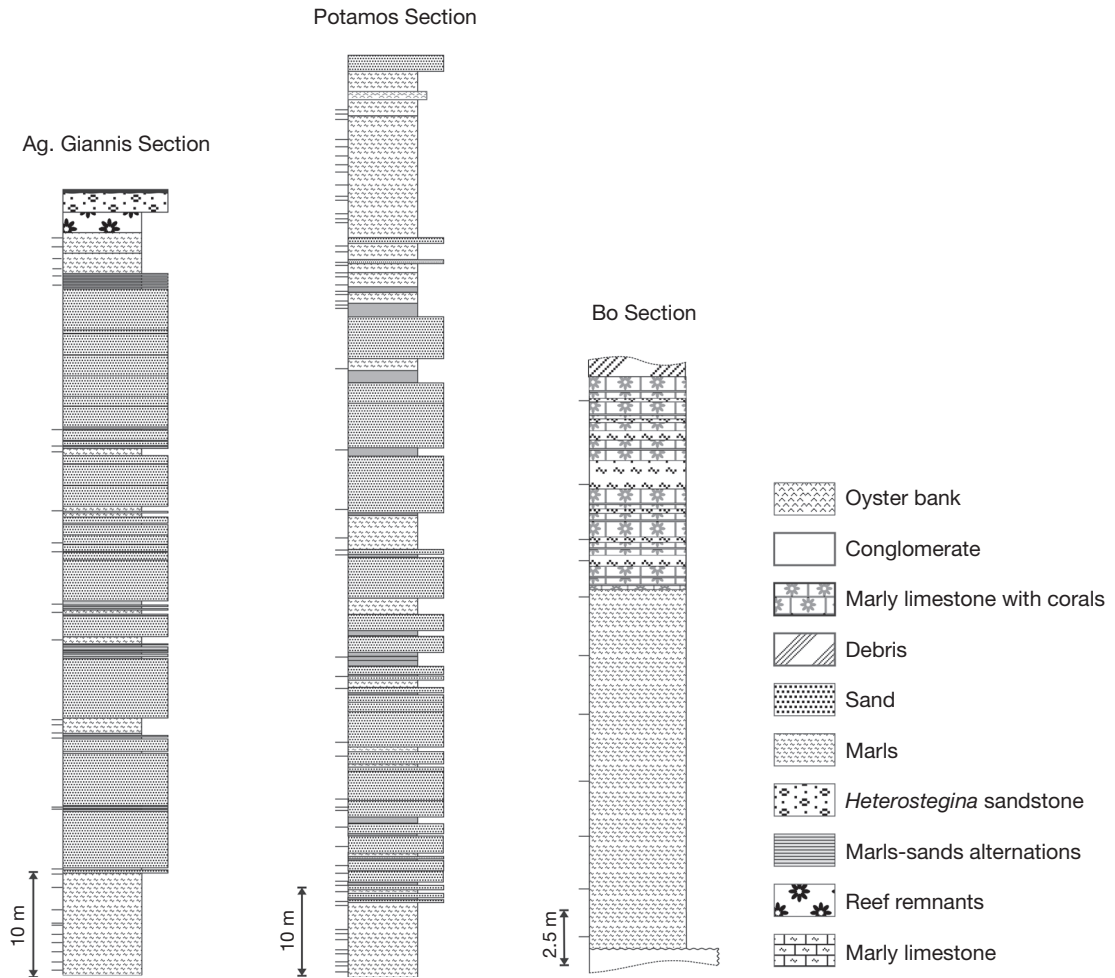


Fig. 2. — Lithostratigraphical columns of the Ag. Giannis, Potamos and Bo sections, Gavdos Island, Greece.

blages extracted from the Q-mode cluster analysis, into environmentally significant groups.

The sea surface temperature record is based on foraminiferal assemblages and relative abundance of each species as indicators of particular environmental conditions. Therefore, SST curves were constructed using the method of Cita *et al.* (1977), and followed by Spezzaferri (1995) and Spezzaferri *et al.* (2002), derived from the algebraic sum of the percentage of warm indices (with a positive value) and cool indices (with a negative value).

DISCUSSION OF THE DATA AND RESULTS

PLANKTONIC FORAMINIFERAL TRENDS

Taxonomical concept

The quantitative analysis of the planktonic foraminifera identified follows a stable taxonomical concept in the three sections, in order to establish a planktonic foraminiferal biostratigraphic framework for the studied sections and examine the changes in sea-surface conditions and climate. Species having similar ecological characteristics and

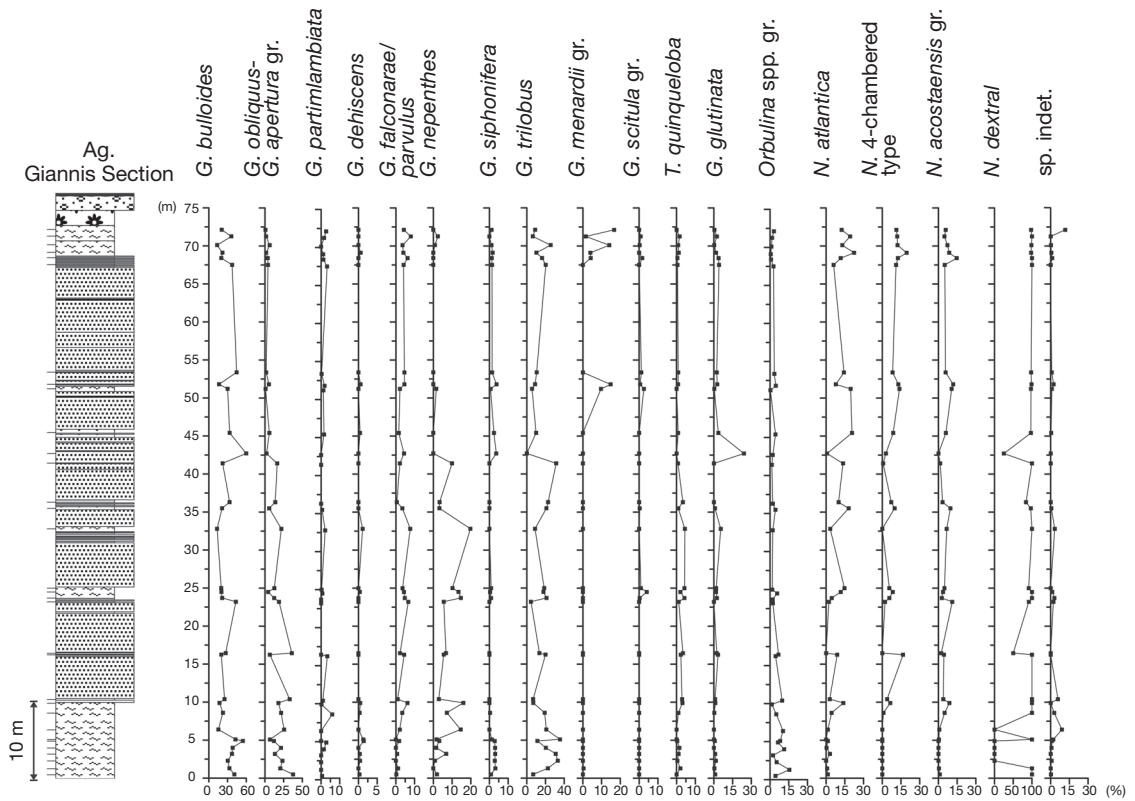


FIG. 3. — Relative frequency curves of the planktonic foraminifera identified in Ag. Giannis Section. Refer to Figure 2 for the explanation of the lithostratigraphical column.

according to their lineage affinities were counted together.

In the three studied sections we identified 24 species lumped into 18 groups presented in the Figures 3, 4 and 5.

The *Globigerina bulloides* group includes the species *G. bulloides* and *G. falconensis*. Small-sized specimens, under poor preservation conditions were difficult to distinguish, while both species have the same ecological requirements.

The species *Globigerinoides obliquus* and *Globoturborotalita apertura* were counted and plotted together. Under conditions of poor preservation, the secondary aperture of *Globigerinoides obliquus* was difficult to identify. However, as these species present the same morphological features and ecological habits, they were lumped into one group.

The specimens identified under the label of *Paragloborotalia partimlabiata* are not the typical ones, resembling more to *P. cf. partimlabiata* described by Foresi *et al.* (2002) and to the ones described by Hilgen *et al.* (2000) and Turco *et al.* (2001) as *Globorotalia partimlabiata*.

Globoquadrina sp. is distinguished from *Globoquadrina dehiscens* and counted separately, following the taxonomic concept of Hilgen *et al.* (2000). Specimens identified as *Globoquadrina* sp. resemble *Globoquadrina* sp. 1 taxon.

Specimens identified as *Globorotaloides falconarae* includes the types described before as *Catapsydrax parvulus* (Kennett & Srinivasan 1983; Zachariasse 1992). In the Mediterranean, the small-size type of *G. falconarae* is indistinguishable from *C. parvulus* and it has been found that there are no differences between these two species (Foresi *et al.* 2002).

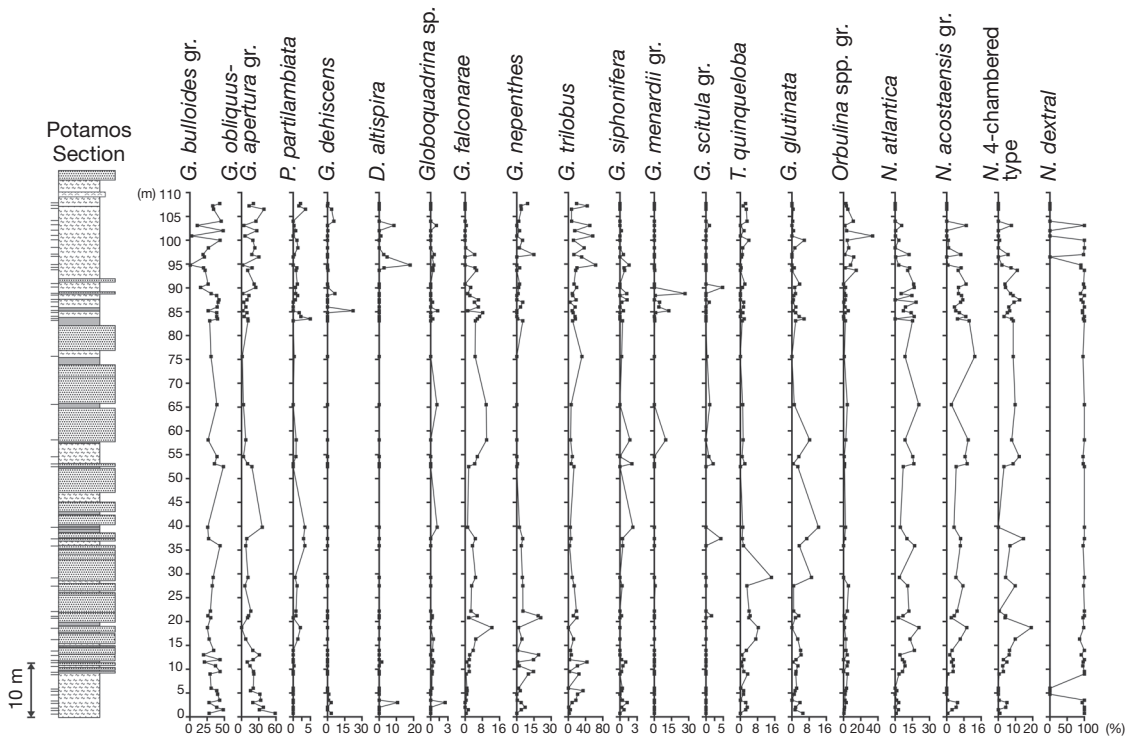


FIG. 4. — Relative frequency curves of the planktonic foraminifera identified in Potamos Section. Refer to Figure 2 for the explanation of the lithostratigraphical column.

The *Globorotalia menardii* group comprises the keeled globorotaliids of the studied time interval whereas the *Globorotalia scitula* group is the label used for all unkeeled globorotaliids.

The *Turborotalita quinqueloba* group includes also relatively small-sized specimens with five chambers in the final whorl which gradually increase in size and low arched aperture, sometimes bordered by a thin lip.

The *Orbulina* spp. group comprises the species *O. suturalis*, *O. universa* and *O. bilobata* and the *Globigerinoides trilobus* group includes *G. trilobus* and *G. sacculifer* type.

Within the group of neogloboquadrinids, for the biostratigraphical framework of the sections, three types have been discerned: *N. atlantica*, *N. acostaensis* s.s. and the so-called *N.* 4-chambered type. We maintain the same species concept as

applied in the study of Monte Gibliscemi Section (Hilgen *et al.* 2000) and in Monte dei Corvi (Hilgen *et al.* 2003) which are astronomically tuned, to compare their distribution pattern and define the biostratigraphic position of the studied sections in absolute ages. The so-called *N.* 4-chambered types are characterized by a medium to low arched extra umbilical aperture with or without lip and generally four chambers in the final whorl (Hilgen *et al.* 2000). Our *N. atlantica* specimens are referred to *N. atlantica praeatlantica* of Foresi *et al.* (2002) and to the small size *N. atlantica* of Hilgen *et al.* (2000) described before as *Neogloboquadrina continuosa* (Dermitzakis 1978).

However, in order to estimate paleoenvironmental changes, we assume that species belonging to the same evolutionary lineage have a similar habitat. Therefore, *N. acostaensis*, *N. atlantica* and

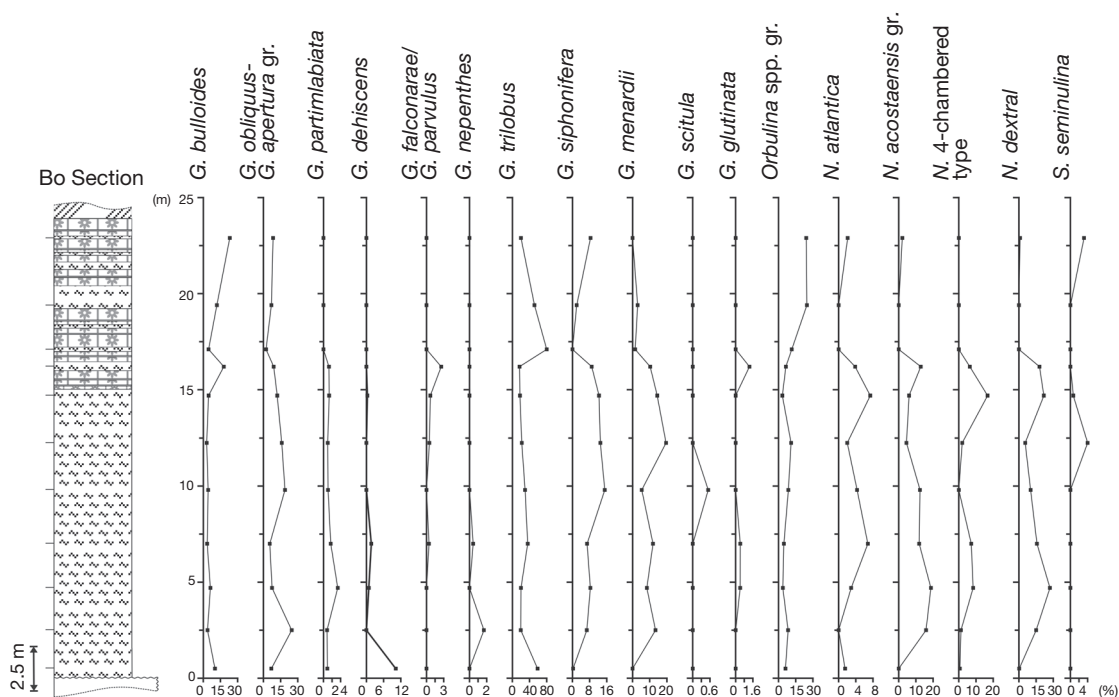


FIG. 5. — Relative frequency curves of the planktonic foraminifera identified in Bo Section. Refer to Figure 2 for the explanation of the lithostratigraphical column.

N. 4-chambered type are combined into the same ecological taxa labeled *Neogloboquadrina acostaensis* group. Different coiling directions of the *Neogloboquadrina* group have been counted separately as for the studied time interval coiling-changes of this group have been proven to have potential biostratigraphic significance.

Faunal Pattern

The percentage curves of planktonic foraminiferal taxa for each section are plotted in Figures 3, 4 and 5. The abundance pattern of each group is analyzed, in terms of abundance, common occurrence, regular occurrence, scattered occurrence and absence in the three studied sections.

The *Globigerina bulloides* group is abundant in Ag. Giannis and Potamos sections, being the main faunal constituent all through the successions. There is a decrease of the group at the last samples of Ag. Giannis and some oscillations are observed in the upper part of Potamos Section (Figs 3; 4).

In Bo Section this group shows an overall upward increase (Fig. 5).

The *G. obliquus-G. apertura* group is continuously present in our records. Particularly, in Ag. Giannis and Bo sections it reaches higher abundance values in the middle part of the successions (at 45.4 m and 16.2 m respectively) whereas, in Potamos Section, the group shows a significant decrease in the middle part (55-75 m), reaching its lowest abundance value and then it increases again.

Paragloborotalia partimlabiata is present in all sections displaying low percentage values. *Globoquadrina* sp. specimens were found in low percentages in Potamos Section. In Ag. Giannis Section the species is present up to 51.2 m in small numbers and for this reason its distribution is not plotted. In Bo Section, poor preservation did not allow the recognition of the species. *Globoquadrina dehiszens* is found only in the lower interval, up to 5 m in Ag. Giannis and Bo sections, while in Potamos Section it is present in the lower and

upper part, showing the same distribution with *Dentoglobigerina altispira*, which is present only in Bo Section.

In Ag. Giannis and Potamos sections, *Globorotaloides falconarae* is continuously present yet in small percentages. This pattern is comparable with that of Gibiliscemi (Hilgen *et al.* 2000), Monte dei Corvi (Hilgen *et al.* 2003) sections and Tremiti Island (Foresi *et al.* 2002). In Potamos Section the group shows an important influx at 23 m and is more abundant from the 55 m to 85 m, while in Bo Section its occurrence is restricted and exists in very small percentages, being more abundant at 15-20 m, yet in small percentages.

The distributional pattern of *G. trilobus* does not display any significant variations, being abundant in the three sections apart from Ag. Giannis Section which seems to be nearly absent in the middle part of the record. In Bo Section the species reaches higher percentages values.

The plot of *Globoturborotalita nepenthes* shows a differential distribution pattern in the three studied sections. In Ag. Giannis Section, it is found in significant percentages up to 42.7 m, being more abundant (up to 20%) at 6, 10, 24.5 and 32.8 m of the section. Then it vanishes to reappear in small numbers at 51.2 and 72.12 m. In Potamos Section, it occurs in the lower part of the succession, it vanishes in the interval 40-80 m to reoccur in the upper part, showing a significant influx at 97 m. In Bo Section the species occurs only in the lower part.

The species *Globigerinella siphonifera* is quite abundant in Bo Section showing a decrease in the upper part, while in Ag. Giannis Section, it exists in the basal and upper parts. In Potamos Section, the species occurs in successive intervals being more abundant in the middle part, yet in small percentages.

The *Globorotalia menardii* group is rare and occasionally reaches significant percentages with the exception of Bo Section. In particular, in Bo Section the group is abundant (max. 20%) from the base up to the 19.4 m displaying two pronounced high values at 2.5 m and 15 m and then decreases significantly. In Ag. Giannis Section two significant peaks at 50 and 68 m were observed. In Potamos

Section these two peaks appear a little later in the succession at 58 and 85-90 m.

The *Globorotalia scitula* group occurs in small percentages in the three sections. In Bo Section, the group shows one short influx at 9.8 m, while in Ag. Giannis and Potamos sections it shows three scattered influxes.

The *Turborotalita quinqueloba* group shows almost the same distribution in Ag. Giannis and Potamos sections, occurring continuously up to 35 and 45 m respectively, and then decreasing gradually showing some short influxes up to the top of the sections. In Bo Section the species was not identified.

The distribution pattern of the species *Globigerinita glutinata* is characterized by high percentage values in the middle part of Ag. Giannis Section, and in the interval 30-70 m in Potamos Section. The species is rare in Bo Section.

The *Orbulina* spp. group displays an opposite distributional pattern between Ag. Giannis and Potamos Section being abundant in the lower part in Ag. Giannis and in the upper part of Potamos Section. In Bo Section is consistently ranging around 15% increasing to the top.

The *N. acostaensis* group is present in low numbers in the basal part of Potamos Section, being regularly abundant after the 10 m. In Ag. Giannis Section the group enters in the planktonic foraminiferal fauna at around 10 m of the section and in Bo Section it is abundant from the base. *Neogloboquadrina atlantica* displays a similar distribution pattern. *Neogloboquadrina* 4-chambered types do not show any significant trend in faunal pattern.

Biostratigraphy

The lack of paleomagnetic data and the direct tuning of the lithological cycles due to intercalated sandstones with the orbital curves in the investigated sections did not allow the astronomical calibration of the investigated sections. Therefore the age control of the three studied sections is based on biostratigraphical criteria such as the regular occurrence of *Globigerinoides obliquus*, the absence of *Paragloborotalia siakensis*, the regular occurrence of neogloboquadrinids and the coiling direction of *Neogloboquadrina* specimens. In order to give a more accurate biostratigraphic correlation we

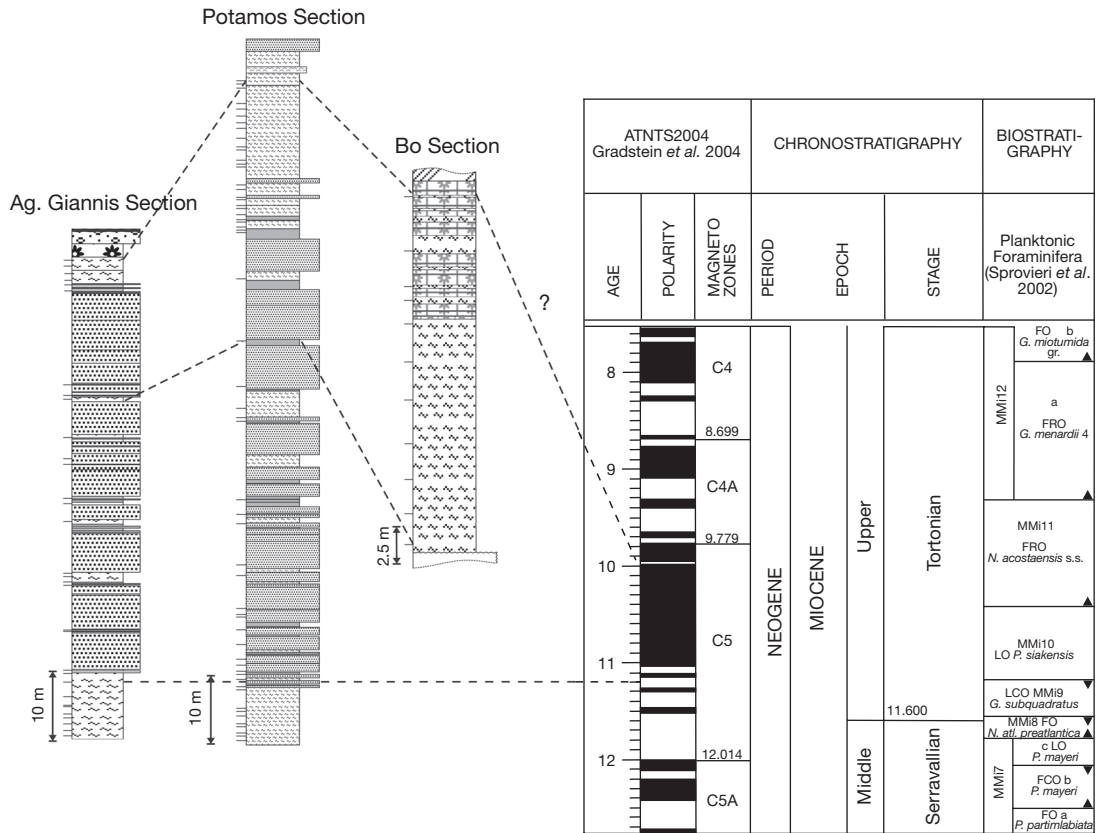


FIG. 6. — Litho-, bio- and chronostratigraphy of the studied sections in Gavdos Island, Greece.

use the *G. menardii* distribution pattern as a local correlative index which seems to show more significant peaks.

In Ag. Giannis and Potamos sections, *G. menardii* shows significant abundances from the middle to the top part of the sections. In Bo Section this group appears to be significant from near the base of the succession.

Neogloboquadrina types are the main constituents in our record, therefore the most significant biostratigraphic marker species. In our record, *Neogloboquadrina* species are continuously present from the base in Bo Section and above the 10 m in Potamos and Ag. Giannis sections. According to the distributional pattern of this group in the investigated sections (Figs 3-5) we assume that this level corresponds to the second influx of the

neogloboquadrinids recognized in the Mediterranean (Giblischemi, Tremiti Island and Monte dei Corvi) dated at 11.178 Ma (Hilgen *et al.* 2000) and 11.21 Ma (Foresi *et al.* 2002), at around the same level of the last occurrence of the species *Paragloborotalia siakensis* (11.21 Ma, Hilgen *et al.* 2000; Caruso *et al.* 2002; Di Stefano *et al.* 2002; Foresi *et al.* 2002; Lirer *et al.* 2004; Iaccarino *et al.* 2004).

Moreover, during the studied time interval, coiling changes of the *Neogloboquadrina* species have been proven to have potential biostratigraphic significance, being random between 11.781 and 11.546 Ma and persistently right coiling (> 80%) between 11.178 and 10.011 Ma (Hilgen *et al.* 2000; Foresi *et al.* 2002). In the three studied sections right coiling seems to prevail in all samples.

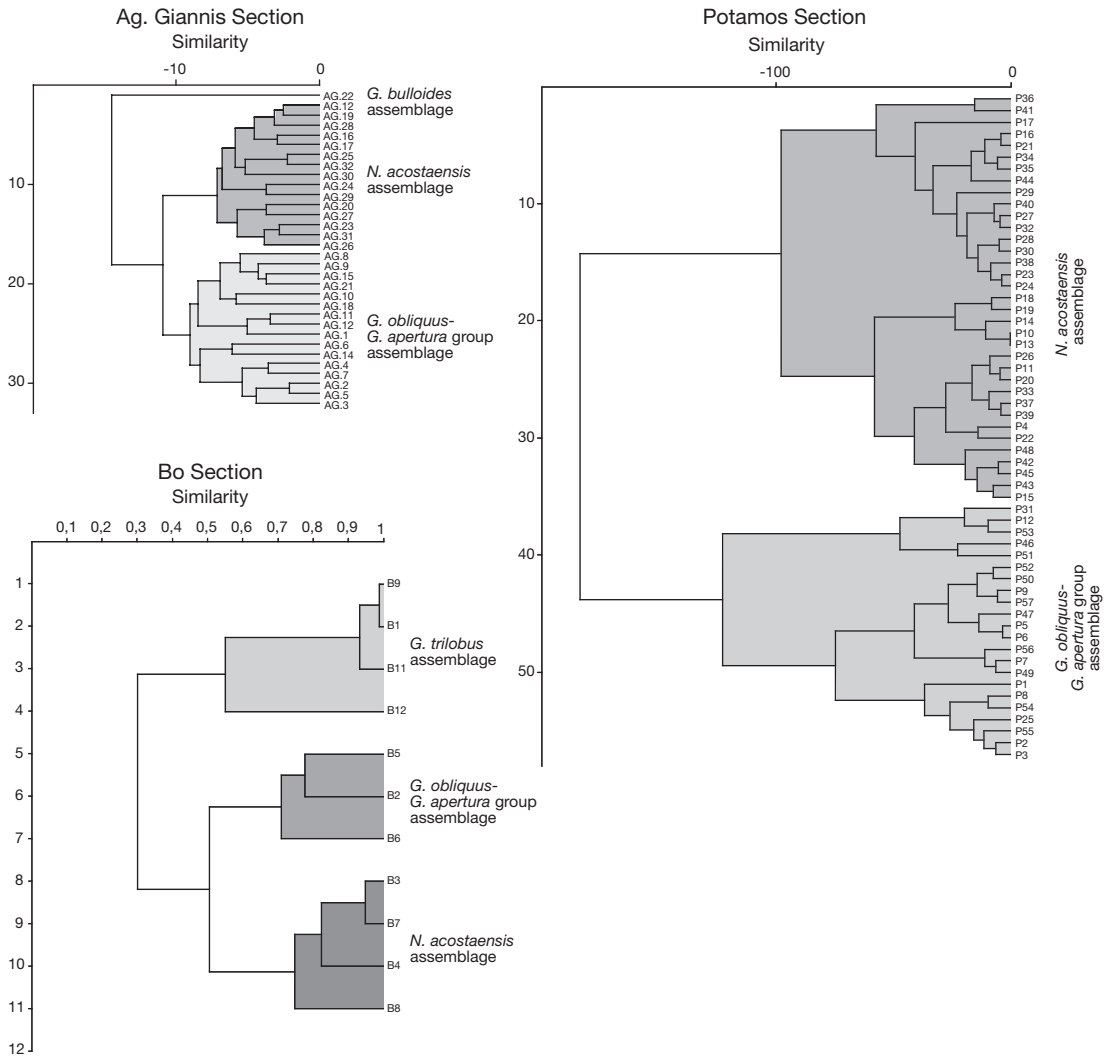


FIG. 7. — Dendrograms resulting from Q-mode cluster analysis and the assemblages identified in each section.

This agrees with the absence of *Paragloborotalia siakensis*, therefore we assume that the sections biostratigraphically span the interval above the last occurrence of this species.

The species *Paragloborotalia partimlabiata*, which is characteristic in the middle Miocene planktonic foraminifera assemblages, occurs in low percentages. The last occurrence of this species in Mediterranean is reported at 9.91 Ma (Hilgen *et al.* 2000).

Consequently and according to the data derived from the distributional pattern of the neogloboquadrinids, Ag. Giannis and Potamos sections are partly isochronous and are attributed to the lower Tortonian, in a time interval spanning from 11.21 to 10.01 Ma (Fig. 6). This conclusion is further supported by the distributional pattern of *G. subquadratus* which occurs very rarely and in low percentages (< 2%) in the basal part of these two sections. The last common occurrence

TABLE 1. — Factor loadings for the planktonic foraminiferal species imported into statistical analysis (Ag. Giannis Section).

Species	PCA1	PCA2
<i>G. obliquus</i> - <i>G. apertura</i> group	-0.4302	-0.3703
<i>G. trilobus</i>	-0.1391	-0.2836
<i>G. bulloides</i> group	-0.2891	0.8219
<i>G. falconarae</i>	0.06748	0.001291
<i>G. menardii</i> group	0.1426	-0.01988
<i>G. nepenthes</i>	-0.04945	-0.2659
<i>P. partimlabiata</i>	0.01394	0.002307
<i>T. quinqueloba</i>	-0.003351	-0.04831
<i>G. scitula</i> group	0.0198	0.001748
<i>G. siphonifera</i>	-0.01252	0.04546
<i>N. acostaensis</i>	0.8189	0.03232
<i>Orbulina</i> spp.	-0.1151	-0.03465
<i>G. glutinata</i>	-0.009742	0.1707

TABLE 2. — Factor loadings for the planktonic foraminiferal species imported into statistical analysis (Potamos Section).

Species	PCA1	PCA2
<i>G. obliquus</i> - <i>G. apertura</i> group	-40.208	83.713
<i>G. trilobus</i>	-42.974	-66.386
<i>G. dehiscons</i>	0.40718	1.8608
<i>G. falconarae</i>	18.984	1.1056
<i>G. menardii</i> group	6.8048	-1.8073
<i>G. nepenthes</i>	0.57255	14.138
<i>P. partimlabiata</i>	1.9447	1.4548
<i>T. quinqueloba</i>	4.0001	4.6631
<i>G. siphonifera</i>	0.67845	0.16323
<i>N. acostaensis</i>	100.89	3.5149
<i>Orbulina</i> spp.	-12.348	-11.195
<i>D. altispira</i>	-4.6052	-8.7671

TABLE 3. — Factor loadings for the planktonic foraminiferal species imported into statistical analysis (Bo Section).

Species	PCA1	PCA2
<i>D. altispira</i>	0.01	-0.06
<i>G. bulloides</i> group	0.00	-0.50
<i>G. dehiscons</i>	-0.05	-0.07
<i>G. menardii</i> group	0.19	0.36
<i>N. acostaensis</i>	0.39	-0.43
<i>G. obliquus</i> - <i>G. apertura</i> group	0.16	0.62
<i>Orbulina</i> spp.	-0.11	0.07
<i>S. seminulina</i>	0.01	0.06
<i>G. siphonifera</i>	0.17	0.15
<i>G. trilobus</i>	-0.86	0.02

(LCO) of *G. subquadratus*, has been dated in the Mediterranean at 11.54 Ma (Hilgen *et al.* 2000; Caruso *et al.* 2002; Lirer *et al.* 2002). This event slightly postdated the first regular occurrence (FRO) of *G. obliquus* (dated at 11.47 Ma) and coincides with the end of the first influx of the neogloboquadrinids (FO of neogloboquadrinids 11.78 Ma) (Hilgen *et al.* 2000, 2003; Foresi *et al.* 2002). In our record, *G. obliquus* occurs regularly in all sections.

As far as Bo Section is concerned, neogloboquadrinids distributional pattern does not display any significant trend, being abundant from the basal part. Besides, *G. menardii* group is abundant from the base (Fig. 5), while in the other two sections this group is abundant at 50 and 55 m respectively. So, the base of Bo Section does not correspond to the base of the other two sections but must be a little younger (Fig. 6).

PLANKTONIC FORAMINIFERAL ASSEMBLAGES

In order to describe the faunal succession, the samples of each section were treated with Q-mode cluster analysis to discriminate critic patterns in planktonic foraminiferal assemblages. Each assemblage is characterized by dominant species as follows.

Ag. Giannis Section

For Ag. Giannis Section, three assemblages were clearly identified (Fig. 7).

Assemblage A is characterized by the abundant occurrence of *Globigerinoides obliquus*-*Globoturbotalita apertura* and accordingly, is identified as a warm-oligotrophic assemblage (Bé 1977; Bé & Tolderlund 1971; Hemleben *et al.* 1989).

Assemblage B is characterized by the dominance of *Neogloboquadrina acostaensis*. *N. acostaensis* thrives in cool water, in particular in oceanographic regions where a shallow nutricline favors the formation of a Deep Chlorophyll Maximum (DCM) (Bé & Tolderlund 1971; Fairbanks & Wiebe 1980). Since *Neogloboquadrina* spp. thrives in eutrophic waters, and is mostly found in association with a DCM at the base of the euphotic layer by upward mixing of nutrients from deeper waters, its high abundance suggests stratified conditions within the euphotic layer.

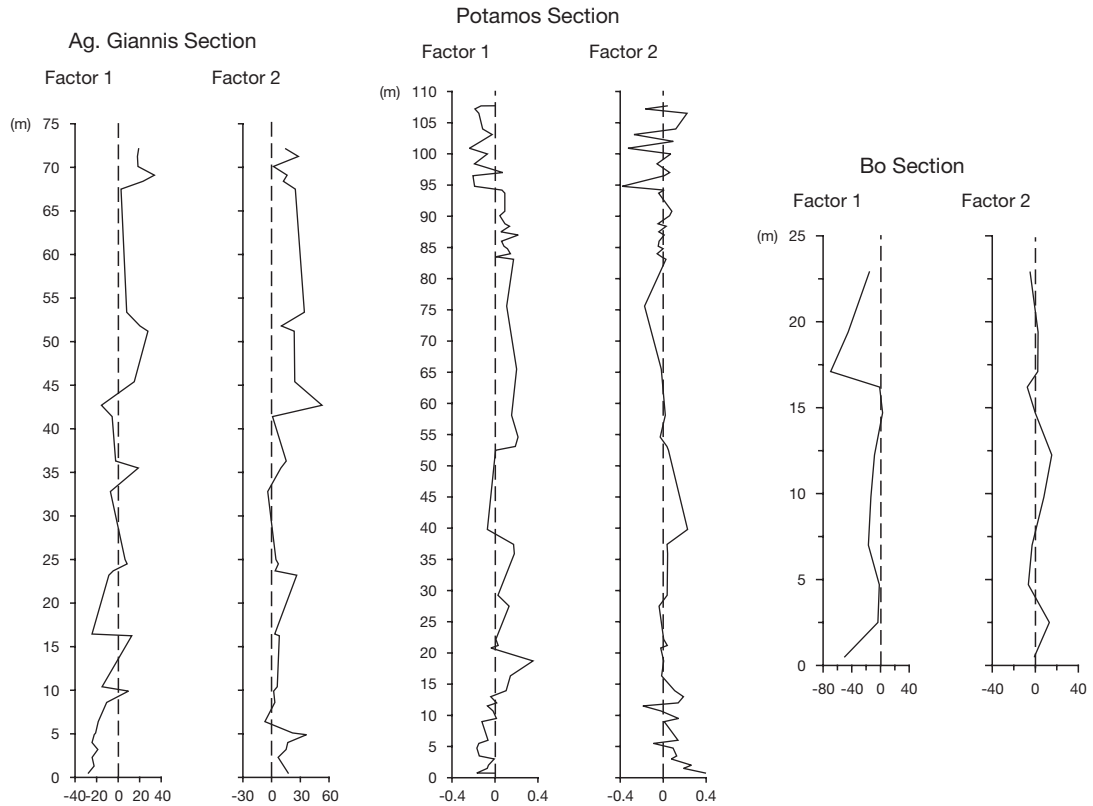


Fig. 8. — The score plots of the factors revealed from the R-mode analysis for each section.

Finally, Assemblage C is dominated by *Globigerina bulloides* and *Globigerinita glutinata* which are both species often associated with highly productive waters (Bé 1977; Bé & Tolderlund 1971; Ottens 1992; Naidu & Malmgren 1996) characterized by vertical mixing of upwelling (Brock *et al.* 1992; Duplessy *et al.* 1981; Hemleben *et al.* 1989; Kipp 1976; Thiede 1983; van Leeuwen 1989; Zhang 1985).

According to the stratigraphic distribution of the three identified assemblages, the Ag. Giannis Section can be divided into four assemblage zones: 1) stratigraphic interval from 0 to 23.7 m composed of Assemblage A; 2) stratigraphic interval from 23.7 to 41.4 m consisting of assemblages A and B; 3) the middle part at 42.7 m composed of Assemblage C; and 4) the upper part 45.4 to 72.12 m composed of Assemblage B.

R-mode factor analysis distinguished two significant factors accounting for 75.2% of the total variance (Table 1). The scores of these factors (Fig. 8) identify three significant planktonic foraminiferal assemblages termed from the dominant taxa. The first factor accounts for 50.06% of the total variance and exhibits a bipolar character: one pole is dominated by *N. acostaensis* (0.819) and the other pole is dominated by *G. obliquus-G. apertura* group (-0.430). The score plot of the first factor indicates paleoceanographic conditions characterized by cool- and warm-water non-upwelling assemblages.

The second factor represents the 24.63% of the total variance and exhibits high positive loadings only in *G. bulloides* (0.822). *Globigerina bulloides* is a species of subpolar water masses but highly dependent on enhanced food levels by strong

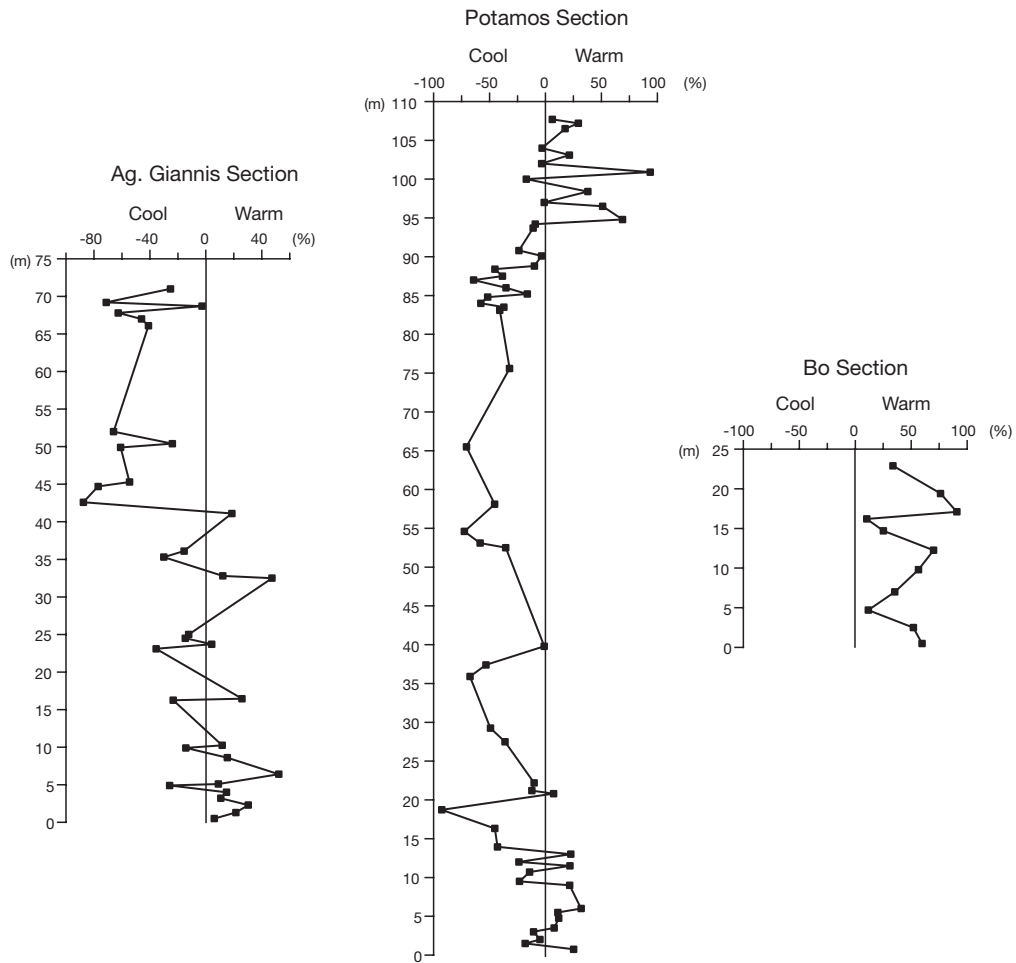


Fig. 9. — SST curves based on the percentages of warm- and cool-water indices.

fresh-water inputs, upwelling or strong seasonal mixing (Hemleben *et al.* 1989; Lourens 1994; Pujol & Vergnaud-Grazzini 1995). Thus, high values of the second factor indicate increased productivity caused by such oceanographic conditions.

Potamos Section

In Potamos Section, Q-mode cluster analysis revealed two distinct assemblages as it is shown in the resulting dendrogram (Fig. 7).

Assemblage A contains 22 samples and contains warm water species such as *Globigerinoides obliquus*-*G. apertura* and *Globigerinoides trilobus*.

The warm-temperate water species *Orbulina* spp., *G. siphonifera* and *G. nepenthes* (Bé & Hutson 1977; Thunnel 1978; Kennett *et al.* 1985; Ravelo *et al.* 1990) also prevail in this assemblage.

Assemblage B is characterized by the abundant occurrence of *Neogloboquadrina acostaensis* and accordingly is identified as a cold-eutrophic assemblage.

The stratigraphic distribution of the two identified assemblages reveals three distinct intervals for the Potamos Section: 1) Interval I represents the lower part of the section from 0 to 14 m consisting mainly of the Assemblage A and one brief intercalation of

Assemblage B; 2) Interval II, from 14 to 95 m, is composed of Assemblage B and three subintervals containing Assemblage A; and 3) Interval III, from 95 to 107 m, consists of Assemblage A.

R-mode factor analysis distinguished two significant factors accounting for 72.87% of the total variance (Table 2).

The score of these factors (Fig. 8) identify two significant planktonic foraminiferal assemblages dominated by the dominant taxa.

The first factor accounts for 49.1% of the total variance and exhibits high positive loadings in *N. acostaensis*. Therefore, the first factor indicates cool periods with relatively high food availability.

The second factor accounted for 23.76% of the total variance and exhibits high positive loadings only in *G. obliquus-G. apertura* which constitutes a warm-oligotrophic component.

These score plots are quite comparable since we can observe that intervals where *N. acostaensis* is abundant *G. obliquus* decreases.

Bo Section

Three assemblages are clearly defined by Q-mode cluster analysis in Bo Section characterized by dominant species (Fig. 7).

Assemblage A is notable for the high percentages of the thermocline dwelling *N. acostaensis*. *Globigerinoides trilobus* and *G. menardii* are the secondary constituents of the assemblage.

The high percentages of *N. acostaensis* in combination with the high abundance values of the warm-oligotrophic *G. trilobus* produces some doubt as to whether the significance of the Assemblage A is exclusively temperate dependent. Modern representatives of neogloboquadrinids proliferate under eutrophic conditions (Ravelo *et al.* 1990; Reynolds *et al.* 1991; Pujol & Vergnaud-Grazzini 1995), spring blooms (e.g., Tolderlund & Bé 1971; Reynolds & Thunell 1986) or DCM (Fairbanks *et al.* 1982; Ravelo *et al.* 1990).

On the other hand, modern representatives of *G. trilobus* dwell in warm and oligotrophic surface waters (e.g., Bé & Hutson 1977). Therefore, the simultaneous increase in abundance of neogloboquadrinids and *G. trilobus* seem to designate increased seasonal contrasts in surface water pro-

ductivity. Moreover, Hallock (1987) suggests that a deeper photic zone in oligotrophic waters would give rise to diversified planktonic faunas due to increased primary productivity at depths. If this is true then Assemblage A is not a function of sea surface temperature but is better associated with changes in the thermocline and subsequent water stratification and increases in food supply.

Assemblage B is characterized by the presence of the species of *G. obliquus-G. apertura* group and *G. trilobus* which proliferate in warm nutrient-poor waters.

Finally, Assemblage C is characterized by the abundant occurrence of *Globigerinoides trilobus*. This almost monospecific assemblage is abundant where surface waters remain relatively warm and low nutrient contents prevail due to the existence of a relatively stable pycnocline at depths (Cifelli 1974; Thunell 1978; Hemleben *et al.* 1989; Pujol & Vergnaud-Grazzini 1989). According to Bé (1977), *G. trilobus* is a high-salinity tolerant, warm surface-water species, yet not so sensitive as *G. obliquus-G. apertura* group in reflecting sea surface nutrient conditions. Therefore, the high dominance of *G. trilobus* in this assemblage suggests that the main paleoenvironmental factor controlling the faunal pattern is temperature rather than productivity.

According to the stratigraphic distribution of the three assemblages, the section is characterized by brief alternating subintervals of assemblages A and B, while Assemblage C characterizes the lower and the upper parts of the section.

R-mode factor analysis yielded a two factor solution accounted for 77.67% of the total variance (Table 3; Fig. 8).

The first factor accounts for 70.45% of the total variance and is dominated by *G. trilobus* (-0.86). This species is considered as a warm climate indicator and thus the first factor emphasizes intervals of enhanced warm conditions (Boltovskoy & Wright 1976). Consequently, the first factor can be regarded as an index of the sea surface temperature variability.

The second factor accounted for 7.22% of the total variance exhibits a bipolar character: one pole is dominated by the *G. obliquus-G. apertura* group (0.62) and

the other is dominated by *N. acostaensis* (-0.43) and *G. bulloides* (-0.50). *Neogloboquadrina acostaensis* and *G. bulloides* flourish at waters with enhanced marine primary productivity whereas *G. obliquus*-*G. apertura* group indicates warm subtropical and oligotrophic conditions. Therefore, the fluctuations of the scores of this factor indicate variations in productivity.

PALEOCLIMATIC CURVES

Correct interpretation of the past climatic record left by fossil planktonic foraminifera in terms of oceanographic characteristics requires an understanding of the modern ecology, life cycle and shell calcification. For this work, we have used Cita *et al.* (1977), Thunell (1978), Spezzaferri & Premoli Silva (1991), Spezzaferri (1995), Pujol & Vergnaud-Grazzini (1995) and Spezzaferri *et al.* (2002).

Recovered species have been subdivided as follows:

- Warm-water indicators: *Globigerinoides trilobus*, *Globoturborotalita nepenthes*, *Globoturborotalita apertura*, *Orbulina* spp., *Globigerinoides obliquus* and *Globigerinella siphonifera*;
- Cool-water indicators: *Globigerina bulloides* group, *Neogloboquadrina acostaensis*, *Globigerinita glutinata*, *Turborotalita quiqueloba*, *Globorotalia scitula* group, *Globrotaloides falconarae*.

The SST curve (Fig. 9) of each section has been determined as the algebraic sum of the percentages of warm-water indicators, considered as positive values, and cold-water indicators, negative values. Other identified species were not included because of their uncertain climatic significance.

The paleoclimatic trend recognized at Ag. Gianis Section determines two major intervals. Each interval is characterized by a certain faunal composition reflecting the dominant climatic condition during the deposition.

The upper part of the paleoclimatic curve shows negative values associated with the high frequencies of *N. acostaensis* assemblage. As the warm water fauna is restricted, except of *G. trilobus* existing in low percentages, this interval is interpreted as a cool-temperate period. The influxes of *G. menardii* enhance the temperate conditions. The abrupt decline of the paleoclimatic curve at 42.7 m is characterized by the higher abundances of *G. bulloides*, indicative

of changing conditions of deposition, suggesting enhanced food levels by upwelling, strong seasonal mixing or river input.

The lower part of the paleoclimatic curve displays warmer conditions which are attested to by abundant frequencies of tropical-subtropical fauna such as *G. obliquus*-*G. apertura*, *G. nepenthes* and *G. trilobus*. The negative fluctuations recorded in this part of the sequence are characterized by short incursions of cold planktonic foraminifera indicative for unstable warming conditions prevailing during deposition.

In Potamos Section, low values of the paleoclimatic curve are more pronounced in the middle part of the section. The high abundance of the cool indices reflects the presence of strong upwelling episodes (dominance of *G. bulloides*), cooler conditions with brief warming periods (dominance of *G. obliquus*-*G. apertura* and *G. trilobus*).

The cooling interval recorded in this part starts after a short warming period at the base which is characterized by the nearly absence of neogloboquadrinids and the increase of the warm water fauna. The invasion of the neogloboquadrinids and the presence of cool planktonic species mark the beginning of the cool period which ends at the upper part. The upper part of the SST curve clearly displays warming conditions reflected by the high abundances of warm water fauna and the restriction of cool water species.

Warm climatic conditions prevail during the deposition of Bo Section. The SST curve shows a different climatic invasion towards high temperatures in contrast with the previous reported sections. Cool-water planktonic foraminifera have been almost removed from this area. Warm water assemblages dominate the fauna composition of the deposits, with the exception of the neogloboquadrinids, which are responsible for the oscillations present in the positive SST curve.

DISCUSSION

PALEOENVIRONMENTAL IMPLICATIONS

It is well documented that the thermocline is the most important element in charge for partitioning

in the water mass, and thus of the vertical distribution of planktonic foraminifera. Either normally warmer surface waters or the existence of a deeper thermocline quantitatively support “shallow water-dwellers” such as *Globigerinoides*, while a shallower thermocline or cool waters support deeper dwelling forms (Kennett *et al.* 1985; Ravelo *et al.* 1990).

Having this assumption in mind along with the distribution patterns of climatic indices in the three sections studied, the reconstruction of the paleoclimatic features for eastern Mediterranean early late Miocene and the variation in planktonic foraminiferal assemblages are attempted.

The three sections are located in the north to northwest side of Gavdos Island and constitute deposition in shelf environment. The prevalent lithologies in Bo shelf are reefal limestones alternating with marls, while marls and sands dominate in Potamos-Ag. Giannis shelves.

SST curves suggest the dominance of a cool-temperate sea-water current for most of the part of Ag. Giannis and Potamos successions, while the SST curve obtained for the Bo Section indicates that warm conditions characterized the Bo shelf, which is currently situated only a few hundred meters from the Potamos shelf. Such a differentiation in temperature cannot be practically explained with different geographical setting only, and an alternative explanation is needed. The overall cooling trend recorded in Ag. Giannis and Potamos sections can be related to the climatic cooling during Mi6 event of Miller *et al.* (1991) recorded also in Monte Gibliscemi Section (Sicily) by Turco *et al.* 2001 (10.4 Ma). This climatic cooling is reflected by significant faunal changes in the Mediterranean, such as the arrival of neogloboquadrinids, the increase in abundance of the *G. obliquus-G. apertura* group, replacing the tropical fauna of *G. subquadratus*, and the areal differentiation between *N. atlantica* and *N. acostaensis*.

The lithological and faunal variations surely reflect the influence of some local hydrological and other environmental factors. Locally, both the temperature and salinity may have accounted for at least part of this phenomenon. The persistent high percentage of *G. trilobus* in the Bo Section bears this information and its uninterrupted occurrence

may signal the existence of a warm shelf current, as this is also depicted by the most positive values in the SST curve of the Bo Section.

Moreover, the lithology and the benthos also bear supportive evidence, though they primarily evince the bottom environment. The occurrence of an epifauna-dominated environment (Drinia & Antonarakou 2004) implies a warmer, mesotrophic to nearly oligotrophic environment on the Bo shelf.

While the Bo shelf water as a whole is warm and oligotrophic, a slightly different situation might exist in Potamos-Ag. Giannis shelves, to the north. These settings are bathed mainly in cooler, mesotrophic to relatively eutrophic waters, with local upwelling occurring from time to time, as it is suggested by the high frequencies of *G. bulloides*, a species which its flourishing is attributed to elevated food levels due to coastal upwelling phenomena.

The comparison between Potamos-Ag. Giannis and Bo sections encourages us to conclude that an island may have acted as a barrier to the distribution of foraminifera. Perhaps its role was more significant during times of sea level fall: it acted as a biogeographic barrier, because there was no passage between the Bo shelf and the Potamos-Ag. Giannis shelves when sea level dropped. The Bo shelf water is warmer and nearly oligotrophic because it receives the gradational influence of warm currents and climatic warming from south to north. Structural limits could restrict water exchanges between the shelves, and a more temperate environment would become stabilized toward the north, subsequently encouraging the deposition of marls and sand.

Therefore, and according to our conclusions, oceanographic conditions were most favorable for the development of the reefal limestones in the Bo shelf. The stability of the water column and the high temperatures and low availability of nutrients that privileged the occurrence of warm-oligotrophic planktonic communities should also favor reef growth. Both reef corals and symbiont-bearing, oligotrophic planktonic foraminifera utilize algae to entrap nutrients in shallow, warm and well illuminated waters. Nowadays, such warm-oligotrophic and well illuminated waters exist in the Red Sea

whereas Sierro *et al.* (1999) mention the growth of reefs in the late Miocene Sorbas Basin.

On the contrary, in the Potamos-Ag. Giannis shelves, unsteady conditions and amplification of vertical mixing drove nutrients upwards and reduced surface temperatures. These conditions favored the flourishing of the symbiont-lacking planktonic foraminifera. Lower temperatures, enhanced salinities and higher levels of eutrophication in the water column were probably unfavorable for reef development in this part of the basin. Higher levels of eutrophication are often related with increasing turbidity in front of rivers, that reduces light intensity and, as a result, the reef development.

CONCLUSIONS

The early late Miocene of Gavdos Island, eastern Mediterranean, was characterized by temperate to cool sea-water temperature conditions interrupted by warming episodes as indicated by the SST curves from the Ag. Giannis and Potamos sections. The Bo Section, although adjacent, underwent different paleoceanographic evolution during that period. The Bo shelf was characterized by warm, nearly oligotrophic conditions which allowed the formation of reefal limestones.

We suggest that this difference between the Bo and Potamos-Ag. Giannis shelves is due to the barrier effect of an island which acted as an oceanographic and biogeographic barrier.

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REFERENCES

- ANGELIER J., LYBERIS N., LE PICHON X., BARRIER E. & HUCHON P. 1982. — The tectonic development of the Hellenic Arc and the Sea of Crete: a synthesis, *in* LE PICHON X., AUGOUSTITHIS S. S. & MASCLE J. (eds), *Geodynamics of the Hellenic Arc and Trench*. *Tectonophysics* 86: 159-196.
- BÉ A. W. H. 1977. — An ecological zoogeographic and taxonomic review of recent planktonic foraminifera, *in* RAMSAY A. T. S. (ed.), *Oceanic Micropaleontology*. Academic Press, London 1: 1-100.
- BÉ A. W. H. & HUTSON W. H. 1977. — Ecology of planktonic foraminifera and biogeographic patterns of life and fossil assemblages in the Indian Ocean. *Micropaleontology* 23: 360-414.
- BÉ A. W. H. & TOLDERLUND D. S. 1971. — Distribution and ecology of living planktonic foraminifera in surface waters of the Atlantic and Indian Oceans, *in* FUNNELL B. M. & RIEDEL W. R. (eds), *The Micropaleontology of Oceans*. Cambridge University Press, Cambridge: 105-149.
- BICCHI E., FERRERO E. & GONERA M. 2003. — Palaeoclimatic interpretation based on middle Miocene planktonic Foraminifera: Silesia Basin (Paratethys) and Monferrato (Tethys) records. *Palaeogeography Palaeoclimatology Palaeoecology* 196: 265-303.
- BOLTOVSKOY E. & WRIGHT R. 1976. — *Recent Foraminifera*. Springer, The Hague, 515 p.
- BROCK J. C., MCCLAIN C. R., ANDERSON D. M., PRELL W. L. & HAY W. W. 1992. — Southwest monsoon circulation and environments of recent planktonic foraminifera in the northwestern Arabian sea. *Paleoceanography* 7: 799-813.
- CARUSO A., SPROVIERI M., BONNANO A. & SPROVIERI R. 2002. — Astronomical calibration Serravallian-Tortonian Case Pelacani section (Sicily, Italy), *in* IACCARINO S. M. (ed.), *Integrated stratigraphy and paleoceanography of the Mediterranean middle Miocene*. *Rivista Italiana di Paleontologia e Stratigrafia* 108: 297-306.
- CIFELLI R. 1974. — Planktonic foraminifera from the Mediterranean adjacent Atlantic waters (cruise 49 of the Atlantis II, 1969). *Journal of Foraminifera Research* 4: 171-183.
- CIFELLI R. 1976. — Evolution of ocean climate and the record of planktonic foraminifera. *Nature* 264: 431-432.
- CITA M. B., VERGNAUD-GRAZZINI C., ROBERT C., CHAMLEY H., CIARANI N. & D'ONOFRIO S. 1977. — Paleoclimatic record of a long deep sea core from the Eastern Mediterranean. *Quaternary Research* 8: 205-235.
- DERMITZAKIS M. D. 1978. — Stratigraphy and sedimentary history of the Miocene of Zakynthos (Ionian Islands, Greece). *Annales géologique des Pays helléniques* 29: 47-186.
- DI STEFANO E., BONOMO S., CARUSO A., DINARÉS-TURELL J., FORESI L., SALVATORINI G. & SPROVIERI R. 2002. — Calcareous plankton bio-events in the Miocene Case Pelacani section (Southeastern Sicily,

- Italy), in IACCARINO S. M. (ed.), Integrated stratigraphy and paleoceanography of the Mediterranean middle Miocene. *Rivista Italiana di Paleontologia e Stratigrafia* 108: 307-324.
- DRINIA H. & ANTONARAKOU A. 2004. — Foraminiferal biofacies on the Bo shelf, Gavdos Island, Eastern Mediterranean: paleoenvironmental implications. *Fourth International Congress "Environmental Micropaleontology, Microbiology and Meiobenthology" Isparta, Turkey, September 13-18, 2004*, Abstracts: 53-54.
- DRINIA H., ANTONARAKOU A., TSAPARAS N., DERMITZAKIS M. D. & DOUKAS C. 2004. — Foraminiferal sequence eco-biostratigraphy of the middle-early late Miocene, Potamos Section from Gavdos Island, Greece, in STEININGER F. F., KOVAR-EDER J. & FORTELIUS M. M. (eds), The middle Miocene environments and ecosystem dynamics of the Eurasian neogene (EEDEN). *Courier Forschungsinstitut Senckenberg* 249: 29-43.
- DUPLESSY J. C., BÉ A. W. H. & BLANC P. L. 1981. — Oxygen and carbon isotopic composition and biogeographic distribution of planktonic foraminifera in the Indian Ocean. *Palaeogeography Palaeoclimatology Palaeoecology* 33: 9-46.
- FAIRBANKS R. G. & WIRBE P. H. 1980. — Foraminifera and chlorophyll maximum: vertical distribution, seasonal succession, and paleoceanographic significance. *Science* 209: 1524-1526.
- FAIRBANKS R. G., SVERDLOVE M., FREE R., WIEBE P. H. & BÉ A. W. H. 1982. — Vertical distribution of living planktonic foraminifera from the Panama basin. *Nature* 298: 841-844.
- FLOWER B. P. 1999. — Data report: planktonic foraminifera from the subpolar North Atlantic and Nordic seas: sites 980-987, 907. *Proceedings of the Ocean Drilling Program Scientific Results* 162: 19-34.
- FLOWER B. P. & KENNETT J. P. 1994. — The middle Miocene climatic transition: East Antarctic ice sheet development, deep ocean circulation and global carbon cycling. *Palaeogeography Palaeoclimatology Palaeoecology* 108: 537-555.
- FORESI L. M., BONOMO S., CARUSO A., DI STEFANO A., DI STEFANO E., IACCARINO S. M., LIRER F., SALVATORINI G. & SPROVIERI R. 2002. — High resolution calcareous plankton biostratigraphy of the Serravallian succession of the Tremiti Islands (Adriatic Sea, Italy), in IACCARINO S. (ed.), Integrated stratigraphy and paleoceanography of the Mediterranean middle Miocene. *Rivista Italiana di Paleontologia e Stratigrafia* 108: 257-273.
- HALLOCK P. 1987. — Fluctuations in the trophic resource continuum: a factor in global diversity cycles? *Paleoceanography* 2: 457-471.
- HAMMER O., HARPER D. A. T. & RYAN P. D. 2000. — PAST. Palaeontological statistics software package for education and data analysis. *Palaeontologia Electronica* 4 (1): 1-9.
- HEMLEBEN CH., SPINDLER M. & ANDERSON O. R. 1989. — *Modern Planktonic Foraminifera*. Springer Verlag, New York, 363 p.
- HILGEN F. J., KRIJGSMAN W., RAFFI I., TURCO E. & ZACHARIASSE W. J. 2000. — Integrated stratigraphy and astronomical calibration of the Serravallian/Tortonian boundary Section at Monte Gibliscemi (Sicily, Italy). *Marine Micropaleontology* 38: 181-211.
- HILGEN F. J., ABDUL AZIZ H., KRIJGSMAN W., RAFFI I. & TURCO E. 2003. — Integrated stratigraphy and astronomical calibration of the Serravallian and lower Tortonian at Monte dei Corvi (middle-upper Miocene, northern Italy). *Palaeogeography Palaeoclimatology Palaeoecology* 199: 229-264.
- IACCARINO S. 1985. — Mediterranean Miocene and Pliocene planktic Foraminifera, in BOLLI H. M., SAUNDERS J. B. & PERCH-NIELSEN K. (eds), *Plankton Stratigraphy*. Cambridge University Press, London: 283-314.
- IACCARINO S. M., LIRER F., BONOMO S., CARUSO A., DI STEFANO A., DI STEFANO E., FORESI L. M., MAZZEI R., SALVATORINI G., SPROVIERI R. & TURCO E. 2004. — Astrochronology of late middle Miocene Mediterranean sections, in D'ARGENIO B., FISCHER A. G., PREMOLI-SILVA I., WEISSERT H. & FERRERI V. (eds), *Cyclostratigraphy: an essay of approaches and case histories. Society for Sedimentary Geology Special Publication* 81: 25-42.
- KENNETT P. J. & SRINIVASAN M. S. 1983. — *Neogene Planktonic Foraminifera: a Phylogenetic Atlas*. Hutchinson Ross Publishing Co., Stroudsburg, PA, 265 p.
- KENNETT P. J., KELLER G. & SRINIVASAN M. S. 1985. — Miocene planktonic foraminifera biogeography and paleoceanographic development of the Indo-Pacific region, in KENNETT P. J. (ed.), *The Miocene Ocean: paleoceanography and biogeography. The Geological Society of America Memoir* 163: 197-236.
- KIPP N. G. 1976. — New transfer function for estimating past sea surface conditions from sea level distribution of planktonic foraminifera in the North Atlantic. *The Geological Society of America Memoir* 145: 3-41.
- LIRER F. & IACCARINO S. 2005. — Integrated stratigraphy (cyclostratigraphy and biochronology) of late middle Miocene deposits in the Mediterranean area and comparison with the North and Equatorial Atlantic Oceans: synthesis of the major results. *Terra Nova* 17 (4): 338-349.
- LIRER F., CARUSO A., FORESI L. M., SPROVIERI M., BONOMO S., DI STEFANO A., DI STEFANO E., IACCARINO S. M., SALVATORINI G., SPROVIERI R. & MAZZOLA S. 2002. — Astrochronological calibration of the upper Serravallian/lower Tortonian sedimentary sequence at Tremiti Islands (Adriatic Sea, Southern Italy), in IACCARINO S. (ed.), Integrated stratigraphy and paleoceanography of the Mediterranean middle

- Miocene. *Rivista Italiana di Paleontologia e Stratigrafia* 108: 241-256.
- LIRER F., CARUSO A., FORESI L. M., IACCARINO S. & IACUMIN P. 2004. — Paleoclimatic changes in the Seravallian record of the Mediterranean area, in COCCIONI R., GALEOTTI S. & LIRER F. (eds), Proceedings of the First Meeting of Environmental Micropaleontology for young Italian researcher. *Grzybowski Foundation Special Publication* 9: 77-96.
- LOURENS L. J. 1994. — *Astronomical Forcing of Mediterranean Climate During the Last 5.3 Million Years*. Ph.D. dissertation, University of Utrecht, The Netherlands, 247 p.
- MCKENZIE D. P. 1978. — Some remarks on the development of sedimentary basins. *Earth Planetary Science Letters* 40: 23-32.
- MEULENKAMP J. E., WORTEL M. J. R., VAN WAMEL W. A., SPAKMAN W. & HOOGERDUYN STRATING E. 1988. — On the Hellenic subduction zone and the geodynamic evolution of Crete since the late middle Miocene. *Tectonophysics* 146: 1-13.
- MILLER K. G., WRIGHT J. D. & FAIRBANKS R. G. 1991. — Unlocking the ice house: Oligocene-Miocene oxygen isotopes, eustasy and margin erosion. *Journal of Geophysical Research* 96, B: 6829-6848.
- NAIDU P. D. & MALMGREN B. A. 1996. — A high resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea, based on planktonic foraminifera. *Paleoceanography* 11: 129-140.
- OTTENS J. J. 1992. — Planktic foraminifera as North Atlantic water mass indicators. *Oceanologica Acta* 14 (2): 123-140.
- PUJOL C. & VERGNAUD-GRAZZINI C. 1989. — Paleooceanography of the Last Deglaciation in the Alboran Sea (Western Mediterranean). Stable isotopes and planktonic foraminiferal records. *Micropaleontology* 15: 153-179.
- PUJOL C. & VERGNAUD-GRAZZINI C. 1995. — Distribution patterns of live planktic foraminifera as related to regional hydrography and productive systems of the Mediterranean Sea. *Marine Micropaleontology* 25: 187-217.
- RAVELLO A. C., FAIRBANKS R. G. & PHILANDER S. G. H. 1990. — Reconstructing tropical Atlantic hydrography using planktonic foraminifera and an ocean model. *Paleoceanography* 5: 409-431.
- REYNOLDS L. A. & THUNELL R. C. 1986. — Seasonal production and morphologic variation of *Neoglobobadrina pachyderma* (Ehrenberg) in the northeast Pacific. *Micropaleontology* 32: 1-18.
- REYNOLDS L. A., SAUTTER L. & THUNELL R. C. 1991. — Planktonic foraminiferal response to upwelling and seasonal hydrographic conditions: sediment trap results from San Pedro Basin, Southern California Bight. *Journal of Foraminifera Research* 21: 347-363.
- RUDDIMAN W. F. 1985. — Climate studies in ocean cores, in HECHT A. D. (ed.), *Paleoclimate Analysis and Modeling*. Wiley, Chichester: 197-257.
- SIERRO F. J., FLORES J. A., ZAMARRENO I., VÁSQUEZ A., UTRILLA R., FRANCÉS G., HILGEN F. J. & KRIJGSMAN W. 1999. — Messinian pre-evaporite sapropels and precession-induced oscillations in western Mediterranean and the APTS. *Marine Geology* 153: 137-146.
- SPEZZAFERRI S. 1995. — Planktonic foraminiferal paleoclimatic implications across the Oligocene-Miocene transition in the oceanic record (Atlantic, Indian and south Pacific). *Palaeogeography Palaeoclimatology Palaeoecology* 114: 43-74.
- SPEZZAFERRI S. & PREMOLI SILVA I. 1991. — Oligocene planktonic foraminiferal biostratigraphy and paleoclimatic interpretation from Hole 538A, DSDP Leg 77, Gulf of Mexico. *Palaeogeography Palaeoclimatology Palaeoecology* 83: 217-263.
- SPEZZAFERRI S., CORIC S., HOHENEGGER J. & ROEGL F. 2002. — Basin-scale paleobiogeography and paleoecology: an example from Karpatian (latest Burdigalian) benthic and planktonic foraminifera and calcareous nannofossils from the Central Paratethys. *Geobios Mémoire spécial* 24: 241-256.
- THIEDE J. 1983. — Skeletal plankton and nekton in upwelling water masses off northwestern South America and northwest Africa, in SUSS E. & THIEDE J. (eds), *Coastal Upwelling*. Plenum, New York: 183-207.
- THUNELL R. C. 1978. — Distribution of recent of planktonic foraminifera in surface sediments of the Mediterranean sea. *Marine Micropaleontology* 3: 147-173.
- TOLDERLUND D. S. & BÉ A. W. H. 1971. — Seasonal distribution of planktonic foraminifera in the Western North Atlantic. *Micropaleontology* 17: 297-329.
- TSAPARAS N. 2005. — *Contribution to the History of Sedimentation of the Upper Cenozoic Marine Formations in Gavdos Island*. Ph.D. dissertation, University of Athens, Greece, 260 p.
- TURCO E., HILGEN F. J., LOURENS L. J., SHACKLETON N. J. & ZACHARIASSE W. J. 2001. — Punctuated evolution of global climate cooling during the late middle to early late Miocene high-resolution planktonic foraminiferal and oxygen isotope records from the Mediterranean. *Paleoceanography* 16: 405-423.
- TURCO E., BAMBINI A. M., FORESI L. M., IACCARINO S., LIRER F., MAZZEI R. & SALVATORINI G. 2002. — middle Miocene high-resolution calcareous plankton biostratigraphy at Site 926 (Leg 154, equatorial Atlantic Ocean): paleoecological and paleobiogeographical implications. *Geobios Mémoire spécial* 24: 257-276.
- VAN LEEUWEN R. J. W. 1989. — Sea-floor distribution and Late Quaternary faunal patterns of planktonic and benthic foraminifera in the Angola Basin. *Utrecht Micropaleontological Bulletin* 38: 1-288.
- ZACHARIASSE W. J. 1992. — Neogene planktonic foraminifera from Sites 761 e 762 off Northwest Aus-

- tralia, in VON RAD U. & HAQ B. U. (eds), *Proceedings of the Ocean Drilling Project, Scientific Results* 122: 665-675.
- ZACHOS J., PAGANI M., SLOAN L., THOMAS E. & BILLUPS K. 2001. — Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 252: 686-693.
- ZHANG J. 1985. — Living planktonic foraminifera from the eastern Arabia Sea. *Deep Sea Research* 32: 289-798.

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