

# On the occurrence of Early Pliocene marine deposits in the Ierapetra Basin, Eastern Crete, Greece

HARA DRINIA, ASSIMINA ANTONARAKOU & GEORGE KONTAKIOTIS



A marine sedimentary sequence of the Pakhiammos section that crops out in the Ierapetra Basin (eastern Crete, Greece) is described here in detail for the first time. Diverse and abundant foraminifera have been recovered from the Pakhiammos section. Planktonic species indicate that sediments span the interval from Zone MPL1 to above the MPL1/MPL2 boundary (Zanclean, early Pliocene). R-mode cluster analysis identified three benthic foraminiferal assemblages named by their dominant taxa: *Bolivina spathulata*, *Cibicidoides pseudoungerianus*, and *Siphonina reticulata* assemblages respectively. Palaeoenvironmental implications of each assemblage and their stratigraphic distribution allow the recognition of two fossil associations: a well-diversified Association A, representative of a stable marine ecosystem, and a less diversified Association B, representative of a sapropel-like event. The deposition of the sapropel-like interval suggests that sapropels resulted from the interaction between sea surface temperature variations, productivity increases and reduced bottom water ventilation. This study represents the first report of early Pliocene marine sediments in the Ierapetra Basin and contributes to the understanding of the evolution of the Neogene basins in eastern Crete. • Key words: biostratigraphy, foraminifera, palaeoenvironment, Early Pliocene, eastern Crete.

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The Ierapetra Basin is located in the eastern part of Crete (Fig. 1). This island is part of the Hellenides mountain range created by the same tectonic activity that was responsible for the orogenesis of the Alps and the formation of the Mediterranean Sea. During the Mediterranean Salinity Crisis (5.96–5.32 My, Krijgsman *et al.* 1999), successive deposits of evaporated minerals accumulated in the Mediterranean basin. At present, the occurrence of the uppermost Messinian post-evaporitic deposits in Crete is a matter of debate. According to some authors the well-known late Messinian Lago-Mare facies does not occur in Crete. However, late Messinian Lago-Mare biofacies has recently been observed on the Messara Plain (southern part of central Crete, Pipponzi *et al.* 2004).

The sediments of the lowermost Pliocene *Sphaeroidinellopsis* acme zone, as a rule, overlie the late Messinian deposits (Meulenkamp *et al.* 1979a, b, 1994). These deposits consist of whitish marls and marly limestones (Trubi-like deposits) of deep water origin and reflect the effects of the Pliocene flooding which followed the Mediterranean Salinity Crisis. However, during this time span, palaeogeographic configurations and sedimentation patterns differed largely in various parts of Crete

(Meulenkamp *et al.* 1994). This may be due to high tectonic instability and rather “independent” vertical movements of separate blocks. According to this setting, the earliest Pliocene marine deposits should not be present in eastern Crete.

The purpose of this paper is to document the presence of early Pliocene marine strata in the Ierapetra Basin and, on the basis of the microfossil assemblages, to determine the age and the palaeoenvironment of the sedimentary succession preserved there. This study contributes to the understanding of the evolution of the Neogene basins in eastern Crete.

## Study area

The Ierapetra Basin is located in the area of the Ierapetra and Merabellou districts of the Prefecture of Lasithi, eastern Crete (Fortuin 1977). The Neogene in eastern Crete was studied by a number of researchers (Dermitzakis 1969; Gradstein 1973; Zachariasse 1975; Fortuin 1977, 1978; Meulenkamp *et al.* 1979a, b; Meulenkamp & Hilgen 1986; Drinia 1989; Postma & Drinia 1993; Pipponzi

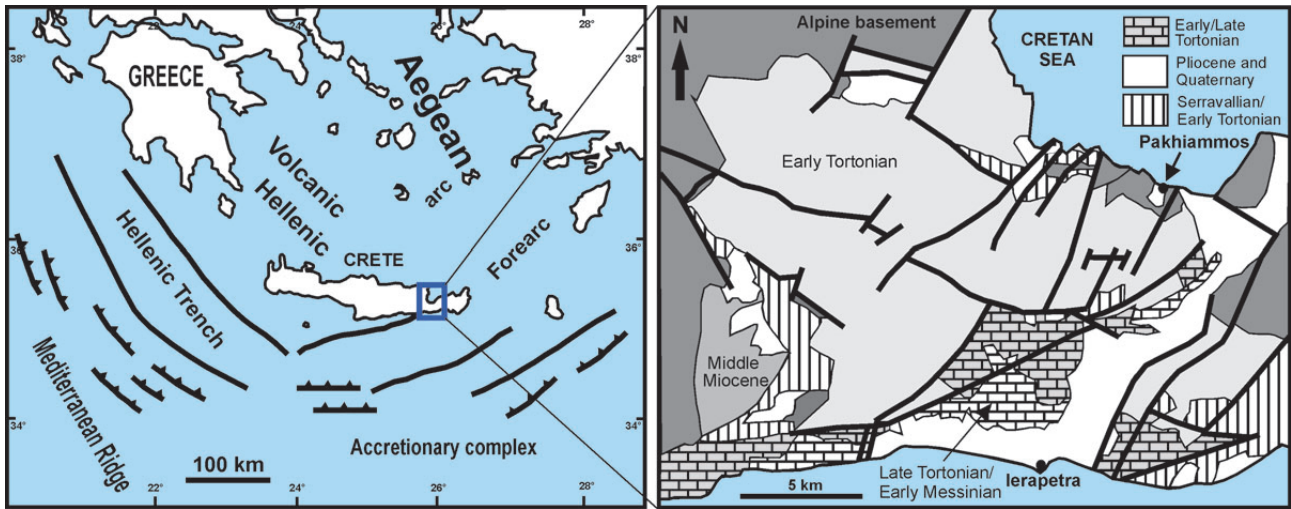


Figure 1. Geological sketch map of the Ierapetra Basin (modified from Fortuin 1977, 1978).

**Pakhiammos Section**

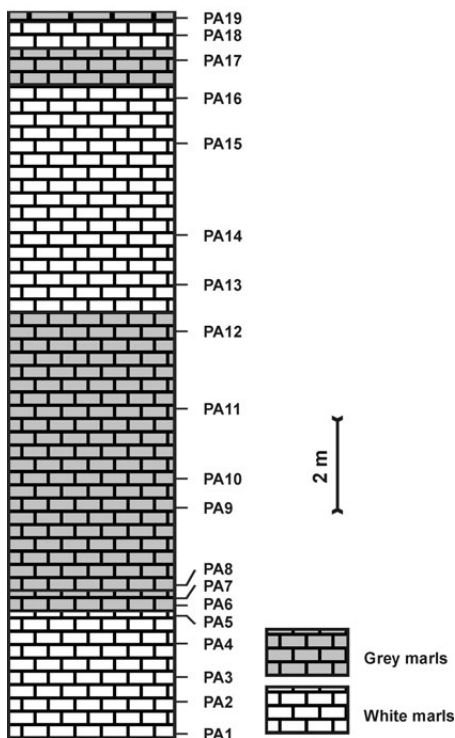


Figure 2. Lithological column of the sediments from the Pakhiammos section.

*et al.* 2004) in various details. According to them, in the Ierapetra Basin, sedimentation started with the deposition of Middle Miocene terrigenous clastics followed by the Upper Miocene fluviolacustrine and open marine shelf, slope and basin-floor sediments. The lowermost Pliocene sediments are generally found as slump components and

debris flow deposits (“marl breccias” *sensu* Fortuin 1977). These deposits overlie the lower Messinian carbonates (Meulenkamp 1985). According to Peters (1985), the marl breccias resulted from the spasmodic subsidence along the pre-existing but still active E–W and N–S trending fault systems. Deep marine marls and clays continued in the sedimentary succession. Finally, Quaternary deposits consisting of bioclastic limestones and Tyrrhenian marine terraces are found mainly on the south coast of the Ierapetra Basin (Angelier 1979, Pirazzoli *et al.* 1982).

The studied Pakhiammos section is located along the northern coast of the Merambellou Bay (Fig. 1). Dermitzakis (1969) was the first to report this section and suggested that these rocks were of Piacenzian age. In 1970s several members of the State University of Utrecht carried out a geological mapping of the rock formations of the Ierapetra Basin (Zachariasse 1975; Sissingh 1976; Fortuin 1977, 1978). Their work indicated that the strata cropping out at Pakhiammos might date back to the late Early Pliocene epoch. Fortuin (1977, 1978) informally used the name “Pakhiammos Formation” and suggested non-marine to brackish sedimentation during its deposition. According to Fortuin, the cumulative thickness of the Pakhiammos Formation is approximately 65 m. It consists mainly of cavernous, micritic limestones and whitish marls overlying unconformably pre-Neogene rocks.

The measured stratigraphic section is 12.5 m thick and consists of brown and white marls displaying rather a typical “Trubi facies” (Fig. 2). The lower limit of the succession was not observed due to the road construction in the area though according to Fortuin (1977, 1978), the section rests unconformably on rocks of the pre-Neogene basement.

## Material and methods

Nineteen samples were taken from this succession to assess their marine character and biostratigraphic position. Samples were processed with traditional micropalaeontological techniques for calcareous microfossils. Preservation of the material in these samples is, in most cases, good with species determination hard in just a few samples. In these samples recrystallization of the fossils and mechanical deformation or dissolution of the tests impeded determination. Therefore, four of nineteen samples proved to be barren and were excluded from the micropalaeontological analysis.

### Planktonic foraminifera

The quantitative planktonic foraminiferal analysis was based on representative splits, using a modified Otto microsplitter, of approximately 300 specimens the size fraction larger than 63  $\mu\text{m}$ . All the representative specimens were picked, identified at specific level and mounted on microslides for a permanent record. Raw data were transformed into percentages over the total abundance of planktonic foraminifera. Finally, the remaining sample was scanned for rare species.

The sea surface temperature record was determined using biogeographic indicators as proxies of temperature. Thereafter, the climatic curve was also constructed using the method of Cita *et al.* (1977), later adopted by Spezzaferri (1995) and Spezzaferri *et al.* (2002); this initiative was derived from the algebraic sum of the percentage of warm indices (with positive value) and cool indices (with a negative value); see Appendix A.

### Benthic foraminifera

For the benthic quantitative analysis, the fraction larger than 125  $\mu\text{m}$  of the washed residue was splitted with a microsplitter to a statistically significant size, which contained more than 250 specimens of benthic foraminifera. All the benthic foraminifera were picked from the split and their species were determined under a light microscope, mounted on Chapman-slides and counted (see Appendix B). In this phase, planktonic foraminifera were only counted in order to obtain P/B ratios, expressed as  $100 \cdot P / (P+B)$ , *i.e.* the percentages of planktonic foraminifera in the total foraminiferal assemblages. Raw data were transformed into percentages over the total abundance of benthic foraminifera and percentage abundance curves were plotted. The Fisher's alpha diversity was calculated using the program "PAST" of Hammer *et al.* (2001). In order to learn more about the trophic conditions, species with relative frequen-

cies above 2% were divided into two groups according to Murray (1991), Jorissen *et al.* (1992), Barmawidjaja *et al.* (1992), Jorissen (1999), and Jorissen & Wittling (1999): epifauna-shallow infauna and deep infauna (see Appendix C). Abundances of groups of species were then plotted in curves.

Reconstruction of bottom water conditions concerning oxygen content was based on the presence of the oxygen indicators in the assemblage. Several methods were developed to tie changes in the benthic foraminiferal assemblages to actual dissolved oxygen levels (*e.g.*, Kowenhoven & van der Zwaan 2006). In our study we use the Benthic Foraminifera Oxygen Index (BFOI) of Kaiho (1991, 1994), following the limitations expressed in Baas *et al.* (1998) and Stefanelli (2004), as this index seems to meet modern open-oceanic faunas more than those of the relatively shallow Mediterranean (see Appendix D).

For palaeoenvironmental reconstructions, R-mode cluster and Principal Component analyses have been performed on the data set, using SPSS statistic package (version 13), after exclusion of rare species (< 2% abundance value) and grouping species that have a discontinuous, scattered distribution to the generic level. These were performed to obtain more information about the faunal composition of the assemblages, their vertical distribution, and environmental parameters, which influenced the foraminiferal distribution during the period of deposition.

## Results

### Planktonic foraminifera

Planktonic foraminifera were used to establish a biostratigraphic framework for the section and to reconstruct the climatic conditions of the studied interval. The distribution pattern of selected indices of planktonic foraminifera species identified throughout the section is presented in Fig. 3.

### Biostratigraphy

The distribution of *Sphaeroidinellops* spp., *Globorotalia margaritae* and the coiling ratio of *Neogloboquadrina aostaensis* are used to determine the chronostratigraphic position of the sediments.

The interval with relatively abundant specimens of *Sphaeroidinellops* spp., in the basal part up to 6.9 m of the section, is assumed to correspond to the *Sphaeroidinellops* acme zone (MPL1 biozone of Cita 1975b). This interval has been recognized in the basal part of Trubi Formation in all the Mediterranean sections and corresponds to the interval from cycle 2 to cycle 6 (Hilgen & Langereis 1993, Sprovieri 1993, Di Stefano *et al.* 1996).

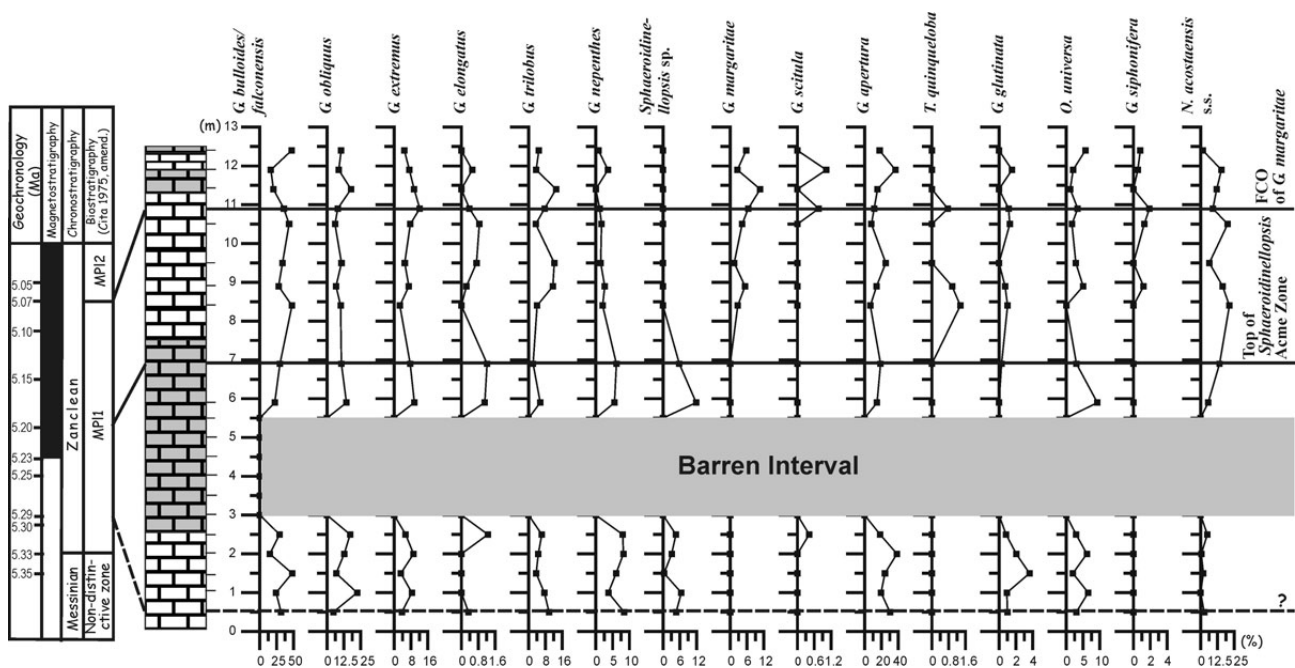


Figure 3. Calcareous plankton biostratigraphy and relative abundance fluctuations of the significant planktonic foraminifera species in the studied sequence.

Apart from this, two sinistral shifts of *N. acostaensis* have recently been reported from the precession-related lithologic cycles 2 and 3 of regional correlation value (Di Stefano *et al.* 1996). In view of the relatively low sample resolution and the poor quality of some samples, we failed to detect this event in our sample set.

At the level of 6.9 m of the section, *Sphaeroidinellopsis* specimens are rarer and, finally, absent at the top of the section. We correlate this level with the top of the acme zone of the species (cycle 6) dated at 5.20 Ma (Lourens *et al.* 1996).

Above this biohorizon, *G. margaritae* occurs scarcely being discontinuously present with a small peak in the abundance curve at 9 m of the section. The level of 10.5 m makes this species substantially increasing and continuously present up to the top. The same pattern has been described in other Mediterranean sections reflecting the FCO of *G. margaritae* and the base of the MPL2 biozone (Cita 1975a), dated at 5.07 Ma (Hilgen & Langereis 1988, 1993; Lourens *et al.* 1996).

Consequently, the studied section starts above the base of the *Sphaeroidinellopsis* acme zone and the second shift of the sinistral *N. acostaensis* (cycle 3) ranges within the MPL1 zone and ends above the MPL1/MPL2 boundary (Zanclean).

### Climatic curve

The constructed climatic curve implies general warm water conditions (Fig. 9). However, two significant events are observed as cooler episodes, at 8.5 m and 10.5 m of the section. After the FCO of *G. margaritae*, warm conditions

generally prevail. This climatic trend is described for the Lower Pliocene (*e.g.*, Crowley 1991, Raymo *et al.* 1996) in accordance with the general climatic conditions.

### Benthic foraminifera

Benthic foraminifera are present throughout the section with the exception of a barren interval about 2.5 m thick, and are generally reasonably well preserved. The benthic fauna is almost entirely calcareous, agglutinated species being rare and confined to *Textularia*. The counting results of the recognized taxa are listed in Appendix B.

The benthic foraminiferal fauna is mainly composed of *Cibicidoides pseudoungerianus*, *C. kullenbergi*, *Bolivina spathulata* gr. (including *B. spathulata*, *B. dilatata*, *B. tortuosa*), *Bulimina aculeata* gr. (*B. aculeata*, *B. lappa*), *Uvigerina* “costate” forms, *U. striatissima*, *Bulimina exilis*, *Planulina ariminensis*, and *Siphonina reticulata*. The distribution of dominant, common or significant species, which characterize the benthic foraminiferal fauna of the studied succession, is reported in Fig. 4.

The common taxa up to the level of 11 m of the section represent a fairly diverse open marine association. At about 11-m-level the *Cibicidoides* species declines together with *S. reticulata* and *H. boueana*, and eventually is replaced by dominated fauna such as *B. exilis* and *B. costata*.

R-mode cluster analysis shows that taxa with similar distribution patterns are grouped by hierarchical clustering into two main assemblages which can be further subdivided into discrete sub-assemblages (Fig. 5).

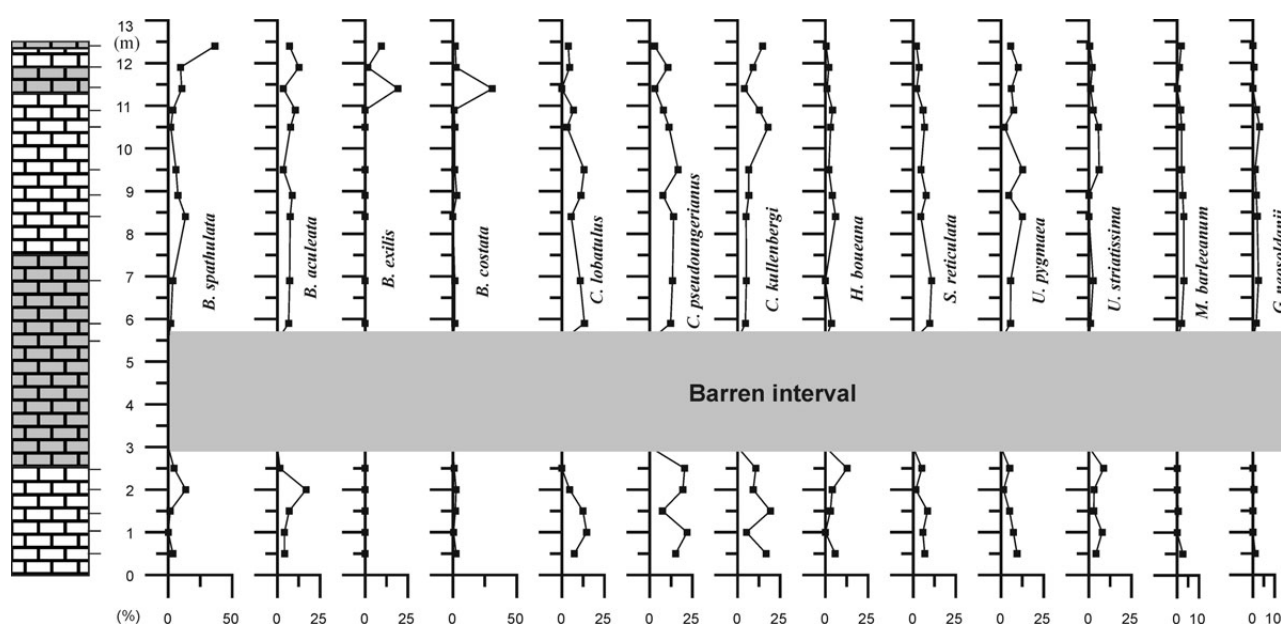


Figure 4. Relative abundance fluctuations of the most significant benthic foraminifera species in the studied sequence.

Assemblage I (*B. spathulata* Assemblage) consists of *B. spathulata* gr., *B. exilis*, *B. costata* and *Uvigerina* “costate” forms.

In Assemblage II, clusters IIa and IIb are important faunal constituents.

In Cluster IIa (*Cibicidoides pseudoungerianus* Assemblage), *C. pseudoungerianus* and *U. striatissima* are the taxa with the highest percentages in frequency. Subordinate taxa include *H. boueana* and *Globocassidulina oblonga*.

Cluster IIb (*S. reticulata* Assemblage) groups *S. reticulata*, *C. lobatulus*, *C. kullenbergi*, *P. ariminensis*, *B. aculeata*, *M. barleeanum*, *Lenticulina* sp. and *Gyroidinoides neosoldanii*.

The cumulative plots of the three determined assemblages are displayed in Fig. 6. They are plotted together with the curves of the Fisher-alpha diversity trend and P/B ratios. The *C. pseudoungerianus* and the *S. reticulata* Assemblages are significantly present from the base up to 10.9 m and at 12.4 m. The *B. spathulata* assemblage is generally represented with moderate frequency values, apart from two levels, at 11.4 and 12.4 m, where it shows abrupt increase (71.21% and 53.55% respectively). In these levels, faunal diversity shows an abrupt decrease, whereas in the remaining part of the section, the faunas are well-diversified.

Epifauna is constantly present in the studied section (Fig. 7). However, it decreases at 11.4 and 12.4 m, where, conversely, the deep infauna component records its maximum frequency.

The palaeoxygen curve (BFOI curve) estimated for the Pakhiammos section shows good correlation with the identified benthic faunal succession (Fig. 7). The well-di-

versified, epifauna assemblage developed under oxygen regime and the increase of the infaunal taxa occurred under moderate oxygen depleted conditions. This is evident from the decline of the BFOI curve at 11.4 and 12.4 m of the record. According to the continuous presence of benthic foraminifera no anoxia resulted during the entire time span of the deposition of the section.

R-mode factor analysis distinguished six significant factors accounting for 88.57% of the total variance (Tab. 1), however, only two factors are significant (Tabs 1 and 2). The first one accounts for the 28.62% of the total variance, which is characterized by high positive loadings for *S. reticulata* (0.76) and *C. lobatulus* (0.73) as well as significant negative loadings for *B. exilis* (−0.85) and *B. spathulata* (−0.74). The second factor accounts for the 17.84% of the total variance and is positively loaded by *M. barleeanum* (0.79) and *G. neosoldanii* (0.63) while *C. pseudoungerianus* and *U. striatissima* show the highest negative loadings (−0.72 and −0.74 respectively).

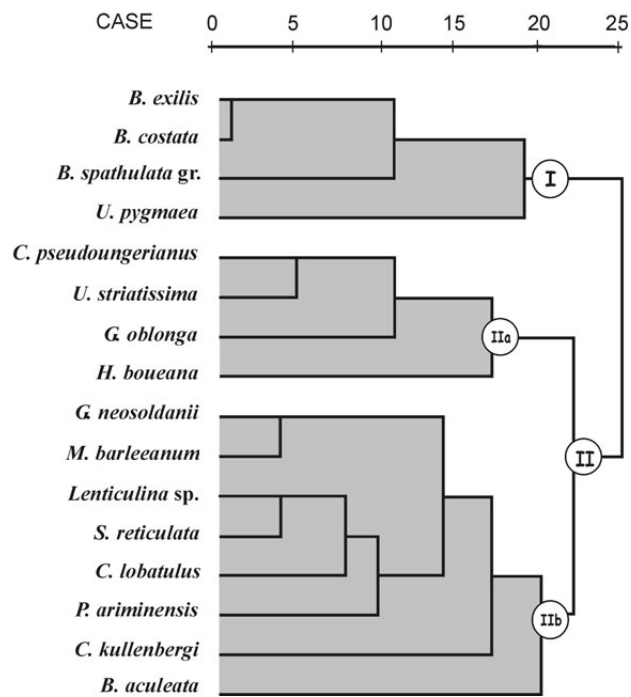
## Discussion

### The palaeoecological significance of benthic foraminiferal assemblages

The benthic foraminiferal assemblages (dominated by *Cibicidoides*, *Siphonina* and *Uvigerina*) indicate the deposition of this succession in a relatively deep sedimentary basin, consistent with the outer shelf-slope environment (e.g., Murray 1991, Schmiedl *et al.* 2003). This is also supported by the lack of shallow water fauna and the absence of pri-

## HIERARCHICAL CLUSTER ANALYSIS

Dendrogram using Average Linkage (Within Group)  
Rescaled Distance Cluster Combine



**Figure 5.** Dendrogram based on R-mode cluster analysis by means of SPSS program. Two clusters and two sub-clusters are recognized, indicated by roman numbers.

mary sedimentary structures. The minor percentage of frequency, throughout the section, of the species *Elphidium crispum*, *E. advenum* and *Ammonia beccarii*, which usually live not deeper than 100 m (Parker 1958, Chierici *et al.* 1962, Jorissen 1988, Sgarrella & Moncharmont-Zei 1993), are probably linked to transport. The near absence of the taxa with a tolerance for salinity fluctuations, *e.g.*, *Ammonia*, *Elphidium* and *Nonion*, and quite diverse character of planktonic foraminiferal assemblages indicate an open marine environment with normal value of salinity.

Moreover, we have recorded that the benthic and planktonic foraminifera relative abundance (P/B-ratio, Fig. 6) remains rather constant, ranging between 40 and 70% and yielding an outer shelf to slope environment (Murray 1991). An improved P/B ratio, worked out by van der Zwaan *et al.* (1990), estimates palaeowater depth (D) directly in meters. The application of the findings of van der Zwaan *et al.* (1990) indicates a palaeodepth ranging from 150 to 500 m, indicating an outer shelf to slope environment.

In the Mediterranean Sea, the oxygen content and food availability are the main environmental factors that control the benthic foraminifera distribution (Jorissen 1999). As a

**Table 1.** Eigenvalues of the six principal components extracted.

Component	Total Variance Explained		
	Total	% of Variance	Cumulative %
1	4.58	28.62	28.62
2	2.85	17.84	46.46
3	2.01	12.54	58.99
4	1.89	11.78	70.78
5	1.50	9.36	80.14
6	1.35	8.43	88.57

**Table 2.** Factor loadings of the taxa on the first and second principal component axes. In bold: the highest negative and positive scores.

Species	Factor 1	Factor 2
<i>B. aculeata</i>	-0.07	0.13
<i>B. costata</i>	-0.67	0.01
<i>B. exilis</i>	<b>-0.85</b>	0.05
<i>B. spathulata</i>	<b>-0.74</b>	0.11
<i>C. kullenbergi</i>	0.15	0.04
<i>C. lobatulus</i>	<b>0.73</b>	0.20
<i>C. pseudoungerianus</i>	0.50	<b>-0.72</b>
<i>G. neosoldanii</i>	0.40	<b>0.63</b>
<i>Gl. oblonga</i>	0.53	-0.37
<i>H. boueana</i>	0.09	-0.34
<i>Lenticulina spp.</i>	0.61	0.39
<i>M. barleeaanum</i>	0.26	<b>0.79</b>
<i>Pl. ariminensis</i>	0.65	-0.28
<i>S. reticulata</i>	<b>0.76</b>	0.46
<i>U. striatissima</i>	0.41	<b>-0.74</b>
<i>U. pygmaea</i>	0.03	0.03

consequence we discuss the life strategies of the encountered taxa in relation to these two environmental factors.

*Bolivina spathulata* assemblage consists of the taxa characteristic of high organic carbon flux and low dissolved oxygen concentrations (Barmawidjaja 1991, Barmawidjaja *et al.* 1992, Kaiho 1994, Duijnste 2001). They are often dominant in the oxygen minimum zone or in upwelling zones (*e.g.*, Phleger & Soutar 1973, Poag 1984, Mullins *et al.* 1985). Their flattened elongate morphology is considered to be an adaptation to the low-oxygen conditions (Bernhard 1986).

*Cibicidoides pseudoungerianus* assemblage consists mainly of the *C. pseudoungerianus* species which has been described in a wide range of trophic conditions (Rathburn & Corliss 1994, Almogi-Labin *et al.* 2000, Schmiedl *et al.* 2000, Fontanier *et al.* 2002). For instance, *C. pseudoungerianus* from north-western Africa flourished in the environment permanently influenced by upwelling (Jorissen

et al. 1998). According to Altenbach et al. (1999), the high dominance of *C. pseudoungerianus* in this assemblage is linked to fluxes of primary productivity ranges comparable to those required by uvigerinid species. Indeed, the subordinate dominance of *Uvigerina striatissima* in this assemblage implies the adaptation to seasonally high fluxes of marine phytodetritus and the tolerance to low quality organic matter from marine or terrestrial origin (Licari & Mackensen 2005). Overall, the characteristic species of this assemblage possibly avoid the most eutrophic areas where they might be out completed by more opportunistic species.

*Siphonina reticulata* assemblage consists of the epifaunal, opportunistic taxa, suspected to be phytodetritus feeders, indicative of a high trophic level in combination with sufficiently high oxygen concentrations (Linke & Lutze 1993). This group of species is commonly found in quite, open-marine Mediterranean environments. The relatively high occurrence of *B. aculeata*, a taxon with a shallow to intermediate infaunal microhabitat, more opportunistic, not particularly dependent on high amounts of fresh and unaltered organic matter but certainly thriving under a high flux (Gupta 1997, Kawagata 2001), may point towards instability of the environment. Therefore, this assemblage is related to the high food supply and good bottom circulation.

## Palaeoenvironmental implications

The complementary distributional pattern of *B. spathulata*, *C. pseudoungerianus* and *S. reticulata* assemblages, as Fig. 6 shows, especially in the upper part of the record, suggests that our succession did not accumulate in a marine environment that remained constantly the same.

Associating the changes in Fisher-alpha diversity to the benthic foraminiferal distribution, two benthic foraminiferal fossil associations can be identified (Fig. 8).

Association A shows a highly diverse fauna in which the taxa, belonging to the three assemblages, are present with significant frequency values. Therefore, the high presence of *S. reticulata* and *C. pseudoungerianus*, the taxa living on the bottom water surface, together with *B. spathulata*, *Uvigerina* costate forms, *B. aculeata*, living 1–2 cm under the sediment surface, clearly suggest the distinct vertical microhabitat distribution in the sediment column.

According to Loubère (1997) and Jorissen et al. (1995), this distribution suggests a palaeoenvironmental setting characterized by high oxygen content at the bottom water surface. This high oxygen content can reach the deep layers within the sediment column, thus the assemblage is very well diversified because the oxygenated zone is thick and the redox layer deep.

However, the relatively low diversity benthic species detected at the upper part of the section, allows the recogni-

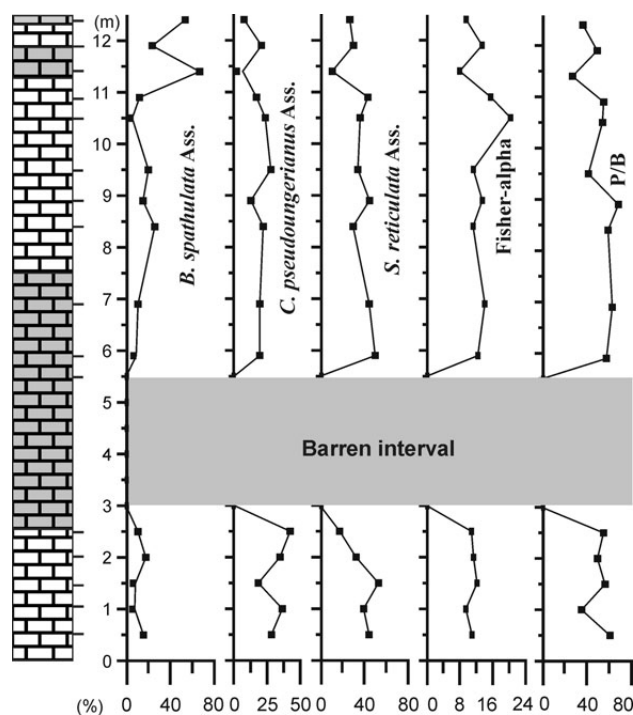


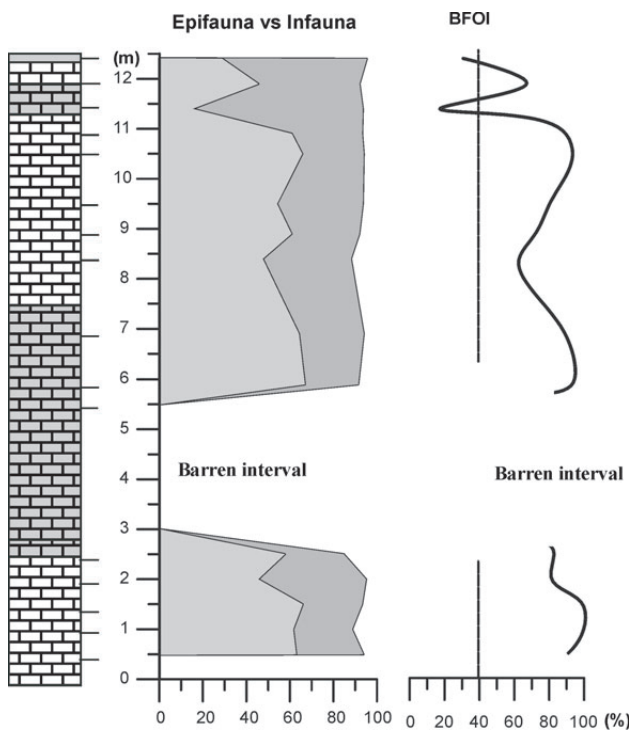
Figure 6. Cumulative plots of the three benthic foraminiferal assemblages in the Pachiammos section plotted with Fisher alpha diversity trend and P/B ratios.

tion of one episode of environmental stress (Association B). In this part of the succession, the faunal composition is indicative of upwelling and enhanced productivity. Important species such as *B. spathulata* and *B. exilis* are reported to prefer such conditions. The species *B. spathulata* is reported to have high tolerance to oxygen deficiency and to prefer high nutrient abundance (van der Zwaan 1982). *Bulimina exilis* is often associated with sapropels and diatomites formed under conditions of significant oxygen depletion (Jonkers 1984). This implies that the bottom oxygen levels were low (although we lack data for organic flux). Therefore, the high frequency values of this species may indicate a temporal reaction of benthic foraminifera to the input of fresh water organic matter.

Hence, the shallowing of the redox front could be linked to the increase of food availability that leads to an increased consumption of oxygen (Jorissen et al. 1995).

The high numbers of *B. exilis* and *B. spathulata* gr. in the assemblage associated with this episode suggest that this may be a sapropel-like event, in agreement with the criteria of Cita & Podenzani (1980), Nolet & Corliss (1990), Sen Gupta & Machain-Castillo (1993) and Jorissen (1999). However, due to the absence, of specific chronostratigraphic references at the moment, it is not possible to associate this event with insolation cycles.

Focusing on the distributional patterns within this unit, *B. exilis* and *B. spathulata* are never simultaneously present in Association B (Fig. 4). The replacement of *B. exilis*



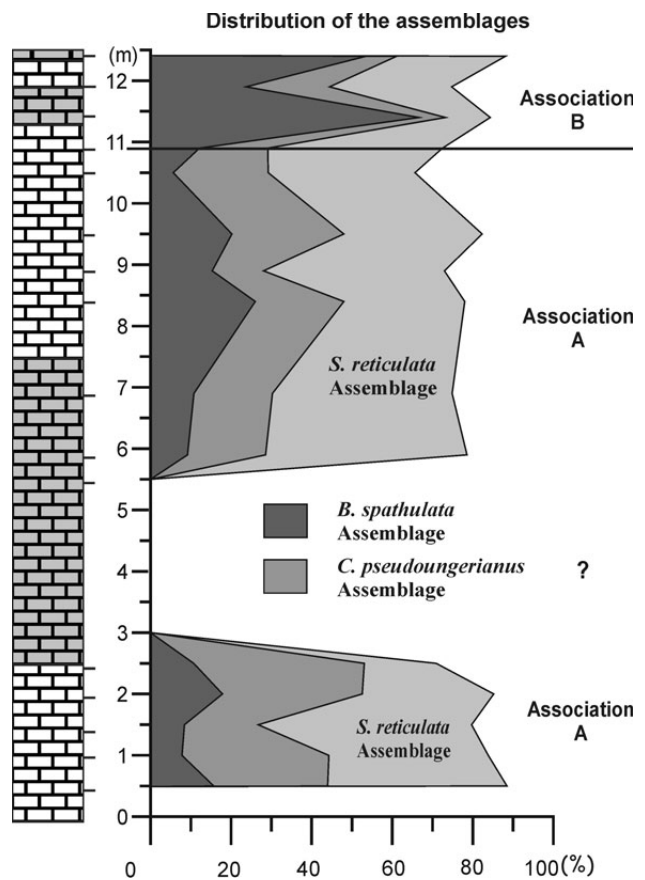
**Figure 7.** Benthic foraminiferal microhabitat preference compared with the palaeoxygen curve. In order to extract the curve of oxygen concentration the Benthic Foraminiferal Oxygen Index (BFOI) values are used. The BFOI is calculated following the equation of Kaiho (1994):  $[O/(O+D)] \times 100$  where O and D are the numbers of specimens of oxic and dysoxic indicators respectively.

by *Bolivina* gr. may be suggestive of oxygen conditions pushed to minimum extreme at the bottom of the sapropel-like unit and a relative improvement of oxygenation at the top.

This palaeoenvironmental reconstruction appears plausible with the different recorded planktonic foraminiferal distributions. In intervals rich in *B. exilis*, the planktonic assemblages are dominated by the *Globigerinoides* spp., which indicates warm conditions and low salinity in surficial water masses (Capotondi & Vigliotti 1999).

Conversely, in intervals rich in individuals of *Bolivina*, the decrease in abundance of the *Globigerinoides* spp. and the dominance of *Globigerina bulloides* suggest cold and productive surface waters (Fig. 3; Rohling *et al.* 1997, Negri *et al.* 2003).

In a short interval, the decrease in abundance of *B. exilis* and *Bolivina*, simultaneously with the repopulation in the assemblage with *C. pseudoungerianus* and *S. reticulata* and the increase in diversity value, allow the identification of a short time interval in which this sapropel-like deposition is interrupted. This change in the assemblage composition is suggestive of an improvement in oxygen content of the bottom water and of sediment pore-water that have caused a temporary deepening of the redox zone.



**Figure 8.** Palaeoenvironmental changes evidenced by faunal changes observed in Pakhiammos section.

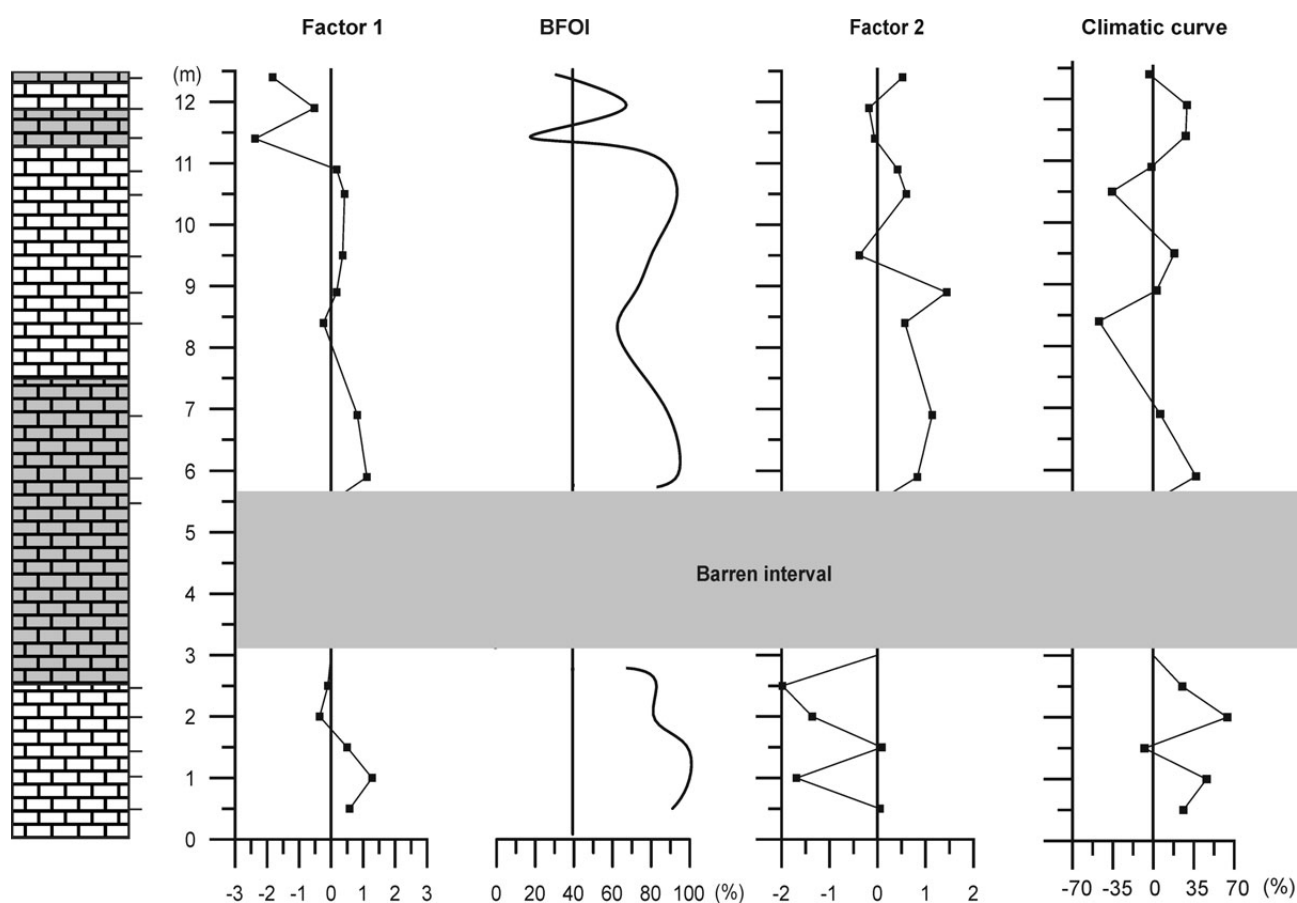
In Fig. 9, the sample scores of Factor 1 and Factor 2 are shown, the principal components being extracted for the studied section by the principal component analysis.

Factor 1 reflects oxygen content since it is loaded by opposing indicators of oxygen. *Siphonina reticulata*, which is reported to prefer the well-oxygenated marine bottom (Murray 1991), shows the highest positive loadings. *Bulimina exilis* and *B. spathulata*, noted to prefer environments with severe oxygen depletions in the bottom and pore-water sediments (Lutze & Coulbourn 1984, Sen Gupta & Machain-Castillo 1993, Rathburn & Corliss 1994), reveal the highest negative loadings.

Factor 1 is plotted together with the palaeo-oxygen curve reconstructed by means of the Kaiho's equation. In the Pakhiammos section, the trend of the palaeo-oxygen curve is similar to the trend of Factor 1. In general, the palaeo-oxygen curve shows fluctuations in the high/medium regime for the phase of "good" oxygenation. In the interval of sapropel-like deposition, the dissolved oxygen regime is interpreted as dysoxic.

At first sight, the associations loading Factor 2 appear not to bring any interesting information likely to explain the factor. This phenomenon can be interpreted in two different





**Figure 9.** The sample scores of Factor 1 and Factor 2 compared with the palaeo-oxygen-curve derived from the use of Benthic Foraminiferal Oxygen Index (BFOI) and the sea surface temperature curve.

ways: either these species agree to live under very varied environmental conditions (eurytype species); or they require a whole set of very strict but intermediate factors (stenotype species living in an environment of average depth, oxygenation, productivity and salinity).

*Melonis barleeanum* prevails in environments characterized by increased fluxes of organic matter to the sea bottom and fine-grained sediments. The abrupt increase of this benthic species indicates an increased delivery of organic matter but not severe low-oxygen conditions within the sediments (Corliss 1985, Caralp 1989). Similar ecological preferences are also in effect for *Gyroidinoides neosoldanii*, also regarded as an indicator of organic enrichment that does not tolerate low oxygen content in sediments (Mullineaux & Lohmann 1981, de Stigter *et al.* 1998). Therefore, ventilation of bottom water is implied, which suggests deep-water formation.

A more careful observation brought out the trend of Factor 2 showing complementary patterns with the trend of the climatic curve (Fig. 9). The modern distribution of *Melonis barleeanum* suggests that it is indicative of increased influx of cold water (Korsum & Polyak 1989, Polyak & Solheim 1994, Steinsund 1994).

At 11.4 m, the trend of the climatic curve implies a general warming of sea surface water just below the sapropel-like event, which continues during the sapropel deposition. This indicates, in conjunction with the low BFOI values, a highly stratified water column, further supporting the sapropel-like deposition.

However, the interpretation of this factor needs additional investigation with a more quantitative analysis involved.

Therefore, palaeo-climatic changes enhanced palaeo-productivity and limited the availability of dissolved oxygen in bottom waters, temporarily establishing dysoxic conditions. A sapropel-like interval was deposited under these conditions.

A comparable situation has been documented in the Pliocene deposits of the Iraklion Basin (central Crete). Danelian & Alexander (2000), Frydas (2004) and Drinia *et al.* (2004, 2005, 2006) maintain that the Pliocene sediments in the Iraklion Basin are probably linked to climate-driven changes in surface runoff (*i.e.* warmer temperatures and/or lower salinities), which influenced the levels of primary productivity. The implications of these hydrological changes would have had a profound influence on the local accumulation of sapropel-like sediments.

According to Hilgen (1991), individual sapropels in the eastern Mediterranean can be correlated with minima of the precessional cycle. Other studies support the precessional cycle as the dominant factor influencing the lower to upper Pliocene climatic evolution (Tiedemann *et al.* 1994). In the absence of high resolution stratigraphic control, we can only speculate as to the precise nature of astronomical forcing behind the brown-white marl cycles studied herein.

Apparently, this is a characteristic event of the Eastern Mediterranean Basin, which points to a major modification of the oceanographic conditions with the eutrophic situation becoming widely distributed.

The scenario reveals similarities with the succession evidenced by high-resolution planktonic foraminiferal investigations of the upper Pliocene C2 sapropel (Singa section, Rohling *et al.* 1993) and for Late Quaternary sapropels (de Rijk *et al.* 1999). Another scenario resembling its predecessor has been described by Stefanelli *et al.* (2005) for the Early-Middle Pleistocene deposits in the southernmost part of the Lucania Basin.

## Conclusions

The reconnaissance study of the deposits in the Neogene Ierapetra Basin of eastern Crete, indicates a marine sedimentary succession – the Pakhiammos section – containing marl deposits considerably rich in species and number of foraminifera.

Based on micropalaeontological data, the marls of the Pakhiammos section were deposited during the Zanclean, in a relatively deep sedimentary environment. Our data contradict the brackish environment of Piacenzian age reported by previous researchers.

The quantitative study of benthic foraminifera faunas points to the fact that the bottom water conditions of the Pakhiammos section did not remain the same during deposition. The palaeoenvironmental implications and the stratigraphic distribution of the benthic foraminiferal assemblages allow the recognition of two fossil associations: a well-diversified Association A, representative of a stable marine ecosystem; and a less diversified Association B, representative of the sapropel-like event not completely devoid of foraminifera.

The deposition of the sapropel-like interval is suggested to have resulted from an interaction between sea surface temperature variations, productivity increase and reduced bottom water ventilation.

This is in agreement with the opinion that the early Pliocene sapropels resulted from overall warming and associated sluggish bottom water circulation.

Unfortunately, the lack of a precise temporal frame does not allow the estimation of the identified sapropel-like event.

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## Appendix A: Ecological preferences of planktonic foraminiferal species

### Warm water planktonic foraminifera species

*Globigerinoides obliquus* Bolli  
*Globigerinoides extremus* Bolli  
*Globigerinoides elongatus* (d'Orbigny)  
*Globigerinoides trilobus* (Reuss)  
*Globoturborotalita nepenthes* (Todd)  
*Globoturborotalita apertura* (Cushman)  
*Orbulina universa* d'Orbigny  
*Globigerinella siphonifera* (d'Orbigny)

### Cool water planktonic foraminifera species

*Globigerina bulloides* d'Orbigny  
*Globigerina falconensis* Blow  
*Globorotalia scitula* (Brady)  
*Turborotalita quinqueloba* Natland  
*Globigerinita glutinata* (Egger)  
*Neogloboquadrina acostaensis* s.s. (Blow)

**Appendix B: Numbers of the detected benthic foraminiferal species in Pakhiammos Section**

Numbers of the detected benthic foraminiferal species in the Pakhiammos section															
height (m)	0.5	1	1.5	2	2.5	5.9	6.9	8.4	8.9	9.5	10.5	10.9	11.4	11.9	12.4
<i>Amphicoryna scalaris</i>	0	0	2	3	0	2	3	0	0	0	0	0	0	0	0
<i>Amphistegina</i> sp.	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Anomalinoidea cicatricosus</i>	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>A. granosus</i>	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
<i>A. helicinus</i>	0	1	3	0	0	5	6	2	3	3	1	4	1	3	0
<i>Anomalinoidea</i> sp.	0	0	0	2	3	0	0	0	0	3	3	0	0	2	0
<i>Asterigerinata planorbis</i>	5	9	7	0	9	2	1	4	0	2	0	3	0	2	0
<i>Bigenerina</i> sp.	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
<i>Bolivina dilatata</i>	3	0	1	2	5	0	0	5	4	0	0	3	2	15	12
<i>B. leonardii</i>	0	0	0	5	0	0	0	0	0	0	1	0	0	0	0
<i>B. pseudoplicata</i>	0	0	3	1	0	2	3	8	12	4	4	16	0	8	2
<i>B. punctata</i>	0	0	0	0	3	0	0	0	0	0	0	2	2	3	3
<i>B. reticulata</i>	0	0	2	8	0	0	0	0	0	3	0	2	0	0	0
<i>B. scalprata</i>	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
<i>Bolivina</i> sp.	0	1	3	0	0	3	0	0	0	0	0	0	0	2	0
<i>B. spathulata</i>	4	0	0	7	0	4	7	19	11	9	3	2	19	4	65
<i>B. tortuosa</i>	0	0	0	5	4	0	0	3	0	0	0	0	0	0	0
<i>Bulimina aculeata</i> group	8	0	14	33	3	11	14	15	17	7	0	20	7	25	15
<i>B. costata</i>	5	1	4	5	2	3	3	0	6	3	3	2	61	5	4
<i>B. elegans</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
<i>B. exilis</i>	0	0	0	0	0	0	0	0	0	0	0	0	38	3	20
<i>B. inflata</i>	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
<i>B. minima</i>	0	8	0	0	0	2	0	0	0	0	12	0	0	0	0
<i>Bulimina</i> sp.	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>B. subacuminata</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
<i>Cancris oblongus</i>	0	0	0	0	2	0	0	0	0	0	0	1	1	1	0
<i>Cassidulina carinata</i>	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>C. laevigata</i>	0	0	4	0	0	0	0	0	1	0	0	0	0	0	0
<i>Cibicides lobatulus</i>	8	11	23	5	0	18	13	10	9	19	0	7	0	3	6
<i>C. refulgens</i>	0	8	0	1	0	4	2	1	8	0	0	2	0	0	2
<i>Cibicides</i> sp.	6	9	2	3	0	4	6	0	5	7	6	4	0	6	0
<i>Cibicoides compressus</i>	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
<i>C. dertonensis</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
<i>C. dutemplei</i>	0	0	0	0	0	0	0	0	0	0	0	0	2	9	2
<i>C. grossoperforatus</i>	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
<i>C. kullenbergi</i>	29	10	37	12	14	9	9	10	12	13	13	20	4	11	24
<i>C. pachyderma</i>	4	8	0	0	7	1	1	0	2	2	2	0	0	0	2
<i>C. pseudoungerianus</i>	25	34	15	38	33	23	25	28	13	31	20	15	6	21	4
<i>C. robertsonianus</i>	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
<i>Cibicoides</i> sp.	0	0	0	0	6	0	0	0	0	0	12	1	1	2	0
<i>C. ungerianus</i>	2	0	2	6	1	0	1	0	0	0	4	1	3	4	7
<i>C. variabilis</i>	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>Coryphostoma</i> sp.	0	0	0	0	0	0	0	4	0	0	0	0	3	0	4
<i>Discorbinella berthelotti</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
<i>Eggerella bradyi</i>	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>Elphidium aculeatum</i>	0	0	1	0	1	2	0	0	2	3	1	0	0	1	0
<i>E. advenum</i>	0	0	0	0	0	0	0	0	0	0	2	2	0	3	0

Numbers of the detected benthic foraminiferal species in the Pakhiammos section															
height (m)	0.5	1	1.5	2	2.5	5.9	6.9	8.4	8.9	9.5	10.5	10.9	11.4	11.9	12.4
<i>E. complanatum</i>	0	5	0	0	0	0	0	0	0	0	0	0	0	3	0
<i>Elphidium</i> sp.	0	4	2	0	8	0	2	7	8	3	0	0	0	1	2
<i>Epistomella lecalvezi</i>	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0
<i>Epistominella</i> sp.	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0
<i>Eponides</i> sp.	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
<i>Gavellinopsis lobatulus</i>	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0
<i>G. praegeri</i>	0	3	1	0	0	0	2	0	0	0	0	3	0	3	4
<i>Globobulimina</i> sp.	0	0	0	1	1	0	0	2	3	8	0	1	2	0	0
<i>Globocassidulina oblonga</i>	3	12	8	10	0	5	6	2	2	6	3	3	0	7	1
<i>G. subglobosa</i>	1	1	0	0	0	0	0	2	0	0	0	0	0	1	0
<i>Griboelphidium</i> sp.	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0
<i>Gyroidina soldanii</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
<i>Gyroidinoides neosoldanii</i>	2	0	0	1	0	3	5	4	3	2	5	3	0	1	0
<i>Hanzawaia boueana</i>	11	0	6	8	25	7	0	12	8	4	6	8	2	4	1
<i>Hetelolepa praecincta</i>	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
<i>Heterolepa</i> sp.	0	0	0	0	0	1	9	0	3	0	14	1	0	0	0
<i>Hoeglundina elegans</i>	0	0	0	0	0	2	1	0	0	0	1	0	0	0	0
<i>Lagena</i> sp.	2	1	0	1	1	2	6	5	6	2	1	3	0	0	1
<i>Lenticulina</i> sp.	9	9	11	3	4	15	7	2	13	4	12	7	5	5	2
<i>Marginulina costata</i>	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
<i>Martinotiella communis</i>	0	1	0	0	1	0	2	0	1	1	1	0	0	0	0
<i>Melonis barleeanum</i>	5	0	1	0	0	4	6	6	5	4	4	3	0	2	4
<i>Neopinooides schreibersii</i>	2	0	1	5	5	2	2	1	0	2	1	0	0	0	0
<i>Nodosaria raphanistrum</i>	0	0	0	1	3	5	2	0	0	0	0	0	0	0	0
<i>Oridorsalis umbonatus</i>	2	1	2	0	0	2	0	1	0	0	0	0	0	0	0
<i>Orthomorphina</i> sp.	0	0	0	0	0	0	1	0	0	0	2	2	0	0	0
<i>Pandagladulina dinapoli</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
<i>Planulina ariminensis</i>	5	10	2	3	4	9	4	3	1	3	2	5	2	0	0
<i>Plectofrondicularia</i> sp.	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
<i>Pseudonodosaria</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
<i>Pullenia bulloides</i>	4	0	3	9	7	1	2	1	2	0	1	1	2	0	2
<i>P. quinqueloba</i>	0	0	1	0	1	0	0	0	0	1	0	1	1	0	0
<i>Siphonina planoconvexa</i>	0	0	1	0	0	0	0	0	3	0	13	0	1	2	0
<i>S. reticulata</i>	13	11	16	3	10	19	21	9	12	9	0	11	3	5	4
<i>Stilostomella</i> sp.	2	1	2	2	0	0	0	2	3	1	1	5	9	5	0
<i>Textularia sagittula</i>	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0
<i>Textularia</i> sp.	0	0	1	0	2	6	2	0	0	0	0	0	0	0	1
<i>Trifarina angulosa</i>	1	0	0	1	0	3	1	1	1	0	1	2	0	0	0
<i>Uvigerina bononiensis</i>	0	0	0	0	0	0	0	0	1	0	2	2	7	0	1
<i>U. cyl. gaudryoides</i>	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0
<i>U. cylindrica cylindrica</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
<i>Uvigerina peregrina</i>	18	14	10	3	10	11	11	25	9	25	4	14	12	20	12
<i>U. rutila</i>	2	4	6	6	9	0	0	0	0	5	1	2	2	4	1
<i>U. semiornata</i>	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
<i>U. striatissima</i>	6	11	0	0	8	2	5	0	0	7	8	3	0	0	0
<i>Vaginulina legumen</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
<i>Vaginulinopsis tricarinata</i>	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Valvulineria bradyana</i>	0	0	4	0	0	0	0	0	0	1	0	0	0	0	0

## Appendix C: Microhabitat preferences of benthic foraminiferal species

### Epifaunal taxa

*Anomalinoidea* spp., *Cassidulina laevigata*, *Cibicides* spp., *Cibicides* spp., *Dentalina* spp., *Gavelinopsis lobatulus*, *Gyroidinoides neosoldanii*, *Hanzawaia boueana*, *Heterolepa* spp., *Lagena* sp., *Lenticulina* spp., *Marginulina* spp., *Marginulinopsis* sp., *Nodosaria* spp., *Oridorsalis umbonatus*, *Orphomorphina* sp., *Planularia* sp., *Planulina* spp., *Plectofrondicularia raricosta*, *Pyrgo depressa*, *Quinqueloculina* sp., *Saracenaria italica*, *Sigmoilinita tenuis*, *Siphonina reticulata*, *Sphaeroidina bulloides*, *Spiroloculina depressa*, *Vaginulina legumen*, *Vaginulinopsis sulcata*, *Valvulineria complanata*.

### Infaunal taxa

*Amphicoryna scalaris*, *Amphicoryna sublineata*, *Astrononion stelligerum*, *Bolivina alata*, *Bolivina dilatata*, *Bolivina punctata*, *Bolivina reticulata*, *Bolivina spathulata*, *Bolivina tortuosa*, *Bulimina aculeata*, *Bulimina costata*, *Bulimina exilis*, *Globobulimina* sp., *Globocassidulina oblongus*, *Globocassidulina subglobosa*, *Melonis* spp., *Nonion* sp., *Nonionella* sp., *Pullenia bulloides*, *Pullenia quinqueloba*, *Uvigerina gaudryoides*, *Uvigerina peregrina*, *Uvigerina striatissima*.

## Appendix D: Oxygen morphogroups of benthic foraminiferal species

### Oxic indicators

*Cibicides lobatulus*, *Cibicides refulgens*, *Cibicides* sp., *Cibicoides kullenbergi*, *Cibicoides pseudoungerianus*, *Cibicoides robertsonianus*, *Cibicoides ungerianus*, *Pyrgo depressa*, *Quinqueloculina* sp.

### Suboxic indicators

*Bulimina aculeata*, *Bulimina costata*, *Cassidulina carinata*, *Cassidulina laevigata*, *Dentalina* spp., *Globocassidulina ob-*

*longa*, *Globocassidulina subglobosa*, *Gyroidina soldanii*, *Gyroidinoides neosoldanii*, *Hoeglundina elegans*, *Lenticulina* spp., *Melonis* spp., *Nonion* spp., *Oridorsalis unbonatus*, *Pullenia* spp., *Sphaeroidina bulloides*, *Uvigerina* spp., *Valvulineria complanata*.

### Dysoxic indicators

*Bulimina exilis*, *Bolivina alata*, *Bolivina dilatata*, *Bolivina spathulata*, *Bolivina tortuosa*, *Chilostomella oolina*, *Fursenkoina schreibersiana*, *Globobulimina* sp.