Benthic Foraminifera assemblages from the Late Pliocene Iraklion Basin in Central Crete, Greece

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With 6 figures and 2 tables

Abstract: Based on quantitative analyses on benthic foraminifera, the environmental evolution of the Late Pliocene Atsipadhes Section, Iraklion Basin, in central Crete, is reconstructed. The Atsipadhes section deposited during a period of marine regression related to the geodynamic regime in the evolution of Iraklion Basin during the Pliocene. The application of the oxygen transfer function – based on the use of benthic foraminiferal taxa from oxyphilic habitats – to the benthic faunas of the Atsipadhes Section, showed that apart from the lower part of the section, no severe disturbances in oxygenation are recorded. In the deep part of the succession, oxygen depletions are recorded and interpreted as sapropel events, based on the dominance of certain opportunistic species. The distributional frequency pattern of the Lucinidae is in agreement with the oxygenation reconstruction based on benthic foraminifera.

Zusammenfassung: Basierend auf der quantitativen Analyse benthischer Foraminiferen wird die Umweltentwicklung des oberpliozänen Profils von Atsipadhes im Iraklion-Becken in Zentral-Griechenland rekonstruiert. Dieses Profil wurde während einer marinen Regression abgelagert, die mit dem geodynamischen Regime der Entwicklung des Iraklion-Beckens verknüpft ist. Die Anwendung der Sauerstoffübertragungsfunktion – basierend auf dem Gebrauch benthischer Foraminiferentaxa aus sauerstoffreichen Habitaten – übertragen auf die Faunen des Atsipadhes-Profils zeigte, dass, abgesehen vom tieferen Profilabschnitt, keine gravierende Sauerstoffunterversorgung nachweisbar ist. Im tieferen Profilabschnitt treten jedoch Sauerstoffmangelanzeichen auf und werden aufgrund der Dominanz einiger opportunistischer Arten als Sapropel-Ereignisse interpretiert. Das Häufigkeitsverteilungs-

muster der Lucinidae stimmt mit den Ergebnissen zum Sauerstoffgehalt anhand der Verbreitung benthischer Foraminiferen überein.

1. Introduction

Benthic foraminifera are a highly successful, diverse and widely distributed group of marine protists. They dominate modern ocean-floor meiobenthic and macrobenthic communities (e.g. GOODAY et al. 1992; GOODAY 1999) and are the most abundant benthic deep-sea organisms preserved in the fossil record. The study of benthic foraminifera has contributed significantly to our understanding of past sedimentary environments. In order to interpret the fossil record of benthic foraminifera, it is clearly important to understand the environmental factors that control their distribution and abundance in the modern ocean.

In early studies, benthic foraminiferal assemblages were related to water depth (e.g. PHLEGER 1960). However, recent studies showed that the abundance and distribution of modern benthic foraminifera is controlled largely by two inversely related parameters, the flux of organic matter to the sea floor and the oxygen concentrations of the bottom-water and sediment pore-water (LUTZE & COULBOURN 1984; VAN DER ZWAAN et al. 1999; LINKE & LUTZE 1993; JORISSEN et al. 1992, 1995; JORISSEN 1999). Recently, MURRAY (2001) argued that oxygen levels and food supply largely control the benthic foraminiferal distribution only in the deep marine environments. On the contrary, in shallow marine environments, he considers that it would be too simplistic to attempt to define their distribution only in terms of oxygen and food supply, because other factors have been shown to play a major role.

The aim of the present study is to increase our knowledge of how shallow marine benthic foraminiferal assemblages develop under fluctuating bottom water oxygen during the deposition of the Late Pliocene Atsipadhes (Iraklion Basin, central Crete) sedimentary record. Previous studies carried out on benthic foraminifera and mollusc assemblages and on sedimentological observations (KOSKERIDOU et al. 2002; DRINIA et al. 2005) indicate a general regressive trend for this succession.
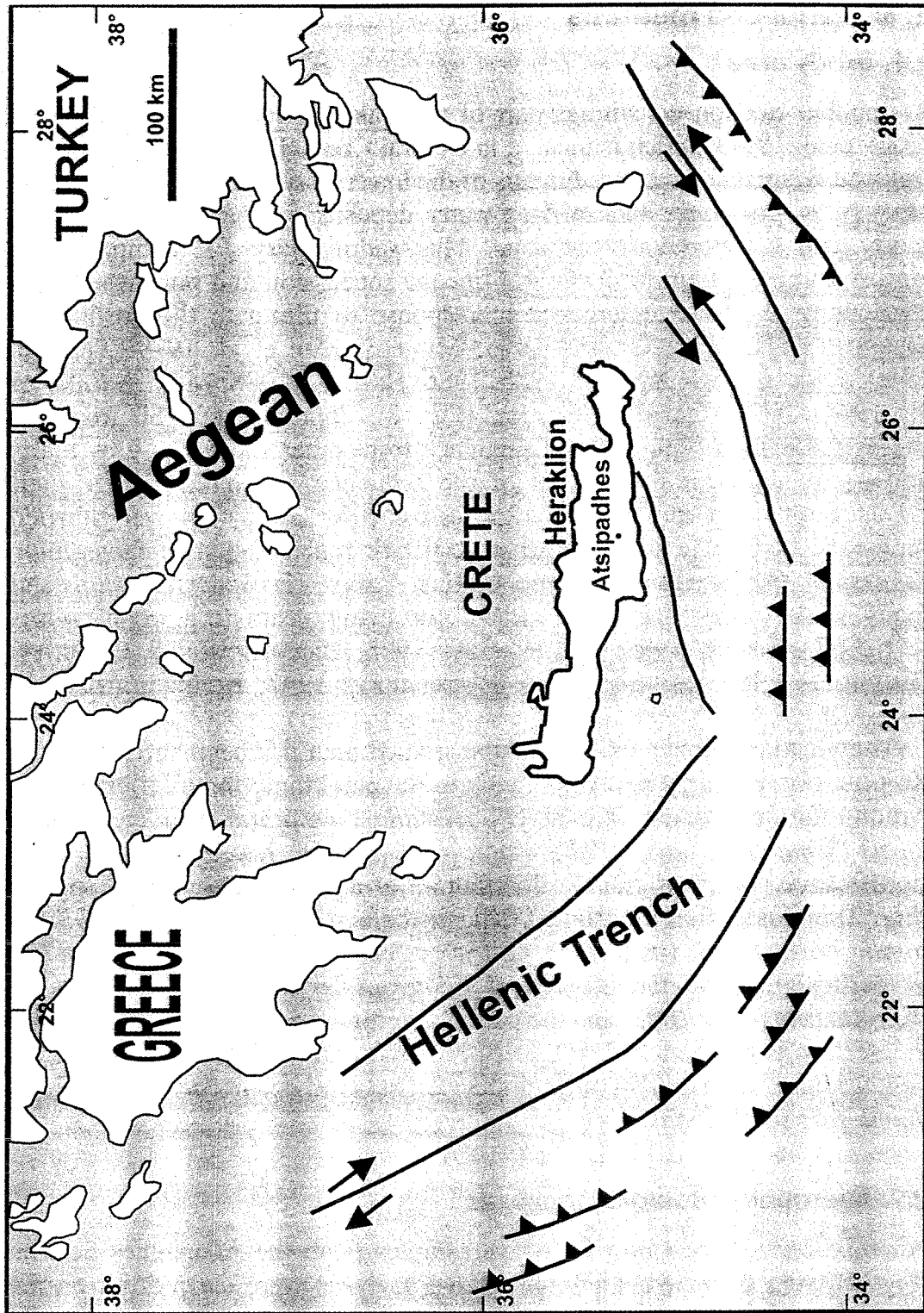
Fig. 1. Schematic map of Crete indicating the location of the study area.

2. Material and methods

2.1. Study area

Atsipadhes Section constitutes part of the Iraklion Basin (sensu MEULEN-KAMP et al. 1994), which is located in Central Crete (Fig. 1). In the southern Iraklion Basin, deepwater sediments of the lowermost Pliocene overlie lower Messinian limestones. These deep-water deposits pass upward into more sandy and conglomeratic deposits. This sedimentary fill comprises an almost complete Late Miocene to Pliocene succession and portrays overall shallowing and even emergence in response to tilting to the north (e.g. SISSINGH 1972; ZACHARIASSE 1975; MEULENKAMP et al. 1979; THOMAS 1980; JONKERS 1984; FRYDAS 1985, 1986; DRIEVER 1988; MEULENKAMP et al. 1994). The Atsipadhes Section (Fig. 2), approximately 80 m thick, represents a shallowing upward sequence from outer shelf blue-gray marls and sandy marls at the bottom of the sequence, to shallow inner shelf deposits at the top. The top of the succession is formed by two well lithified limestone beds. The presence of a very rich malacofauna of *Dentalium*, *Amussium*, *Pecten*, *Cardium*, *Arca*, oysters, *Natica*, *Vermetus*, *Aporrhais* and many other genera has been known for many years (e.g. SYMEONIDIS & KONSTANTINIDIS 1967; ZACHARIASSE 1975; DERMITZAKIS & GEORGIA-DIKEOULIA 1983; JONKERS 1984; KOSKERIDOU 1997; KOSKERIDOU et al. 2002).

The biostratigraphic analysis of the studied area has been carried out by KOSKERIDOU et al. (2002) on the basis of the planktonic foraminifera fauna. Among the determined species, *Globorotalia crassaformis, Sphaeroidinellopsis seminulina* and *Globorotalia bononiensis*, have biostratigraphic significance. The stratigraphic distribution of the above mentioned species (Fig. 2) indicates that the studied deposits belong to the Biozone of *Globorotalia crassaformis* (interval IV) of SPAAK (1983) and MPL4 (CITA 1975). In particular, using the biochronology given by the nannofossil record (KOSKERIDOU et al. 2002) and the planktonic foraminifera record, the base of the section is defined at 3.61 Ma (top of the paracme zone of *Discoaster pentaradiatus*) and the top range up to 3.21 Ma (last occurrence of *Sphaeroidinellopsis seminulina*).

2.2. Micropaleontological analysis

For this study, a total number of 38 samples from the Atsipadhes Section (Fig. 2) were collected. The quantitative analyses were carried out on the total assemblage (>125 μm fraction) and about 300 individuals were counted from subsamples obtained by a microsplitter and re-calculated as percentage values. For paleoenvironmental reconstructions, R-mode cluster and Prin-
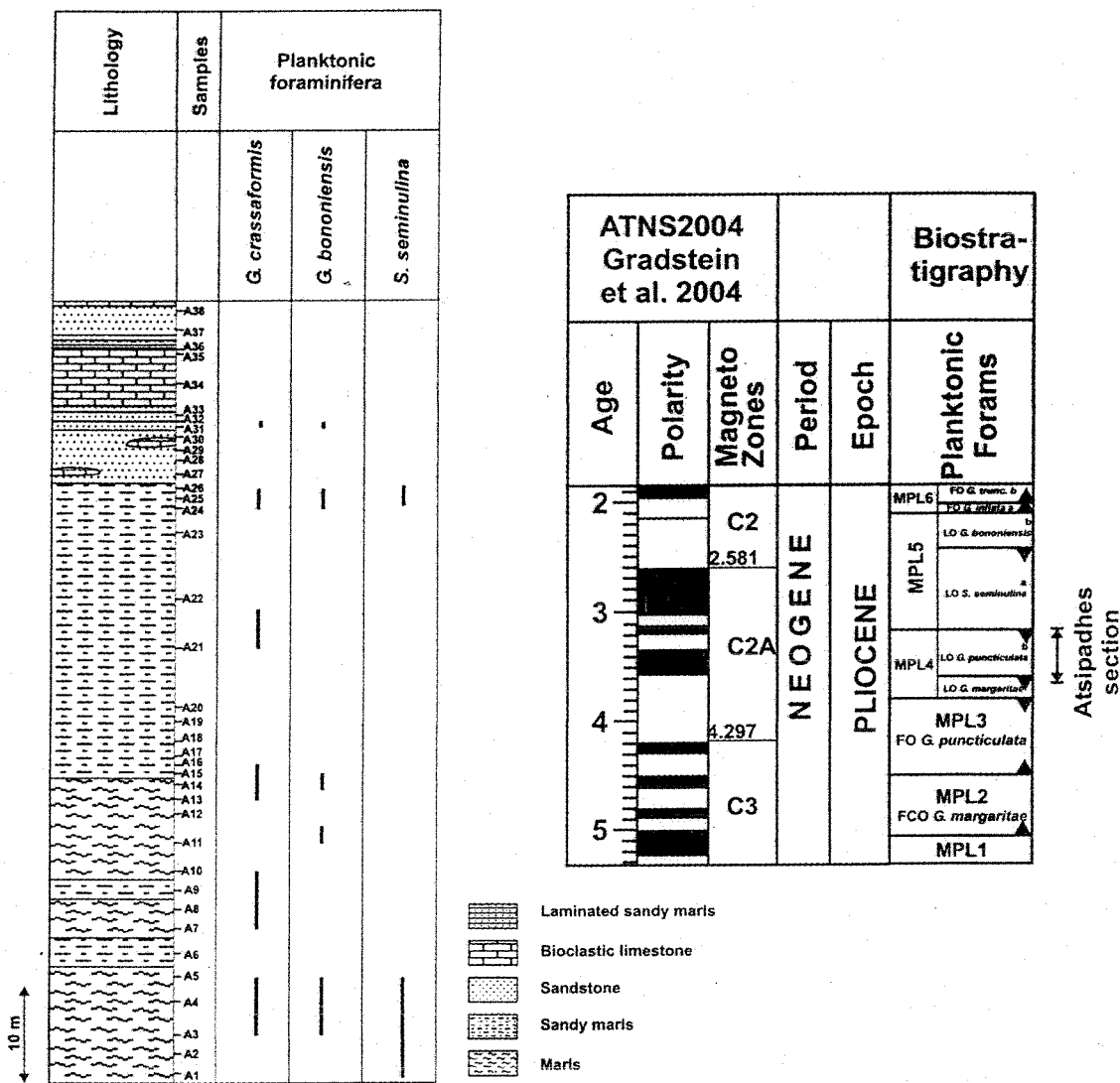
Fig. 2. Lithostratigraphical column of the Atsipadhes Section indicating the position of sampling and the stratigraphic distribution of the biostratigraphically significant planktonic foraminifera (after KOSKERIDOU et al. 2002).

cipal 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 the environmental parameters, which influenced the foraminiferal distribution during the period of deposition.

For the paleobathymetric reconstruction of the sedimentary basin, the formula of VAN DER ZWAAN et al. (1990) was used:

$$\text{Depth (m)} = e^{(3.58718 + (0.03534 * \%P))}$$

where "% P" represents the percentage of planktonic foraminifera present in the assemblages.

Finally, we applied the oxygen transfer function of VAN DER ZWAAN et al. (subm.) to the benthic faunas of the Atsipadhes Section, according to the formula:

$$[\text{Oxygen content } \mu\text{Mol/lt}] = 7.9602 + 5.95 \, [\% \text{ oxyphilic taxa}]$$

We selected a group of calcareous oxyphilic species (Table 1) in order to reconstruct the oxygen contents of the bottom waters. Agglutinated species were omitted because of the evident fragility and rather low preservation potential of a number of them.

Table 1. Species used as input for the transfer function calculating bottom-water oxygenation.

Oxyphilic Group

Cibicidoides brady	*Sphaeroidina bulloides*
Cibicidoides italicus	*Quinqueloculina* spp.
Cibicidoides kullenbergi	*Spiroloculina depressa*
Cibicides lobatulus	*Pyrgo oblonga*
Cibicides refulgens	*Siphonina reticulata*
Cibicidoides ungerianus	*Globocassidulina subglobosa*
Cibicidoides wuellerstorfi	*Gavelinopsis lobatulus*
Cibicidoides robertsonianus	*Gavelinopsis praegeri*
Lenticulina spp.	

3. Results and interpretation of the data

3.1. Benthic foraminifera assemblages and paleoecological implications

Appendix I shows the determined species in Atsipadhes section. The distributional pattern of the most significant species is presented in DRINIA et al.

(2005). Fig. 3 illustrates the dendrogram classification of the taxa produced by the cluster analysis. The clusters represent informal foraminiferal assemblages, labeled I and II. Assemblage I includes the species *Bulimina marginata, Cassidulina carinata, Bulimina exilis, Gyroidina soldanii, Bolivina spathulata* group (including *B. spathulata, B. dilatata, B. tortuosa*), *Uvigerina peregrina, Melonis barleeanum, Valvulineria bradyana* and the taxa *Globobulimina* spp., *Cibicidoides* spp. and agglutinants. Assemblage II consists of the species *Ammonia beccarii, Asterigerinata planorbis, Cibicidides lobatulus, Rosalina globularis, Gavelinopsis praegeri, Nonion boueanum, Haynesina depressula, Hanzawaia boueana, Bolivina pseudoplicata* and the taxa *Elphidium* spp. and Miliolidae. A qualitative analysis of the taxa present in Assemblage I and in Assemblage II indicates that the two assemblages reflect differences in bathymetric zones. Indeed, Assemblage I consists of taxa that are present in modern deep marine waters, from the lower neritic zone (200-100 m; VAN MORKHOVEN et al. 1986) to the upper bathyal zone (200-600 m, VAN MORKHOVEN et al. 1986), whereas Assemblage II contains taxa commonly distributed in modern shallow waters, in the middle neritic zone (30-100 m; VAN MORKHOVEN et al. 1986).

The cumulative plots of Assemblage I and Assemblage II (Fig. 4) show that Assemblage II increases at the expense of Assemblage I further supporting the regressive trend of the depositional environment. Assemblages I and II are characterized by generally low abundances of planktonic foraminifera (DRINIA et al. 2005). However, the occurrence of four distinct sub-assemblages indicates that there were systematic changes in foraminiferal composition, and thus changes in paleoenvironment during the Late Pliocene in the Atsipadhes area. The cumulative plots of the four sub-assemblages reconstructed in the dendrogram are presented in Fig. 4.

Sub-assemblage Ia is characterized by the dominance of the species *C. carinata, Bulimina marginata* and agglutinants. *Globobulimina* spp. and *B. exilis* are less abundant. According to MURRAY (1991), VAN DER ZWAAN et al. (1999) and BERNHARD & SEN GUPTA (1999), species belonging to sub-assemblage Ia suggest an oxygen-depleted environment. Indeed, according to KAIHO (1999), *C. carinata* indicates suboxic sediments ($O_2 < 1.2$ ml/l), while *Globobulimina* spp. and *B. exilis*, which both inhabit sediment depths greater than 1.5 cm and are thought to be deep endobenthic species, are considered to belong to the dysoxic indicators (MULLINEAUX & LOHMANN 1981; HERMELIN & SHIMMIELD 1990; BERNHARD 1992; BERNHARD et al. 1997). Finally, GOODAY (1994) inserts *B. marginata* among the species preferring a poorly oxygenated environment.

Sub-assemblage Ib consists mainly of *B. spathulata* group (max abundance 46.2 %) and *Uvigerina peregrina*. These abundant occurrences indicate adaptation to high-organic carbon and low-oxygen conditions (MURRAY

HIERARCHICAL CLUSTER ANALYSIS

Dendrogram using Average Linkage (Within Group)

Rescaled Distance Cluster Combine
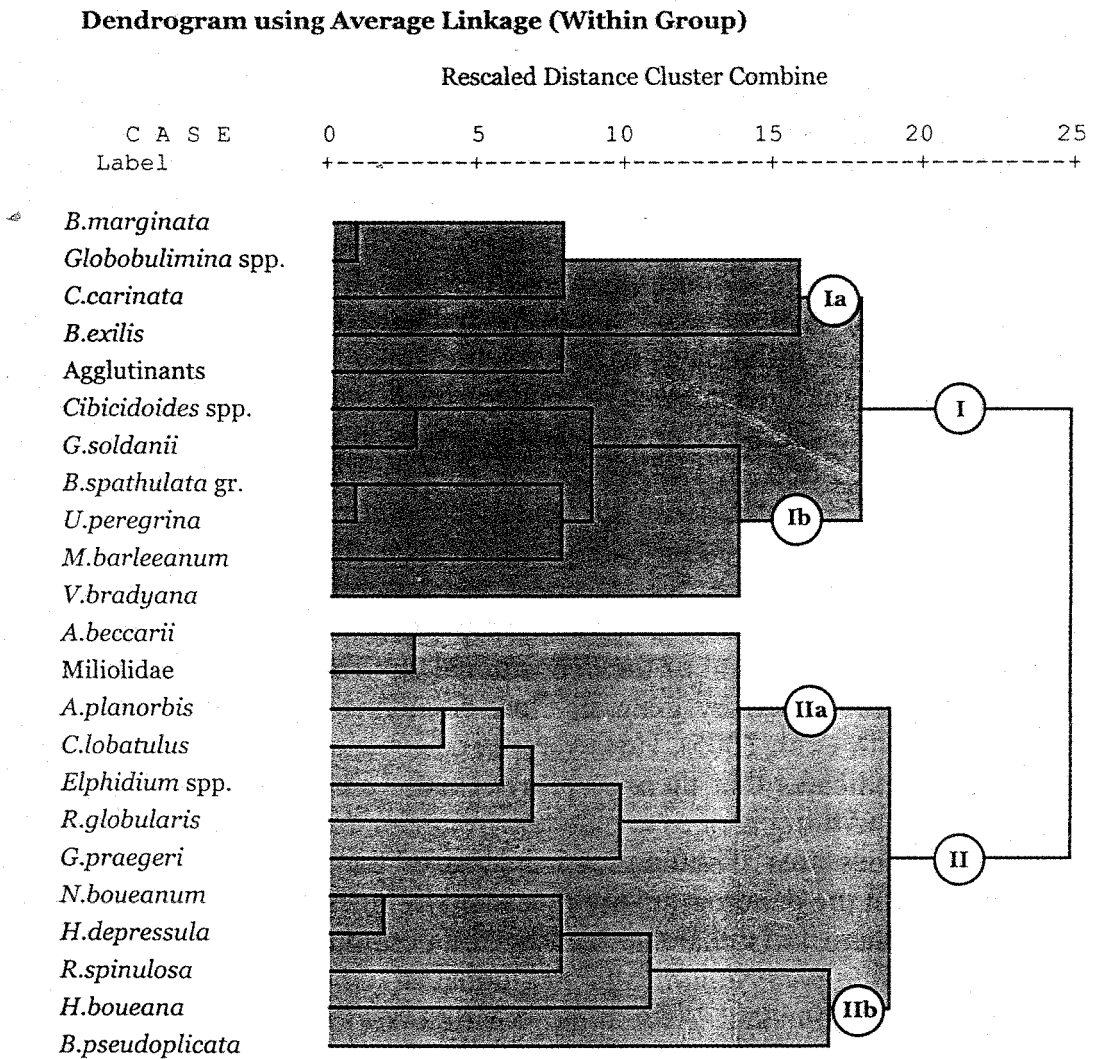
Fig. 3. Dendrogram classification of the benthic foraminifera species, produced by R-mode cluster analysis.

1991). In particular, high *U. peregrina* abundance is generally associated with high sedimentary organic-content (MILLER & LOHMANN 1982; WOODRUFF 1985; CORLISS et al. 1986; BOYLE 1990; GUPTA & SRINIVASAN 1992; BURKE et al. 1993) while *B. spathulata* has frequently been associated

with low-oxygen conditions in the bottom-waters (RATHBURN & CORLISS 1994).

The sub-assemblage IIa groups together species such as *Elphidium* spp., *C. lobatulus, A. beccarii, A. planorbis, R. globularis, G. praegeri* and Miliolids. These species, which have a strictly epibenthic life-style, are known as cosmopolitan and suspension filtrating inhabitants of shelf and upper slope areas (e.g. MURRAY 1991; KITAZATO 1994; MACKENSEN 1997) and can be correlated with the presence of an algal covered sea-bottom. *Elphidium advenum* which is the most common representative of the *Elphidium* spp. group is common in somewhat sheltered situations, often at slightly lowered salinities (HAYWARD & BROOK 1994).

Sub-assemblage IIb contains the species *B. pseudoplicata, H. boueana, R. spinulosa, H. depressula* and *N. boueanum*. The bulk of species of this assemblage (especially *B. pseudoplicata* and *H. depressula*) are adapted to salinity stressed conditions (VAN DER ZWAAN 1982; VAN DER ZWAAN & HARTOG JAGER 1983; JONKERS 1984). According to FIORINI (2004) this association is characteristic of river influenced environments. Based on the aforementioned qualitative analysis, the subassemblages appear to reflect different oxygen contents at the bottom-water surface and in the sediment pore-water.

For the better documentation of the parameters that influenced the distribution of benthic microfauna, the same data set was subjected to Principal Component Analysis (PCA). The PCA, which has been carried out considering only the foraminiferal species frequencies, can test the validity of the assemblages defined through cluster analysis. Based on a screeplot of eigenvalues and viewing of the component scores (Table 2) and species associations, three components were considered that account for 48.48 % of the total variance (Fig. 5). Components that do not show appropriate species associations were not considered to make out assemblages.

PCA 1 is characterized by high positive loadings for the species comprising Assemblage I, and significant negative loadings for the species comprising Assemblage II. Therefore, the taxa showing positive PCA 1 loadings are indicative of rather deep marine waters (the lower neritic-upper bathyal zone). Moreover, the high positive values of *B. spathulata* gr. appear to reflect conditions of lowered oxygen concentration and enlarged food availability (PHLEGER & SOUTAR 1973; SEN GUPTA et al. 1981; CARALP 1989; GOODAY 1993). The taxa with negative loadings apparently indicate a shallow marine environment (the middle neritic zone). These taxa prefer environments, which are characterized by a minimum of stress, high oxygen content of the bottom-water, and stable salinities. Thus the negative scores of this factor suggest a shallow and well-oxygenated environment. Conclusively, PCA 1 reflects both depth and oxygenation. On the contrary, PCA

2 component has no clear significance since it is loaded, both positively and negatively, with taxa that are indicators of different environmental conditions. Therefore, we do not take this component into consideration. PCA 3 is loaded, both positively and negatively, with opportunistic high-productivity species (*B. exilis* and *M. barleeanum*). Many studies have shown that these species prefer a shallow to deep infaunal life style and are related to high organic matter fluxes and low dissolved oxygen concentrations (e.g. MURRAY 1991; SEN GUPTA & MACHAIN-CASTILLO 1993). CARALP (1989a, b) observed that the benthic foraminiferal fauna in a late Quaternary sediment core off Northwest Africa is controlled by the quality as well as the quantity of the deposited organic matter. She found that the occurrence of *B. exilis* is related to large inputs of freshly produced phytodetritus, whereas *M. barleeanum* prefers organic matter in slightly altered form. Therefore, this food preference may be reflected in the regional distribution pattern of these species. At the southwest African continental margin, while *B. exilis* inhabits the upper continental slope that is directly influenced by upwelling, *M. barleeanum* is abundant only at the lower continental margin (SCHMIEDL, 1995). This area probably receives terrigenous organic matter or organic material derived from the resuspension of sediments of the shelf and upper continental margin (EMBLEY & MORLEY 1980).

The calculated results according to the formula of VAN DER ZWAAN et al. (1990) support the already inferred shallowing trend of the succession, from the bottom towards the top (Fig. 5). The lower part of the succession, where Assemblage I predominates, deposited in a deep marine environment with a depth-range of 600-200 m, which corresponds to the upper bathyal-lower neritic zone. The rest of the succession deposited in a shallow environment corresponding to the middle neritic zone.

3.2. Oxygen-content

The result of the oxygen transfer function as applied to data from the Atsipadhes Section is presented in Fig. 6. The reconstructed oxygen record represents the variation of the oxygen contents at the sediment-water interface, and suggests that the actual concentrations were moderate (ranging from 100 to 200 μMol/lt). Sometimes oxygen levels dropped to values below 100 μMol/lt, a value relatively low for most macrofaunal species (e.g. TYSON & PEARSON 1991). In this respect the reconstructed oxygenation curve is certainly supported by independent faunal evidence: in many parts of the succession we observe signs of meager macrofaunal presence. These temporal decreases are reflected in the frequencies of the determined species (DRINIA et al. 2005).
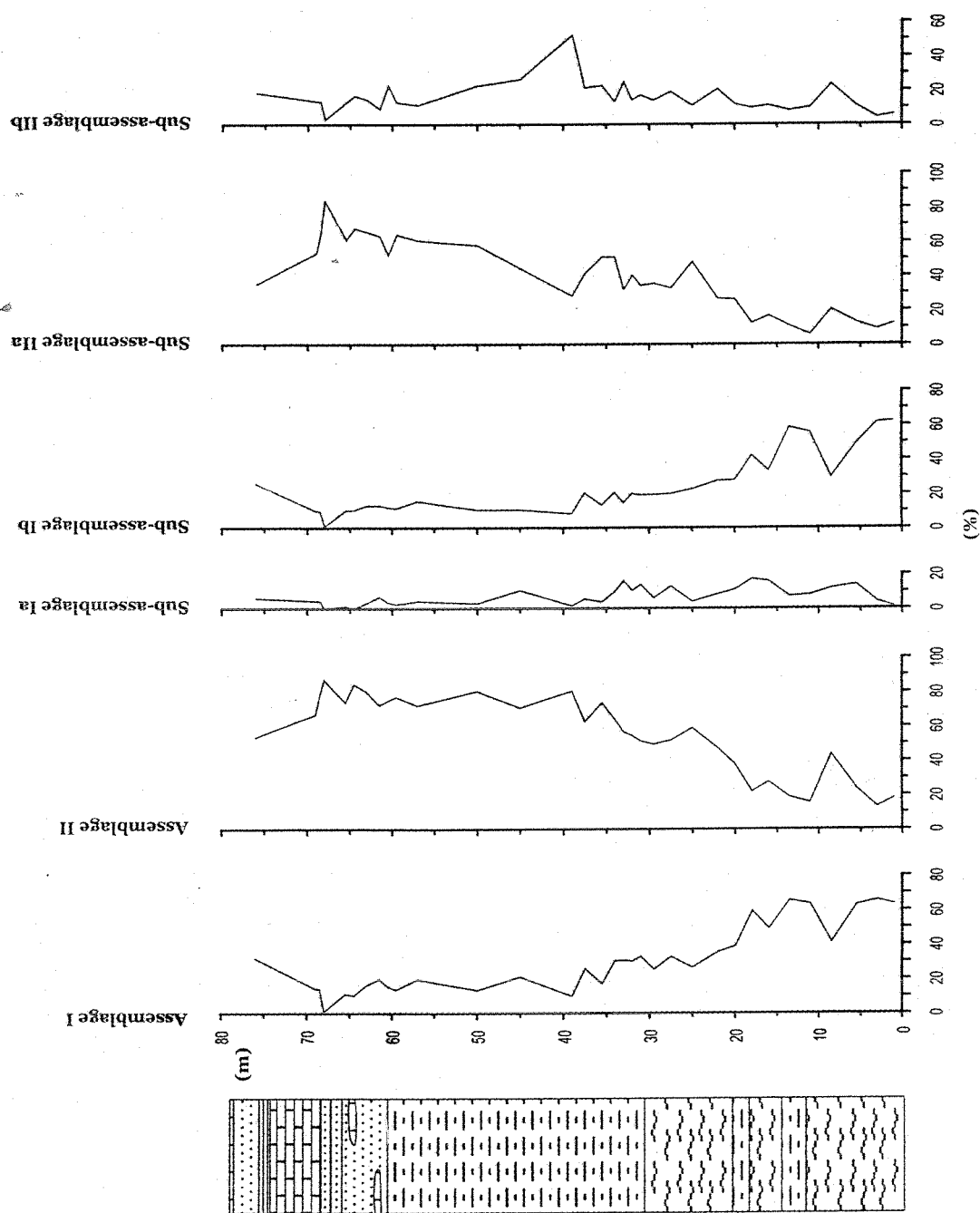
Fig. 4. Cumulative plots of Assemblage I, Assemblage II and Sub-assemblages Ia, Ib, IIa and IIb.

Table 2. Component loadings for the benthic foraminiferal species from the Atsipadhes section, imported into statistical analysis.

Component Matrix (a)

	Component 1	2	3
% Variance	25.63	12.07	10.78
A. beccarii	-0.51	-0.05	0.43
A. planorbis	**-0.75**	-0.18	-0.15
Agglutinants	0.31	0.25	-0.18
B. exilis	0.41	-0.01	**-0.61**
B. marginata	0.63	0.29	-0.32
B. pseudoclicata	-0.08	0.22	-0.46
B. spathulata gr.	**0.79**	-0.27	-0.10
C. lobatulus	-0.77	-0.18	-0.09
Cas. carinata	0.20	0.73	-0.05
Cibicidoides spp.	0.65	0.12	0.27
Elphidium spp.	-0.64	-0.08	-0.31
G. praegeri	-0.29	0.23	-0.47
G. soldanii	**0.74**	-0.01	-0.10
Globobulimina spp.	0.41	0.31	-0.13
H. boueana	-0.09	0.64	0.17
M. barleeanum	0.34	-0.28	**0.69**
Miliolidae	-0.38	-0.31	0.05
N. boueanum	-0.42	0.49	0.45
H. depressula	-0.15	0.58	0.28
R. globularis	-0.65	-0.31	-0.15
R. spinulosa	-0.42	0.51	0.35
U. peregrina	0.67	-0.46	0.43
V. bradyana	0.08	0.02	0.04

The reconstructed oxygen curve suggests that at the lower part of the section (0-18 m), a gradual decrease is reflected in the benthic counts, which coincides with the gradual decrease in frequency values of the epiphytic group. At 13.5 m, the oxygen content reaches its lowest value, around 40 µMol/lt (~0.9 ml/lt), which coincides with the peak occurrences of the B. spathulata group and U. peregrina and the lowest frequency values of Cibicidoides spp. This drop of oxygen levels is followed by a gradual in-
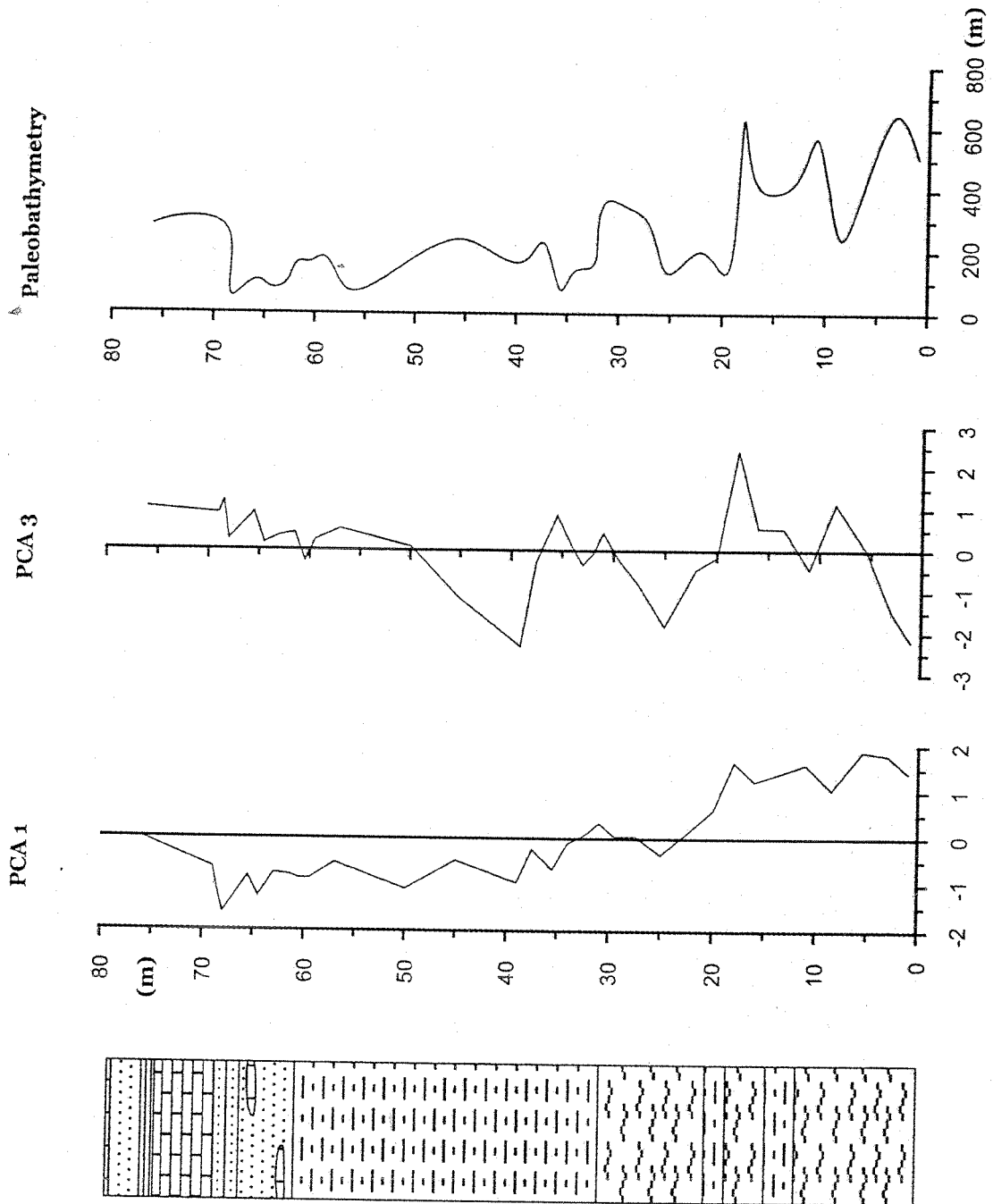
Fig. 5. Plot illustrating the sample score of the extracted PCA 1 and PCA 3 and the paleobathymetric reconstruction of the sedimentary basin in which the succession was deposited.
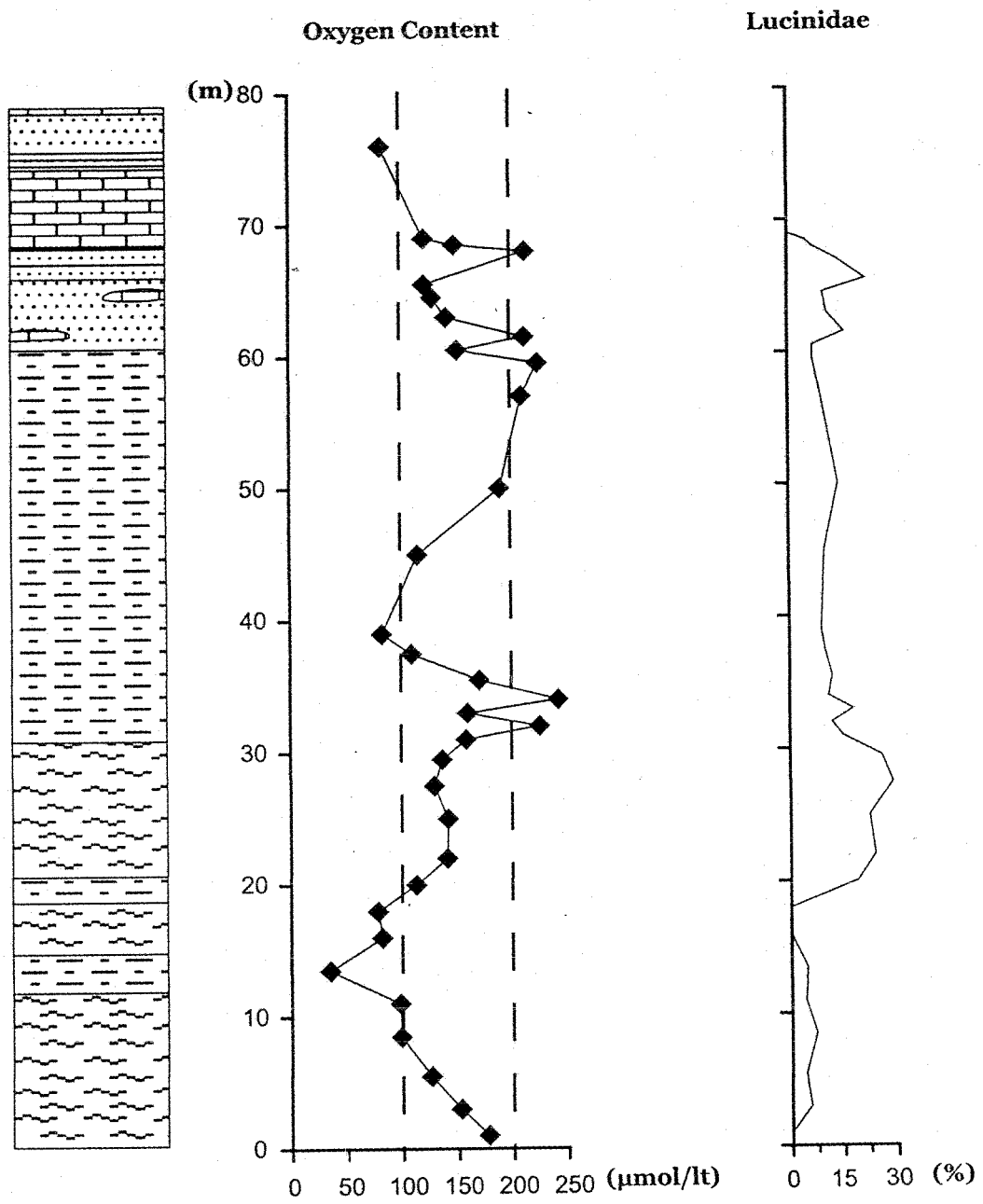
Fig. 6. Plot illustrating the bottom-water oxygen content distribution, reconstructed with the transfer function and the distributional pattern of the family Lucinidae.

crease until 34 m followed by a decrease until the 39 m. This trend is in line with the pattern in frequency of the *B. spathulata* group and the increasing trend of *C. lobatulus*, which is characteristic of non-stressed conditions. No severe disturbances are recorded from 39 m up to top of the section, pointing to the fact that we are dealing with an overall rather well ventilated water column during most of this part of the sequence. Finally, in the uppermost part of the section, an assemblage composed of *Bolivina, Bulimina* and *Uvigerina* species was established, pointing to a drop in oxygenation.

The distributional pattern of the contained Lucinids (molluscs) can be used as an additional evidence of the oxygenation trend.

Lucinids have a significant participation in almost all the deposits of our section, including *Megaxinus (Megaxinus) transversus, Megaxinus (Megaxinus) ellipticus, Megaxinus (Megaxinus) incrassatus, Myrtea spinifera, Lucinoma borealis*. All of these species are deep burrowers and deposit feeders. Their presence is related to physico-chemical environmental conditions. In particular, this group is influenced by bottom water oxygenation, with low numbers prevailing under low oxygen values. The frequency curve of Lucinidae (Fig. 6) indicates low oxygen content in the lower part of the section (0-18 m). In these deposits, the Lucinidae specimens belong mainly to *Lucinoma borealis* that represents a depth range of the upper bathyal zone (PARENZAN 1974). The density of Lucinidae increases at about 20 m and stays relatively stable (higher than 10 %) up to 68 m. This is in accordance with a well ventilated water column. The specimens belong mainly to *Megaxinus* and *Myrtea*. Upwards, the gradual decrease in density maybe is due to the low salinity waters as the dominance of *Ostrea (Ostrea) lamellosa* and *Thericium vulgatum* indicates (GITTON et al. 1986).

4. Discussion

4.1. Paleobathymetry

The Late Cenozoic evolution of Crete has been controlled by the final northward subduction of the African plate and incipient collision with the Anatolian-Aegean microplates (MAKRIS & VEES 1977; LE PICHON & ANGELIER 1979). Although parts of Crete have been subaerially exposed since Mid-Miocene time, extensional faulting combined with eustasy resulted in local nonmarine and marine basins. Shallow marine sequences along the north and south coasts of Crete suggest an overall emergence and northward tilting of the island starting in late Early Pliocene time (4.4 Ma; MEULENKAMP 1985; MEULENKAMP & HILGEN 1986; MEULENKAMP et al. 1994). Therefore, the southern part of Iraklion area emerged earlier than the northern part, where deep marine conditions lasted until after approximately

3 Ma. Uplift of Crete was most pronounced during Plio-Pleistocene time (ANGELIER et al. 1982). Various sections provide conclusive evidence for uplift of Crete during the Pliocene. According to KRÖGER et al. (2003), Neogene near shore sediments in the southern part of the Iraklion basin record fault movements contemporaneous to sedimentation and sedimentary input from the hinterland. Shallow water sediments reflect these tectonic movements.

The paleobathymetric calculation used in this study reveal a shallowing trend on Atsipadhes section. The shallowing of the depositional environments was mainly the result of the uplift of the basin floor, whereas the coeval sea-level fall (HAQ et al. 1988) only contributed to it a small extent. In the upper part of the section tectonic quiescence allowed eustasy to become the main controller of bathymetric changes. In the deep part of the succession (lower part of the section), significant fluctuations of paleowater depth (in the order of 200 m) occurred (Fig. 5), evidencing regular alternations between shallowing and deepening phases. We think that the quantitative method used might underestimate water depth because of benthic foraminifera redeposited from shallower parts of the sedimentary basin. Indeed, these high amplitude fluctuations at the lower part of the section were probably caused by fluxes of sediment from shallower parts of the basin with excess benthic foraminifera, which make the estimation shallower than the actual water depth.

4.2. Oxygenation

The application of the oxygen transfer function - based on the use of benthic foraminiferal taxa from oxyphilic habitats – to the benthic faunas of the Atsipadhes Section, shows good correlation with the benthic faunal succession identified. The shallow Assemblage II developed under oxic regime and the deep Assemblage I occurred under moderate oxygen depleted conditions. According to the continuous presence of benthic foraminifera and molluscs within the succession, no anoxia resulted during the entire time span of deposition.

Benthic foraminiferal associations in the lower part of the Atsipadhes section, between 1 and 18 m, are dominated by the peak of the sub-assemblage Ib (*B. spathulata* gr.). According to DRINIA et al. (2005), in this interval, the planktonic assemblage is characterized by high frequencies of *Globigerina bulloides* which constitutes an ambiguous signal of cooling, of upwelling, or of both (e.g. PRELL & CURRY 1981; RAO et al. 1989), a sharp decrease in frequencies of *Globigerinoides ruber* gr. and a planktonic/benthic ratio as high as 60 %. According to MILLER & LOHMANN (1982), MULLINS et al. (1985), QUINTERO & GARDNER (1987) and SEN GUPTA & MACHAIN-CASTILLO (1993), high abundance of the genus *Bolivina*, together

with planktonic foraminifera, may indicate decrease in SST and higher productivity in oxygen-poor waters, connected to periods of sapropel deposition (e.g. STEFANELLI et al. 2005). Recent results indicate that these cold spells are part of the millennial-scale climate variability of the northern hemisphere (ALLEY et al. 1997; BOND et al. 1997; ROHLING et al. 2002).

The origin of sapropels is related to paleoclimatic changes. Sapropels are thought to form during wet climate caused by precession-induced insolation variations and concomitant enhanced precipitation over parts of Africa and the Mediterranean borderlands. During these wet periods, increased input of fresh water caused a higher stability of the water column and perhaps even a circulation reversal from antiestuarine circulation to estuarine circulation (e.g. ROSSIGNOL-STRICK et al. 1982; ROHLING & HILGEN 1991; FONTUGNE & CALVERT 1992). Furthermore, increased input of nutrients in freshwater or via upwelling of deep water to the surface waters of the eastern Mediterranean caused enhanced productivity of organic matter. Increased productivity in the surface waters and/or enhanced preservation due to oxygen depletion in the bottom waters were reported to be possible causes of increased accumulation of organic carbon and sapropel formation (e.g. OLAUSSON 1961; ROSSIGNOL-STRICK et al. 1982; CALVERT et al. 1992). Paleoclimatic and paleoceanographic patterns recorded in Pliocene deposits indicate that conditions during this interval were generally warmer than today. However, there is not much direct evidence in favour of wet periods in the Pliocene; there are no detailed pollen studies, for instance. According to JONKERS (1984), Pliocene data indicate that intense stagnation only occurred in relatively shallow environments, suggesting that obstruction of the vertical circulation was only effective in a marginal setting. This may plead for a local supply of fresh water. The nutrients that were brought into the marine environment gave rise to enhanced primary production.

According to BRACHERT et al. (2004), the change in sedimentation patterns from clastics to carbonates, in the southern Iraklion basin, both, in shallow and deep water, must correspond with a climatic shift form more humid to more arid conditions, because the general organization of the basin did not change over time. Therefore, in Atsipadhes section, the observed clastic-carbonate change is not only an effect of hinterland topography but also of rainfall patterns. An inconsistency is observed in the uppermost part of the section. At 76 m, the oxygen values move towards minimum, indicating dysoxic conditions. However the strong dominance of Assemblage II (57 %) over Assemblage I (32 %) does not indicate low oxygenation. Moreover, this interval is characterized by high frequency of the species *B. pseudoclicata* (DRINIA et al. 2005), a species with unclear ecological preference which, however, has been interpreted as an epiphyte living in a normal marine environment (VAN DER ZWAAN 1982; JONKERS 1984). Therefore and

following STEFANELLI et al. (2005), this inconsistency in the results might be, probably, linked to the taxa used to illustrate the changes in oxygen content.

5. Conclusions

The foraminiferal assemblages of the Late Pliocene deposits of the Atsipadhes Section allow us to show the paleoenvironmental changes during their deposition. The quantitative analyses show that depth and oxygenation regulated the faunal composition and the distribution in the studied section. Our data indicate that the regressive trend of the depositional environments was mainly the result of the uplift of the basin floor, whereas the coeval sea-level fall only contributed to it a small extent. The oxygenation state of the bottom waters at the sediment-water interface was calculated using the regression of VAN DER ZWAAN et al. (submitted). It appears that at the Atsipadhes Section, the bottom waters were well aerated apart from a conspicuous drop in oxygen content in the lower part of the sequence, which is related to sapropel deposition. The proportional increase of *Bolivina*, *Bulimina* and *Uvigerina* occurring as bottom-water oxygenation decreases is thought to be related to their ability to profit from the prevailing environmental conditions. This trend is in accordance with the semi-quantitative proxy reconstructed on basis of benthic faunal assemblages.

Acknowledgements

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Appendix I

SAMPLES	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25	A26	A27	A28	A29	A31	A32	A33	A36
A. beccarii	1	3	1	1	0	0	1	0	0	2	2	6	7	2	5	2	5	0	9	15	3	8	1	4	4	1	0	2	1	23	5	5	1
A. granosus	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A. stelligerum	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A. planorbis	3	1	18	25	9	15	13	7	20	21	38	27	20	21	18	0	29	20	29	8	30	27	40	36	35	27	60	60	53	76	26	36	16
A. scalaris	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A. sublineata	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B. gibba	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bigenerina sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B. aenariensis	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
B. alata	1	0	0	0	2	1	1	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B. costata	1	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	2	0	0	0	1	0	0	2	0	1	1	0
B. exilis	0	3	5	5	2	2	7	4	3	1	1	2	2	3	3	4	4	1	1	0	1	2	2	2	2	0	0	3	2	0	3	4	3
B. dilatata	10	3	6	12	13	37	3	20	2	5	1	3	1	1	5	6	0	1	0	1	2	8	4	4	0	1	5	5	13	0	0	8	17
B. marginata	0	0	5	4	6	1	2	5	0	0	0	0	0	0	0	0	0	0	11	11	2	0	0	0	0	0	0	0	0	0	0	0	0
B. placentina	3	4	1	0	1	0	4	1	9	3	0	1	2	5	3	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B. pseudoclicata	0	3	5	22	4	4	1	4	6	5	5	6	3	4	6	9	0	0	0	0	0	4	0	5	0	4	5	5	9	0	3	0	0
B. punktata	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B. seminuda	0	1	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B. spathulata	28	31	34	12	47	48	30	26	10	15	2	9	12	5	8	4	4	0	12	5	5	10	9	9	8	7	10	9	9	1	10	7	28
B. tortuosa	0	0	0	0	3	6	0	8	1	0	0	0	0	0	0	1	1	0	2	0	0	0	0	0	0	0	1	0	2	1	0	0	0
Bolivina sp.	0	0	0	2	1	0	1	1	0	0	0	1	1	0	1	1	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	0
Bulimina sp.	0	0	1	1	1	3	4	6	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
B. multicamera	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C. auriculus	0	0	9	7	3	1	1	5	8	1	1	8	0	0	7	0	0	0	2	2	7	2	1	2	2	0	0	0	0	0	0	0	0
Cas. carinata	0	0	0	3	0	0	0	0	0	2	12	0	0	0	0	0	1	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
Cas. crassa	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Cas. inflata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cas. laevigata	0	0	4	1	4	0	3	0	2	6	7	2	0	2	0	3	0	0	0	0	2	2	2	0	6	3	2	0	0	0	0	0	0
C. brady	0	13	0	0	0	0	0	0	0	6	2	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
C. italicus	0	0	8	9	4	1	3	2	8	6	7	6	6	9	10	3	8	1	8	0	0	4	5	6	1	1	21	12	1	54	8	9	16
C. kallenbergi	13	0	0	1	1	1	1	5	2	1	3	3	3	6	19	11	11	7	11	27	20	28	35	16	22	23	12	54	1	1	19	6	0
C. lobatulus	10	5	0	1	1	1	0	5	1	3	4	8	10	6	14	10	10	12	4	0	0	16	0	4	10	0	8	0	0	0	0	3	1
C. refulgens	3	3	2	3	1	1	0	3	3	4	2	6	0	2	8	8	1	1	1	4	7	2	2	7	4	7	0	0	0	0	0	0	0
C. ungerianus	10	8	11	0	6	2	2	3	6	7	3	3	3	7	7	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C. wuellerstorfi	2	7	8	6	5	0	3	2	4	3	2	4	5	2	7	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C. robertsonianus	1	0	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cornuspira sp.	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0
C. silvestrina	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
D. bertheloti	0	0	0	0	0	0	0	0	1	0	0	0	2	1	0	0	0	3	0	0	0	2	0	0	0	2	0	0	0	1	0	0	0

Appendix I (cont.)

SAMPLES	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25	A26	A27	A28	A29	A31	A32	A33	A36
Dentalina sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dorothia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium sp.	1	3	3	2	0	0	7	3	3	7	6	2	6	10	7	7	7	8	9	6	3	14	4	9	22	27	22	14	13	12	9	12	14
E. lecarvezi	0	0	0	0	1	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	1	1	0
Eponides sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fissurina sp.	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	7	0	0	0	1	1	3	0	0	0	0
F. schreibersiana	1	0	1	0	5	2	1	1	2	3	4	2	0	0	2	0	0	0	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Fursenkoina sp.	0	0	1	0	1	0	1	1	1	1	5	0	2	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
G. laevigata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G. lobatulus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G. praegeri	6	6	9	0	2	2	2	2	6	6	0	1	2	2	5	2	6	0	0	0	2	5	4	0	4	0	1	1	2	6	6	0	0
G. soldanii	2	1	7	2	2	0	4	4	2	2	0	5	5	2	0	2	0	0	0	0	2	0	0	3	1	1	0	0	2	1	0	4	1
G. subglobosa	1	1	2	2	3	0	1	1	2	2	0	1	1	2	2	2	1	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0	1
Globobulimina sp.	0	0	4	2	4	0	12	0	2	2	0	2	0	3	3	7	0	0	0	0	0	2	0	0	2	1	2	0	2	0	6	0	0
G. gibba	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G. communis	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
H. boueana	1	1	0	0	3	3	3	1	5	0	2	5	2	3	3	3	3	3	4	4	5	2	3	5	3	0	0	0	5	0	0	0	0
H. dertonensis	1	1	1	0	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	2	1	2	2	0	1	1	0	1
H. elegans	1	2	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
H. floridana	1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lagena sp.	0	2	0	1	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lenticulina sp.	2	3	2	0	2	0	2	2	3	3	2	2	2	0	1	3	0	0	1	1	2	2	0	0	1	1	1	0	1	0	1	3	0
Marginulina sp.	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M. costata	1	1	1	1	0	0	0	0	2	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0
M. communis	0	0	0	0	0	1	1	1	2	3	1	0	1	1	2	4	4	4	4	4	2	4	0	0	2	2	0	2	0	0	0	0	0
M. pompilioides	7	0	3	2	5	0	1	1	3	8	0	5	3	1	2	0	0	0	15	3	2	1	3	3	2	2	4	1	2	2	0	0	2
N. boueanum	0	0	0	0	0	0	0	0	2	4	3	2	1	0	5	9	0	0	0	21	0	2	6	1	2	4	4	2	2	0	0	0	0
N. depressulum	7	0	14	23	12	11	14	9	5	14	2	14	11	10	6	9	9	9	24	59	21	21	18	11	18	7	10	9	3	2	3	5	5
N. schreibersi	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	2	0	0
Nodosaria sp.	0	2	1	1	1	0	1	0	1	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nonionella sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O. globosa	1	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
O. stellatus	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O. umbonatus	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0
Oxangulara sp.	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
P. acuminata	0	0	2	2	0	0	0	0	2	0	0	0	0	0	3	2	2	5	2	3	2	2	2	2	0	0	0	0	2	0	0	3	0
P. alternans	0	0	2	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	1
P. ariminensis	2	8	3	2	0	0	1	1	2	0	0	0	2	0	0	2	2	2	3	2	0	1	1	2	2	0	0	0	2	0	0	0	0
P. wuellestorfi	0	0	0	2	0	1	3	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Appendix I (cont.)

SAMPLES	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25	A26	A27	A28	A29	A31	A32	A33	A36
P. bulloides	3	3	0	1	2	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P. quinqueloba	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
P. mediterranensis	1	0	0	5	1	0	0	0	1	4	1	1	2	0	1	1	2	2	0	1	1	0	3	0	0	1	2	0	14	4	4	3	2
P. ovata	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P. oblonga	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Quinqueloculina sp.	0	0	0	0	0	0	1	1	1	1	3	4	4	1	1	4	2	0	1	1	0	0	0	0	1	0	2	2	29	3	3	1	5
R. globularis	2	0	2	2	0	2	1	0	3	4	2	7	3	7	1	5	4	6	6	5	5	10	5	6	7	6	15	2	11	3	1	3	5
R. spinulosa	3	4	3	1	3	1	3	3	8	9	6	6	5	7	22	8	6	2	2	9	9	10	4	4	15	8	15	0	4	4	9	3	4
R. siphogeneroides	0	2	0	1	2	1	1	1	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rectobolivina sp.	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rotalia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
S. aspera	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S. monilis	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
S. complanata	1	0	0	0	0	0	0	0	0	1	0	0	0	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
S. bulloides	0	0	1	0	1	0	1	0	0	0	1	0	2	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
S. depressa	1	0	0	0	1	0	0	0	2	0	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S. reticulata	6	1	0	2	0	0	0	0	0	4	1	3	3	0	0	0	0	0	0	0	2	1	0	2	2	0	0	0	1	3	0	0	3
Textularia sp.	2	4	4	4	1	3	9	0	4	2	3	6	6	2	0	2	2	2	3	4	0	0	1	7	7	2	0	0	1	1	3	1	0
T. bradyi	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
T. angulosa	0	1	0	1	2	2	0	3	0	0	2	2	2	2	1	1	0	1	1	0	0	0	1	0	0	0	1	1	0	1	0	1	0
U. bononiensis	0	0	3	1	14	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5	0	1	1	6
U. cyl gaudrynoides	0	0	1	0	0	1	2	0	0	0	1	1	0	2	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
U. mediterranea	0	0	4	6	0	5	0	1	1	2	4	1	1	0	0	0	3	1	0	0	1	0	1	0	1	0	1	1	2	1	0	1	2
U. peregrina	20	23	12	0	13	13	2	6	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0	1	0	1	0	0	1	0	1	0	3
U. proboscidea	0	0	3	1	4	2	0	0	1	0	2	0	4	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	4
V. bradyana	7	6	3	3	4	2	1	8	4	3	4	4	1	4	2	2	1	10	7	4	3	7	6	2	2	6	5	6	2	0	2	2	2
TOTAL	172	169	202	197	192	197	145	187	119	161	129	147	166	158	156	180	175	106	182	184	133	173	168	170	194	177	186	186	172	246	143	141	151