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Foraminiferal stratigraphy and palaeoecological implications in turbidite-like deposits from the Early Tortonian (Late Miocene) of Greece

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ABSTRACT – The Lower Tortonian Ag. Giannis section, in Gavdos Island, Greece, consists of an outer neritic to upper bathyal, marly hemipelagic sequence which is interrupted by thick turbidite-like sandy deposits. During deposition of the marly intervals, reworking was considerably reduced.

This paper contributes to knowledge concerning benthic foraminiferal response to dynamic sedimentary environments. Important palaeoecological information for benthic foraminiferal assemblages was gathered and analyzed in order to create a regionally consistent picture of the palaeoenvironment. Samples were analyzed statistically in order to identify the different palaeoenvironmental settings during turbiditic sedimentation. Undisturbed basal marls of the section are characterized by the predominance of a diversified *Uvigerina striatissima* assemblage typified by a broad variety of morphotypes with different inferred habitat preferences and feeding strategies, indicating rather well-oxygenated bottom waters. This environmental stability was subsequently disrupted by recurrent deposition of turbidite-like sands. A low-diversity *Valvulineria complanata–Globobulimina* sp. assemblage is dominant in this part of the succession, as these specialized endobenthic species could keep pace with high-energy sedimentary settings. Just above the turbidites, a “recolonization” fauna (*Bolivina alata* assemblage), composed entirely of infaunal elements is observed, indicating a nutrient-rich substrate. This oligotypic fauna is later replaced by a more diversified microfauna capable of occupying a wider range of ecological niches. *J. Micropalaeontol*. **26**(2): 145–158, October 2007.

KEYWORDS: *benthic foraminifera, turbidites, recolonization, Early Tortonian, eastern Mediterranean*

INTRODUCTION

Gavdos Island (Fig. 1) forms the southernmost exposed part of the Hellenic Arc. Together with Crete, it is located between a volcanic arc to the north and a northward subduction zone (the Hellenic Trench) to the south. The Hellenic Arc and the Hellenic 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 ongoing.

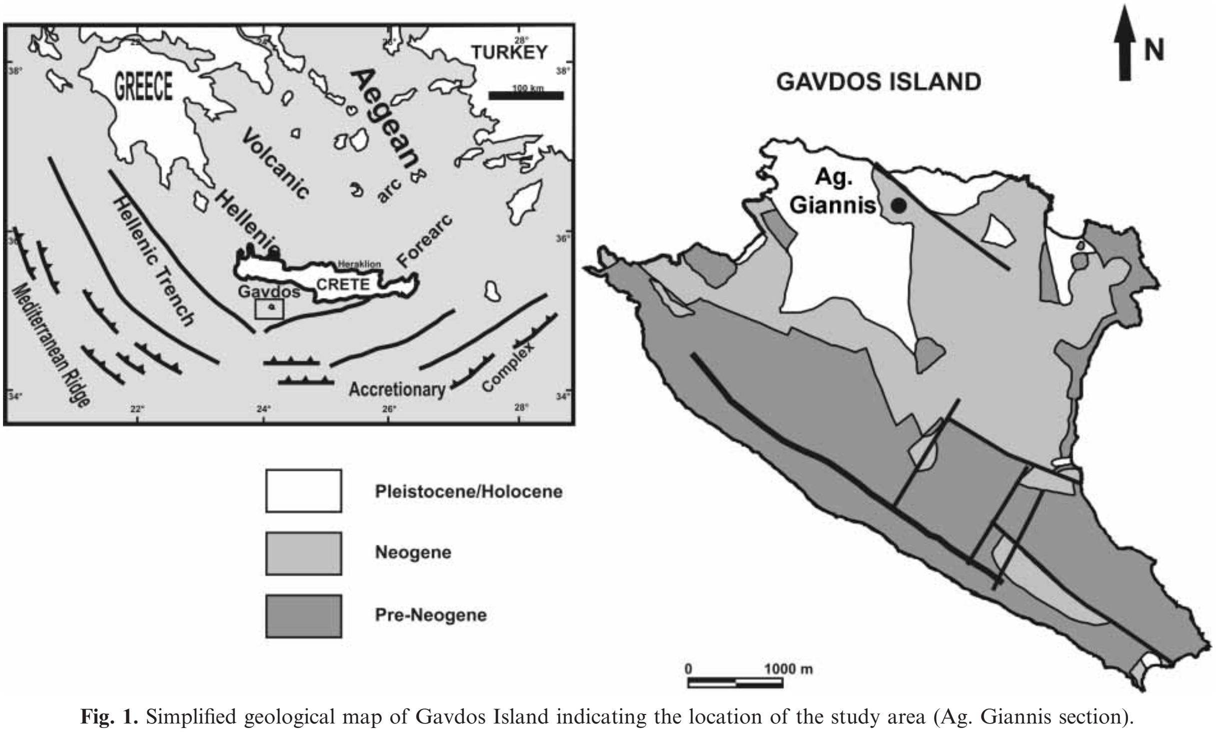

Fig. 1. Simplified geological map of Gavdos Island indicating the location of the study area (Ag. Giannis section).

Therefore, the Neogene basins on Crete and Gavdos are part of an outer-arc setting. During the Tortonian, marked changes along the southern margin caused the Cretan area to be connected for the first time to the open sea (Fortuin, 1977, 1978). At that time, Crete and Gavdos became separated by an extensional basin (Peters & Troelstra, 1984).

The pre-Neogene basement of the island of Gavdos consists of a Maastrichtian–Danian calcareous sequence topped by Eocene flysch (Vicente, 1970) belonging to the Pindos–Ethia geotectonic zone. Towards the northeastern part of the island, a Mesozoic volcano-sedimentary series is exposed and is thrust above the Pindos–Ethia sequence (Vicente, 1970; Seidel & Okrusch, 1978). Neogene sediments have a maximum thickness of 150 m and cover about one half of the surface area of the island, unconformably overlying the Mesozoic substrate basement.

The island was probably affected by drastic subsidence during the Serravallian as documented by the changes in planktonic foraminifera, calcareous nannoplankton and molluscs (Anastasakis *et al.*, 1995). According to these authors, the Neogene sediments of Gavdos Island can be subdivided into two lithostratigraphical formations: the Potamos and the Metochia formations.

The Potamos Formation (Late Serravallian–earliest Tortonian) is encountered along an elongate northwest–southeast-trending trough occupying the middle part of the island. An angular unconformity, marked by a pronounced erosional surface, denotes the initiation of deposition of the Neogene sediments. At the base of the unconformity, a basal conglomerate is developed with pebbles derived from the Alpine units exposed on the island. Above this conglomerate, a coral limestone is usually present, overlain by a fossiliferous sandstone displaying alternations of grey-whitish bluish beds rich in shallow-marine molluscs, corals and *Heterostegina* larger foraminifera, as well as pebbles derived from the Alpine units.

The Metochia Formation occupies most of the northeast quarter of Gavdos Island. These sediments are found to overlay either the Alpine basement rocks or the Potamos Formation. They mostly comprise rhythmic alternations of poorly to non-bioturbated brown-grey sapropelic and bioturbated white-grey marly beds which show conspicuous clustering. The origin of this rhythmic layering has been related to orbital-forced variations in climate (Hilgen, 1991; Hilgen *et al.*, 1995; Krijgsman *et al.*, 1995). Its type-section spans the interval from 9.7 Ma to 6.6 Ma (Hilgen *et al.*, 1995; Krijgsman *et al.*, 1995). The sapropel-bearing succession is overlain conformably by cyclically bedded diatomites of Messinian age (Krijgsman *et al.*, 1998; Triantaphyllou *et al.*, 1999; Kouwenhoven *et al.*, 2003; Drinia *et al.*, 2004a).

Despite the extensive high resolution biostratigraphic studies and palaeoenvironmental reconstructions carried out in the Metochia Section, the older Potamos Formation of the island remains comparatively unexplored (e.g. Anastasakis *et al.*, 1995; Drinia *et al.*, 2004b).

The Ag. Giannis section is located in the northwestern part of Gavdos Island and is comprised of the Potamos Formation. The 77 m thick section consists of monotonous white to grey-blue marls, with abundant and generally well-preserved microfossils, and thick, turbidite-like sands.

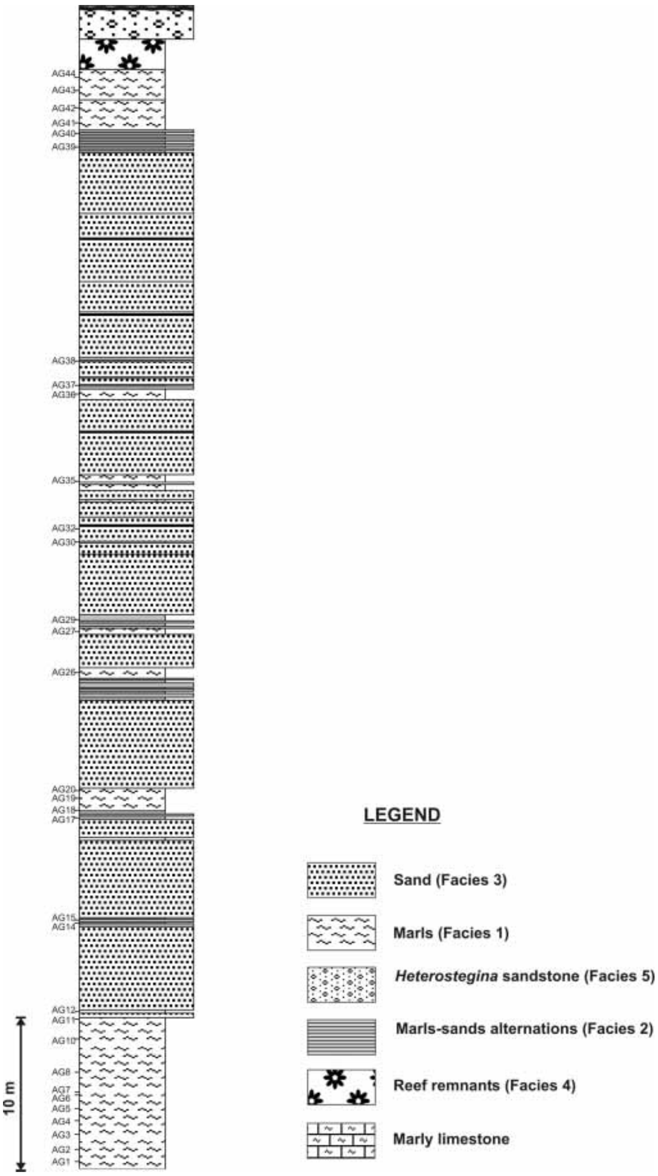

Fig. 2. Stratigraphical column of the Ag. Giannis section indicating sampling and Facies 1–5.

The purpose of the present research is threefold: (1) to trace the distribution of benthic foraminiferal assemblages in the turbiditic succession of the Ag. Giannis section; (2) to relate the faunal assemblages to environmental factors and to lithology; and (3) to reconstruct the palaeoenvironmental setting.

Important palaeoenvironmental information can be obtained through analyses of the fossil assemblages just before, during and after the turbiditic deposition.

MATERIAL AND METHODS

Description of the studied section

The Ag. Giannis section (77 m thick) has been divided into five sedimentary facies (Fig. 2), each one identified by lithology, physical and biological sedimentary structures and grain size.

Facies 1. Dominates the basal part of the studied section and comprises bluish, fossiliferous marls with occasional lenses or layers of fine- to very fine-grained sands. The marls are generally massive but, in places, thin laminations are visible.

Facies 2. Consists of thin-bedded and very fine- to fine-grained sands embedded in marls. All these sandy beds show a sharp base and fine upwards into marly layers. The thinly interbedded sands–marls facies resemble distal storm sands deposited below storm wave base (Rosenthal & Walker, 1987; Pirrie, 1989) or, alternatively, fine-grained turbidites (Stow & Piper, 1984) interbedded with marls deposited under lower-energy conditions.

Facies 3. Characterized by fine- to medium-grained, poorly sorted sands, which are laterally persistent. Generally, the base and the top of each sandstone bed are sharp and smooth surfaces. These beds are intercalated with thin marly horizons or very thin alternations of mudstone and very fine-grained sandstones. The rarity of sedimentary structures probably reflects the high rate of deposition.

Facies 4. In the upper part of the succession, there are relicts of a fractured reef with abundant corals, *Chlamys latissima*, *Ostrea lamellosa*, *O. plicatula* and gastropods. The presence of *Porites*, which is the main reef-builder in this part of the Ag. Giannis basin, indicates tolerance to salinity changes (Esteban, 1979). The presence of oysters indicates a nearshore shallow-water, reef environment with clear water and low turbidity (Korringa, 1952; Wells, 1961).

Facies 5. The uppermost levels consist of medium-sized partially cemented sandstone with no visible stratification. Bivalves, bryozoans, echinoids (*Clypeaster*) and larger foraminifera (*Heterostegina*) dominate, with minor proportions of gastropods. The biogenic content of this facies implies a fully marine shelf setting. The biota is well preserved, indicating a rather calm depositional setting below wave abrasion depth (WAD), (Brachert *et al*., 2003). The presence of *Heterostegina* indicates a depositional environment in the lower part of the photic zone (e.g. James *et al*., 2001), characterized by warm-temperate surface temperatures (Betzler *et al*., 1997).

Based on the facies description above, the sediments of the Ag. Giannis section are characterized by the presence of turbidite-like sediments interbedded into hemipelagic marls. However, they differ from typical turbidites by the absence of graded bedding, moderate sorting and well-developed primary sedimentary structures, as described by Bouma *et al.* (1985).

Moreover, the lack of evidence for significant slumped beds indicates the presence of a very low palaeo-gradient. This gentle gradient immediately excludes slope- and base-of-slope fans, which have gradients of 1–10° (Stow, 1986), whereas the average gradient of modern shelves is only 0.1° (Shepard, 1963). Hence, facies associations are consistent with a shelf environment. The turbidite-like deposits in this shallow-water setting are likely to have been triggered by stream floods during periods of extreme discharges rather than by slope instability (cf. Balance, 1988; Colmenero *et al*., 1988; Dabrio & Polo, 1988; Marzo & Anadon, 1988).

Micropalaeontological analyses

Quantitative analysis of benthic foraminifera has been carried out in order to document changes in assemblages throughout the Ag. Giannis section.

Samples analysed were collected from Facies 1 and from the marly intervals of Facies 2. Sands (Facies 3) above and below the marly intervals were generally not sampled but, when studied, yielded poorly preserved microfossils.

Forty-four samples were washed and dried (Fig. 2). After drying, they were wet-sieved through a 125 μm mesh sieve. Of the 44 samples analysed, only 32 proved to be suitable for quantitative analysis. In the remaining samples, foraminifera are present but in very low, insignificant numbers. Two fractions from each sample were taken to carry out an analysis of benthic and planktonic foraminifera.

Planktonic foraminifera were studied for age determination, using a quantitative approach; all representative specimens were picked from the split, 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 (Fig. 3). Finally, the remaining sample was scanned for rare species.

All benthic foraminifera were picked from the split, identified and counted. Planktonic forms were also counted and the percentage of planktonics (%P) was computed.

Raw data of benthic foraminifera were then transformed into percentages over the total abundance, and percentage abundance curves were plotted (Fig. 5). Taxonomic concepts were based on Wright (1978), Blanc-Vernet *et al*. (1979), AGIP (1982), Bizon & Bizon (1984), Venec-Peyre (1984), Jorissen (1988), Cimerman & Langer (1991) and Van de Poel (1992). The generic attribution follows Loeblich & Tappan (1988).

For each sample, the Fisher-α index, the dominance and the percentages of epifaunal–shallow infaunal and deep infaunal forms were calculated (Fig. 6). The identification of epifaunal vs. infaunal groups (Fig. 9) was carried out using the morphogroup classification of Murray (1991), Barmawidjaja *et al*. (1992), Jorissen *et al*. (1992), Jorissen (1999) and Jorissen & Wittling (1999). The inferred mode of life for each taxon is reported in Appendix A.

In order to estimate the changes in palaeobathymetry during the deposition of the Ag. Giannis section, the percentage of planktonic foraminifera [$\%P/(P+B)$] was calculated, where P is the number of specimens of planktonic foraminifera and B is the number of specimens of benthic foraminifera (Fig. 11), and each assemblage was compared with other Late Miocene and Recent assemblages from the available literature.

Dysoxic, oxic and suboxic environments were identified (Fig. 10) using the Benthic Foraminifera Oxygen index (BFOI) of Kaiho (1991, 1994), following the limitations expressed in Baas *et al*. (1998) and Stefanelli (2004); this index appears to be designed more for modern open-oceanic faunas than for shallow Mediterranean faunas.

Multivariate analyses were performed on benthic foraminiferal species relative abundance data for palaeoenvironmental reconstructions. For this purpose, some species, represented by small numbers in the fauna, were lumped together (e.g. *Lenticulina* spp., *Lagena* spp., *Nodosaria* spp., Miliolidae, Agglutinants).

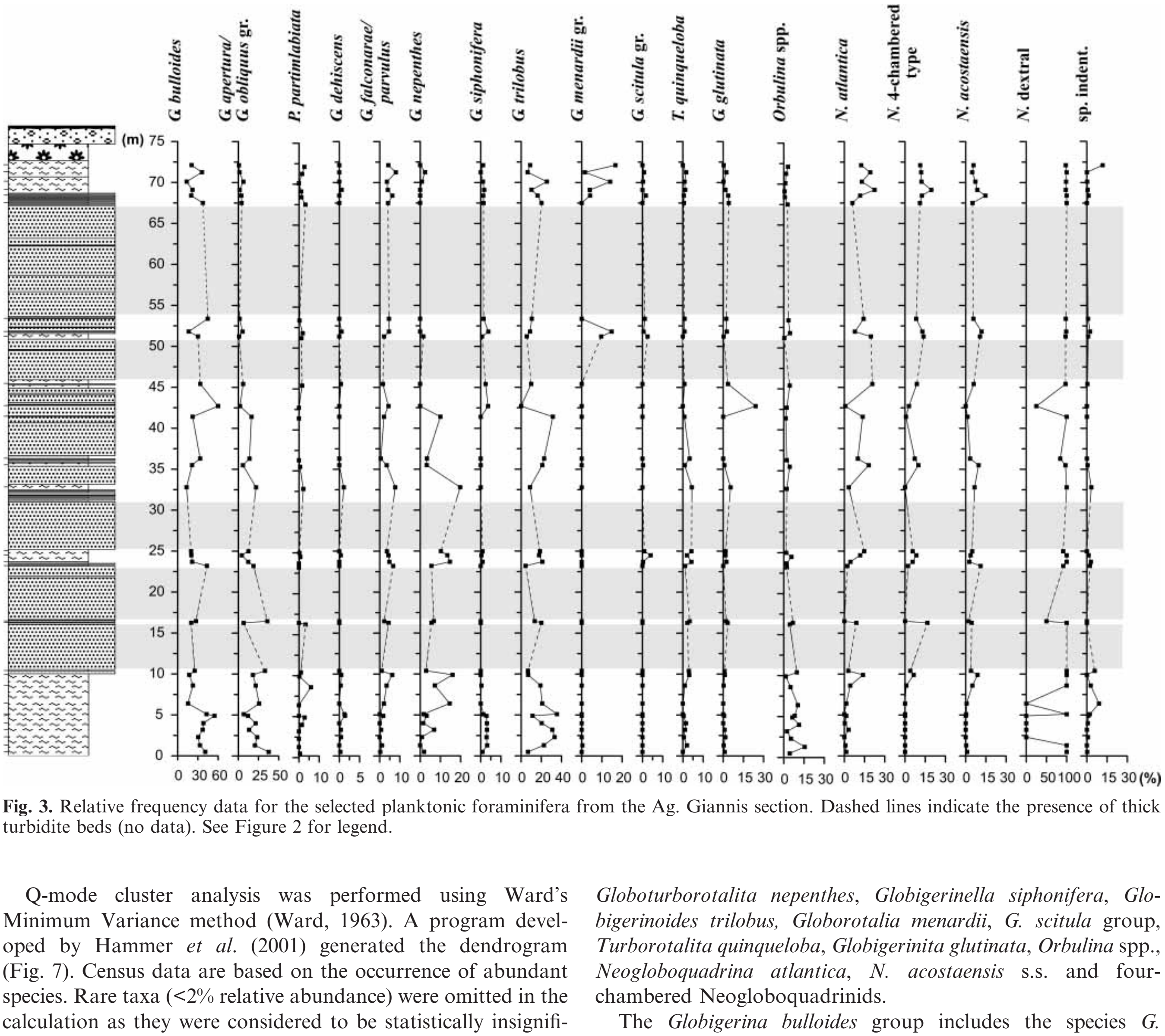

Fig. 3. Relative frequency data for the selected planktonic foraminifera from the Ag. Giannis section. Dashed lines indicate the presence of thick turbidite beds (no data). See Figure 2 for legend.

Q-mode cluster analysis was performed using Ward's Minimum Variance method (Ward, 1963). A program developed by Hammer *et al.* (2001) generated the dendrogram (Fig. 7). Census data are based on the occurrence of abundant species. Rare taxa (<2% relative abundance) were omitted in the calculation as they were considered to be statistically insignificant (Kovach, 1987, 1989). Consequently, the 174 benthic foraminiferal species identified were reduced to the 37 species and groups of species considered to be the most significant.

Finally, a standardized principal component analysis (PCA; R-mode) was also performed in order to trace the palaeoecological significance of each assemblage (Fig. 8).

RESULTS

Biostratigraphy

Distribution patterns of the most representative planktonic foraminiferal taxa are summarized in Figure 3. Preservation is generally good in the bluish marls and fairly poorer in the thin marly layers that are intercalated in the sands. The 22 identified planktonic foraminiferal species were lumped into 16 categories: *Globigerina bulloides* group, *Globigerinoides obliquus*/*Globoturborotalita apertura*, *Paragloborotalia partimlabiata*, *Globoquadrina dehiscens*, *Globorotaloides falconarae*, *Globoturborotalita nepenthes*, *Globigerinella siphonifera*, *Globigerinoides trilobus, Globorotalia menardii*, *G. scitula* group, *Turborotalita quinqueloba*, *Globigerinita glutinata*, *Orbulina* spp., *Neogloboquadrina atlantica*, *N. acostaensis* s.s. and four-chambered Neogloboquadrinids.

The *Globigerina bulloides* group includes the species *G. bulloides* and *G. falconensis*. The species *Globoturborotalita apertura* and *Globigerinoides obliquus* were counted together because the poor preservation often obscured the supplementary opening. This group also includes the species *Globoturborotalita decoraperta* which was identified in some samples. The *Globorotalia scitula* group comprises all the unkeeled globorotaliids. *Paragloborotalia partimlabiata* was counted and plotted separately for biostratigraphy.

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

Specimens identified as *Globorotaloides falconarae* include the types described previously as *Catapsydrax parvulus* (Zachariasse, 1992; Krijgsman *et al.*, 1995, 1999). In the Mediterranean, the small-size type of *G. falconarae* cannot be distinguished from *C. parvulus* (Foresi *et al.*, 2002a).

Species having biostratigraphical significance in our record are the neogloboquadrinids and the occurrence of

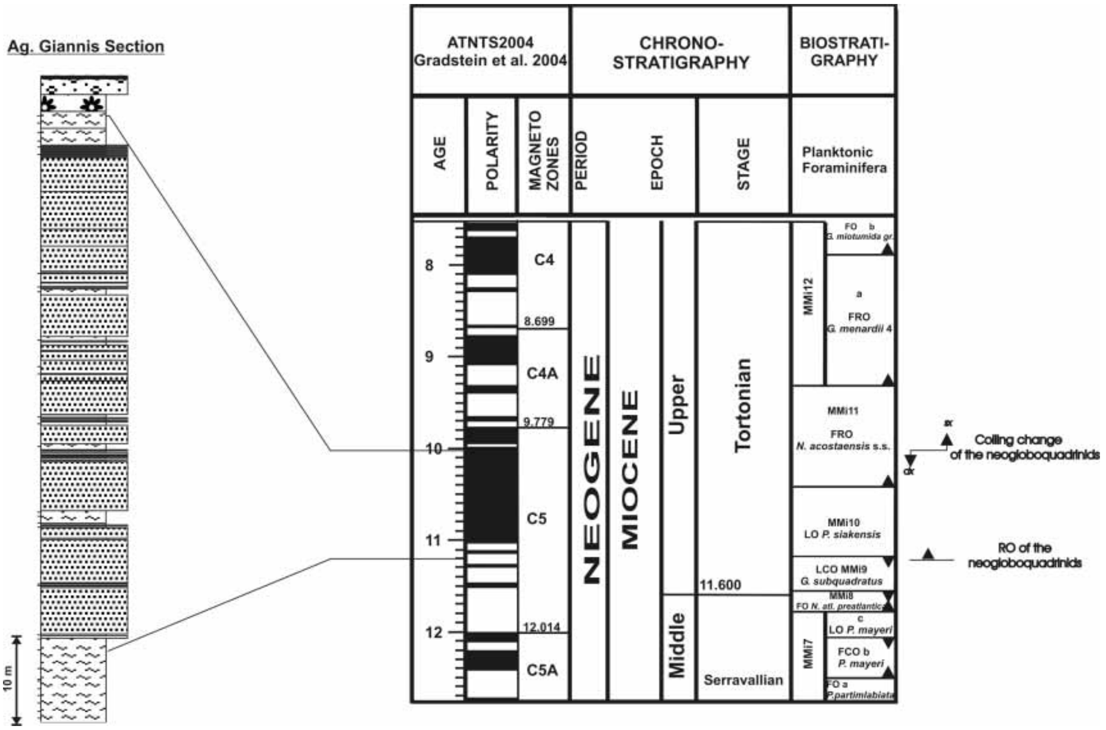

Fig. 4. Chronostratigraphic framework of the studied section (ages based on Gradstein *et al.*, 2004). See Figure 2 for legend.

Paragloborotalia partimlabiata (Fig. 4). The last species, although present, is rare throughout. According to Hilgen *et al.* (2000), *P. partimlabiata* occurs up to 9.91 Ma (absolute ages derived from Gradstein *et al.*, 2004).

Specimens identified as *Globigerinoides subquadratus* occur very rarely (<2%), in particular in the basal 3 m of the section and for that reason it was not plotted. The last common occurrence (LCO) of *G. subquadratus* has been dated in the Mediterranean at 11.54 Ma. This event slightly postdates the first regular occurrence (FRO) of *Globigerinoides obliquus* (11.478 Ma) and is close to the end of the first influx of the neogloboquadrinids (Hilgen *et al.*, 2000, 2003; Foresi *et al.*, 2002a). *Globigerinoides obliquus* is present in all the samples, from the base of the studied section.

Neogloboquadrinids are the main constituents in the record. Within this group three types are distinguished: *N. atlantica*, *N. acostaensis* s.s. and the so-called *Neogloboquadrina* four-chambered type of Hilgen *et al.* (2000), as it was observed in the Monte Gibliscemi section (Hilgen *et al.*, 2000) and in Monte dei Corvi (Hilgen *et al.*, 2003). Specimens of *N. acostaensis* are typical, as described by Blow (1969). The *N.* four-chambered types follow the taxonomic concept of Hilgen *et al.* (2000). Such specimens have a medium to low-arched extra-umbilical aperture with or without lip and four chambers in the final whorl.

Specimens identified as *N. atlantica* are characterized by their generally small-sized tests, four chambers in the final whorl, with the last chamber slightly depressed. They have an arched umbilical–extraumbilical aperture bordered by a thick lip. This definition follows that of Foresi *et al.* (2002b) for *N. atlantica praeantlantica*, whereas Hilgen *et al.* (2000) described these forms as *N. atlantica* small-size. In the current record, *N. atlantica atlantica* (Foresi et *al.*, 2002b) was not identified, as the wall structure was not recognized easily and bigger sized tests were not present.

Neogloboquadrina atlantica praeatlantica first occurs at 11.78 Ma astronomical age of Hilgen *et al.* (2000) and Foresi *et al.* (2002a) and vanishes within the *Globigerinoides extremus* Zone of Foresi *et al.* (1998). According to Hilgen *et al.* (2000), its LRO is recorded around 10.48 Ma. In the Mediterranean, the first occurrence of the neogloboquadrinids is also recorded at 11.78 Ma. Within the distribution pattern of the neogloboquadrinids, Foresi *et al.* (2002a) and Hilgen *et al.* (2000) recognized a paracme interval which includes only rare and scattered occurrences of the *Neogloboquadrina* types. This interval is recorded from 11.54 Ma to 11.21 Ma, and ends just after the last occurrence of *Paragloborotalia siakensis*. Above this level, *Neogloboquadrina* species have a continuous distribution.

In the Ag. Giannis section, the neogloboquadrinids are continuously present from 10 m of the section upward. According to Foresi *et al.* (2002a), it was assumed that this level corresponds to the second influx of neogloboquadrinids with an astronomical age of 11.21 Ma. The absence of *P. siakensis* supports this interpretation.

Coiling changes in this species have been proven to have potential biostratigraphical significance, being random between 11.781 Ma and 11.546 Ma and persistently right (>80%) between 11.178 Ma and 10.011 Ma. According to the percentage curve, dextral neogloboquadrinids seem to prevail in all the samples.

Within the studied time span, the regular occurrence of *G. obliquus*, the absence of *G. subquadratus*, the absence of *P. siakensis* (LO 11.205 Ma, Hilgen *et al.*, 2000; 11.21 Ma, Foresi *et al.*, 2002a) and the regular distribution of *Neogloboquadrina* group, dextral coiling were observed.

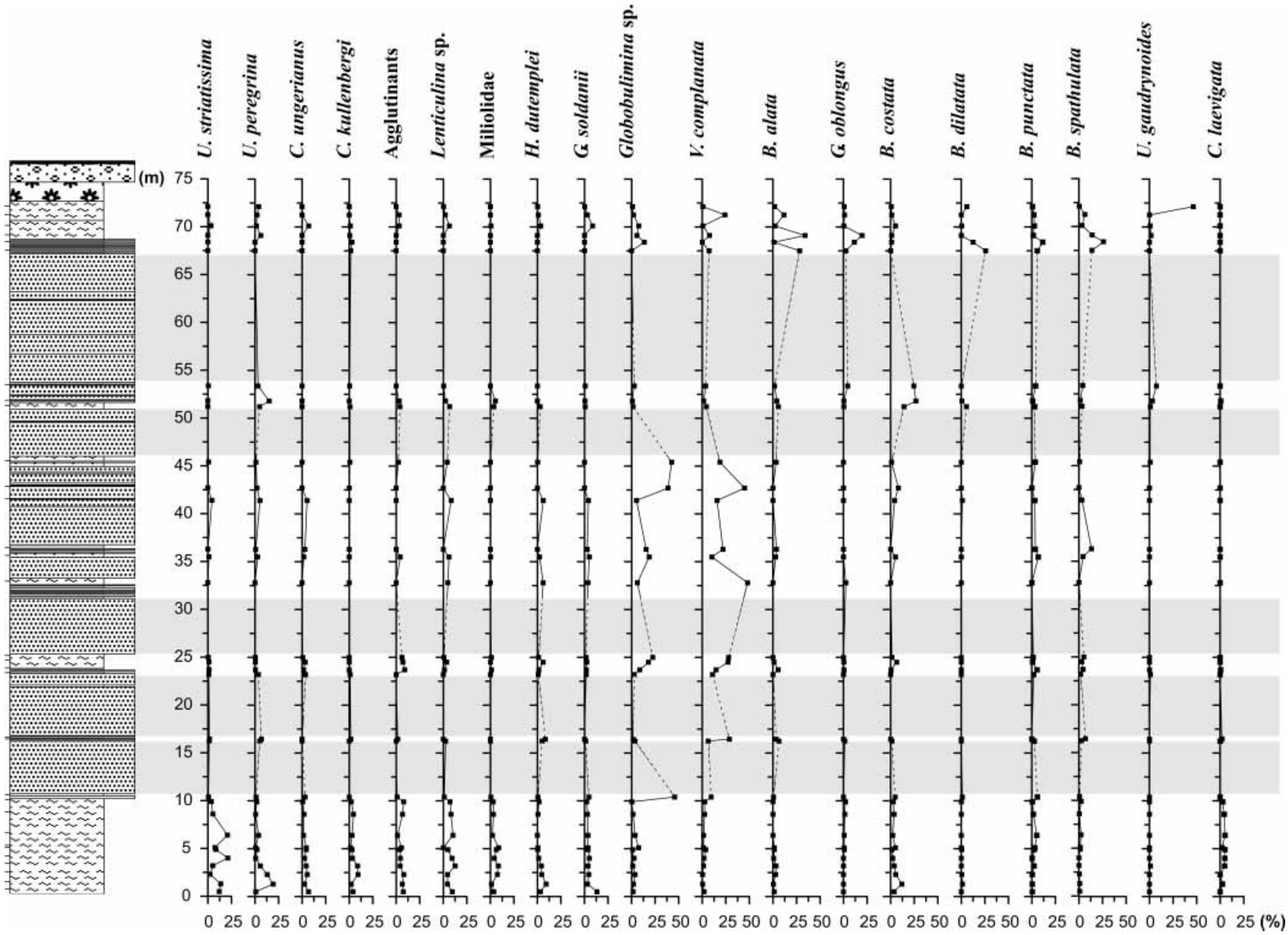

Fig. 5. Relative frequency data for the selected benthic foraminifera from the Ag. Giannis section. Dashed lines indicate the presence of thick turbidite beds (no data). See Figure 2 for legend.

Consequently, the sediments of the Ag. Giannis section were deposited between the age of the second influx of *Neogloboquadrina* species (11.21 Ma), as defined in the astronomical tuned sections of Tremiti Island and Monte Gibliscemi, and the shift in coiling direction of *N. acostaensis* at 10.011 Ma (Fig. 4).

Benthic foraminiferal trends

Figure 5 displays the stratigraphic distributional pattern of the most common and ecologically significant species and groups of species.

Among the uvigerinids, *Uvigerina peregrina* is common throughout the succession, with average percentage values fluctuating in the range of 1–20% and an abundance peak at 1.3 m. *U. striatissima* shows two maxima, at 4 m and 5.1 m, but it is rare in the rest of the succession. *U. gaudrynoides*, which is absent in the basal part of the section, first appears at 45.4 m, reaching an abundance peak of 46.34% in the uppermost part of the record, at 72.12 m.

Bolivina punctata and *B. spathulata* are common from the base up to the top of the succession, with a peak at 68.4 m (12% and 26%, respectively). *B. alata* is generally rare and increases in abundance from 67.5 m up to the top of the section, showing its highest occurrence at 69.1 m (34.02%). A similar trend in abundance has been observed for *B. dilatata*, which appears at 51.2 m and shows its highest percentage value at 67.5 m (25.81%). *Bulimina costata* is abundant in the 42–53.37 m interval, but is rare in the other intervals.

Among the epifaunal taxa, *Cibicidoides kullenbergi* and *C. ungerianus* are rare throughout the section. Their highest abundance values are in the lower 10 m of the record (16.7%).

Finally, *Globobulimina* sp. and *Valvulineria complanata*, although well presented throughout the section, display highest occurrence in the middle part of the record, in the marly intervals of the turbidite-like deposits of Facies 2, from 25 m to 51.2 m, with peak percentage values at 45.4 m (42.57%) and 32.8 m (48.15%), respectively.

At 16.25 m and 23.2 m, above thick sandy levels, specimens of *Ammonia beccarii* and *Elphidium* spp. have been also recorded in significant abundance. These species are commonly found displaced to greater depths in Mediterranean sediments (e.g. Van der Zwaan, 1983; Jorissen, 1987). Consequently, they are considered to be allochthonous species.

Concerning the diversity indices of the studied record (Fig. 6), dominance ranges from 5% to about 50%, with highest values at

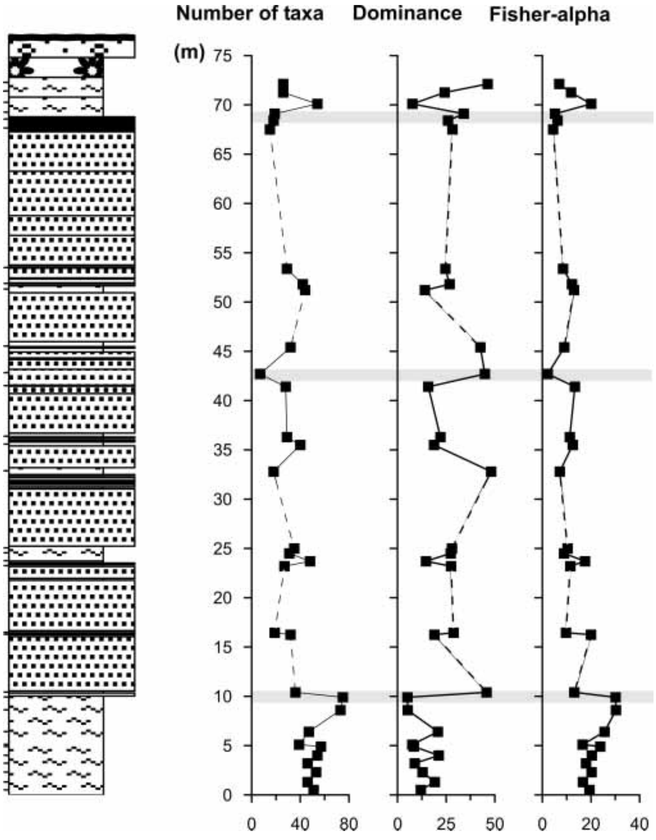

Fig. 6. Distribution patterns of the calculated diversity indices (number of taxa, dominance and Fisher-alpha). Note the considerable differences in diversity below, across and above the turbitic episodes. Dashed lines indicate the abrupt changes in diversity indices. See Figure 2 for legend.

32.8 m (Facies 2), where *V. complanata* predominates. Intervals with high benthic diversity contain about 50–70 different taxa, with dominance ranging from 8% to 30%. In low-diversity intervals, the number of taxa decreases to fewer than 20. The least number of species (7) was found at 42.7 m (Facies 2) and the maximum number (75) at 9.9 m (Facies 1) of the studied succession. The Fisher-α index shows its highest values at 9.9 m (30.13), suggesting a well-diversified fauna, and its lowest values (2.23) at 42.7 m, indicating some deviation from the norm of the palaeoenvironmental parameters (Jorissen, 1987; Van der Zwaan & Jorissen, 1991).

Q-mode clustering of the percentage contribution of 37 species to each of 32 samples clearly separates two major groups, each one corresponding to groups of samples containing similar benthic foraminiferal assemblages. The first group consists mainly of twelve samples, representing samples in between the turbiditic sands (Facies 2), whereas the second group includes all the remaining samples. A further subdivision of the second cluster enables one to distinguish seven samples, representing the stratigraphic interval above the turbiditic sands. The dendrogram (Fig. 7) groups the samples into clusters characterized by the dominance of certain species.

Cluster I (*V. complanata–Globobulimina* spp. assemblage) covers the middle part of the succession and includes the samples recovered from the marly beds of Facies 2 (samples AG12–AG35 and AG43). According to Van der Zwaan (1982), these species are particularly frequent during periods of increased productivity. Moreover, they are not tolerant of increased salinities. In fact, Jorissen (1987, 1988) found benthic foraminiferal communities very similar to the assemblage of Cluster I in the pelitic belt created in the Adriatic Sea by the sediment supply of the Po River. In addition, Van der Zwaan & Jorissen (1991) stressed the high impact of increased terrestrially

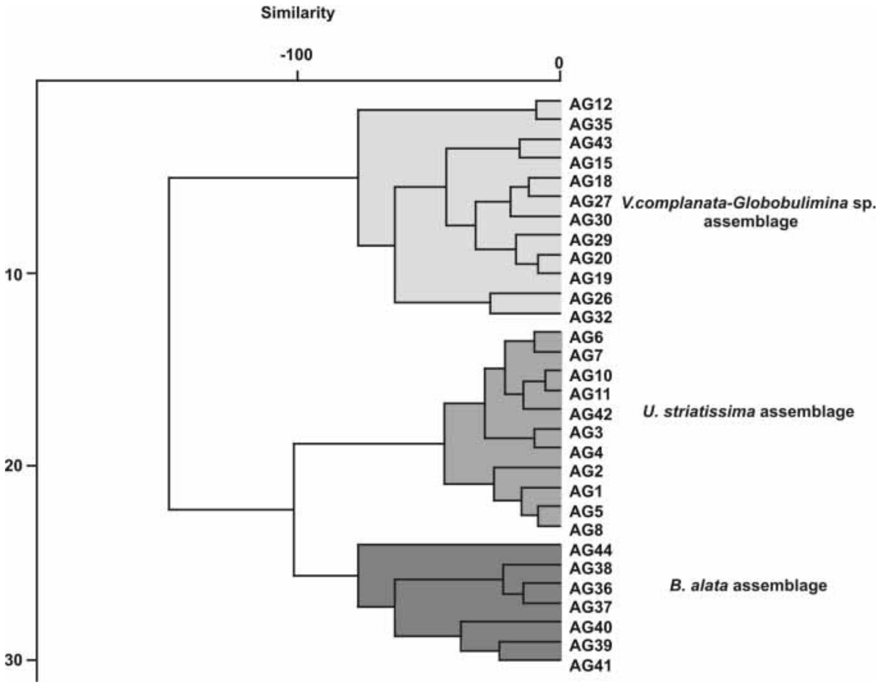

Fig. 7. Dendrogram classifications of the benthic foraminfera samples produced by Q-mode cluster analysis, indicating the three assemblages defined.

derived nutrient, organic matter and sediment input on this kind of assemblage. A comparable association was found in Upper Miocene sediments of Potamidha on Crete (Wonders & van der Zwaan, 1979), in the northern Italian Sant'Agata section and in the Scardilli section (Van der Zwaan & den Hartog Jager, 1983). Therefore, the *V. complanata–Globobulimina* assemblage is interpreted to indicate an increased amount of C_{org} in the bottom sediments due to increased input of nutrients from the continent.

Cluster IIa (*U. striatissima* assemblage) is recorded in the basal part of the section (Facies 1). It includes samples AG1–AG11 and AG42, and is dominated by *Uvigerina striatissima* with rarer *Cibicidoides* spp. *U. striatissima* is reported as a species tolerant of only moderate oxygen deficiency (Borsetti *et al.*, 1986; Bellanca *et al.*, 2002). The contemporaneous presence of *Cibicidoides* spp., epifaunal taxa with planoconvex or biconvex trochospiral tests, is considered indicative of oxic environments (e.g. Corliss, 1991; Kaiho, 1994). Moreover, the joint percentages of *Lenticulina* species (Fig. 5) are highest in this part of the section and support the hypothesis of a higher oxygen content (e.g. Van Leewen, 1986; Corliss & Emerson, 1990; Sjoerdsma & van der Zwaan, 1992; Kaiho, 1994). Some elements of this assemblage are present in the Scardilli (Van der Zwaan & den Hartog Jager, 1983) and Falconara sections (Van der Zwaan, 1982). They were regarded by Van der Zwaan (1982) as characteristic of stable, deep-marine conditions, not affected greatly by changes in salinity, oxygen content or nutrient amount.

Cluster IIb (*B. alata* assemblage) is recorded in the upper part of the section (Facies 1) and includes samples AG36–AG41 and AG44. This assemblage is characterized by a great number of individuals, belonging to the infaunal species *B. alata*, *B. dilatata* and *B. spathulata*, with *Bulimina costata* also present in significant abundances. In sample AG44 (uppermost part of the section) *Uvigerina gaudrynoides* – a species that displays high relative abundances in oxygen-deficient and presumably nutrient-rich environments (Van der Zwaan, 1982) – replaces *B. alata* and *B. dilatata/spathulata*, suggesting that the depositional environment became shallower. All these species are tolerant of low-oxygen conditions (Van der Zwaan, 1982; Jonkers, 1984; Katz & Thunell, 1984; van der Zwaan & Gudjonsson, 1986). A comparable association has also been observed in the Skardilli section in Sicily (Van der Zwaan & den Hartog Jager, 1983), as well as in other Cretan sections.

The aforementioned qualitative interpretations of the assemblages are confirmed by the R-mode factor analysis, resulting in two principal axes accounting for 35.35% and 30.99% respectively. Loading scores for the first two axes are reported in Table 1. Based on PCA scores, three assemblages dominated by particular taxa were identified (*Bolivina alata* assemblage, *V. complanata–Globobulimina* spp. assemblage and *Uvigerina striatissima* assemblage). These display a distinctive distribution across the Ag. Giannis section (Fig. 8).

Figure 9 displays the distributional pattern of epifauna–shallow infauna and deep infauna throughout the Ag. Giannis section. Below the turbiditic sands, the assemblages (*Uvigerina striatissima* assemblage) are characterized by a rather stable epifaunal/infaunal ratio, with an average relative abundance of infaunal forms around 35%. The 'bloom' in the elongate morphotypes that dominate the *Bolivina alata* assemblage is reflected in a peak of infaunal forms, occurring just above the turbiditic sands, with a maximum value of 90%.

Species	Factor 1	Factor 2
Bolivina alata	**0.94**	−0.11
Bulimina spp.	−0.10	−0.11
Cancris auriculus	−0.01	−0.02
Cibicidoides kullenbergi	−0.01	−0.05
Cassidulina laevigata	−0.03	−0.04
Cibicides lobatulus	−0.01	0.01
C. pseudoungerianus	−0.01	0.01
C. ungerianus	−0.04	−0.02
Gyroidina altiformis	−0.01	−0.01
Gavelinopsis lobatulus	0.00	−0.02
Gyroidinoides neosoldanii	−0.02	−0.02
Gyroidina soldanii	−0.03	0.00
Globocassidulina oblonga	0.13	−0.03
Globobulimina spp.	−0.02	**0.53**
Hoeglundina elegans	−0.01	−0.02
Heterolepa sp.	−0.04	0.01
Lagena sp.	−0.01	0.03
Lenticulina spp.	−0.07	−0.04
Miliolidae	−0.04	−0.06
Nodosaria sp.	−0.02	0.01
Oridorsalis umbonatus	−0.02	0.00
Pullenia bulloides	−0.01	0.00
Plectofrondicularia sp.	−0.01	−0.02
Siphonina reticulata	−0.02	−0.02
Stilostomella sp.	−0.01	0.02
Uvigerina striatissima	−0.25	**−0.53**
Valvulineria complanata	−0.05	**0.63**

Table 1. Factor loadings for the benthic foraminiferal species from the Ag. Giannis section, imported into statistical analysis.

Although based on few samples, a gradual recovery to average values comparable to that of the pre-turbiditic interval can be observed upsection.

Oxygen content

The benthic foraminiferal assemblages recovered from the Ag. Giannis section reveal Benthic Foraminifera Oxygen Index (BFOI) values ranging from −6 to 80. Index values between −6 and 39 correspond to oxygen concentrations between 1.5 $\mathrm{ml\,l^{-1}}$ and 3 $\mathrm{ml\,l^{-1}}$, values >39 correspond to >3 $\mathrm{ml\,l^{-1}}$ oxygen content (Kaiho, 1994).

Figure 10 shows that the entire section is characterized by high abundance of the dysoxic and suboxic taxa while the oxic indicators are of minor importance. The abundances of oxic indicators decline slightly, while suboxic and dysoxic increase upsection. On the basis of this pattern, three intervals are distinguished:

Interval I (from 0 to 9.9 m) is characterized by higher oxic conditions. The assemblage of this interval records BFOI values between 33 to 80 indicating a high/medium oxic regime.

Interval II (9.9–53.37 m) is characterized by a decline in abundance of the oxic indicators and an increase in the suboxic–dysoxic morphogroups. BFOI values range from 12.5 to 36, suggesting a low oxic regime.

Interval III (53.37–72.12 m) is characterized by the presence of potentially infaunal taxa, suggesting that a suboxic period occurs. The BFOI values range from −6 to 4 due to the high ratios of suboxic indicators, while the oxic indicators are

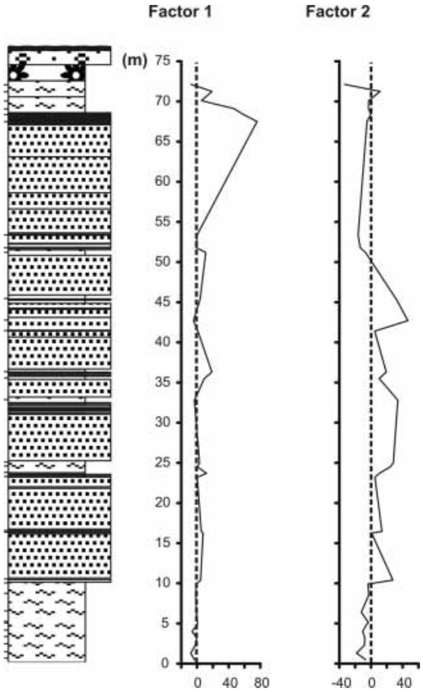

Fig. 8. Vertical distribution of the benthic foraminifera factor scores extracted by R-mode factor analysis which allowed the 27 species and species groups to be classified into three assemblages. Factor 1 shows positive factor loadings for the *B. alata* assemblage. In factor 2, positive loadings are for the *V. complanata–Globobulimina* spp. assemblage, whereas negative loadings are for the *U. striatissima* assemblage. See Figure 2 for legend.

practically absent. In a short interval, at 70.1 m, the small peak in abundance of the oxic indicators, suggests a more oxygenated environment.

Palaeobathymetry

As is documented by recent studies, the high occurrence of planktonic foraminifera suggests at least an outer neritic environment, with water depths exceeding 150 m (Hemleben *et al.*, 1989). In modern seas, the percentage of planktonic specimens tends to increase from <10% in sheltered coastal water to >95% in the open ocean at depths greater than 1000 m (Gibson, 1989).

Planktonic foraminiferal percentages in the Ag. Giannis section are mostly between 40% and 70%, commonly 60%, which is consistent with an outer neritic to upper bathyal environment (Murray, 1976).

The overall nature of the benthic assemblages was examined to check the reliability of the aforementioned interpretation. The comparison of the microfossil fauna with habitats of their modern counterparts can be used to estimate the palaeobathymetry.

The *U. striatissima* assemblage, present in the basal part of the section, can be compared with upper bathyal habitats where *U. peregrina* occurred with fewer *Cibicidoides* spp. and *Lenticulina* spp. Indeed, in many regions, *U. peregrina* is presently the dominant taxon in the upper bathyal zone (Pflum & Frerichs, 1976; Schnitker, 1979, 1980; Streeter & Shackleton, 1979; Qvale & van Weering, 1985; Gupta & Srinivasan, 1990), although this

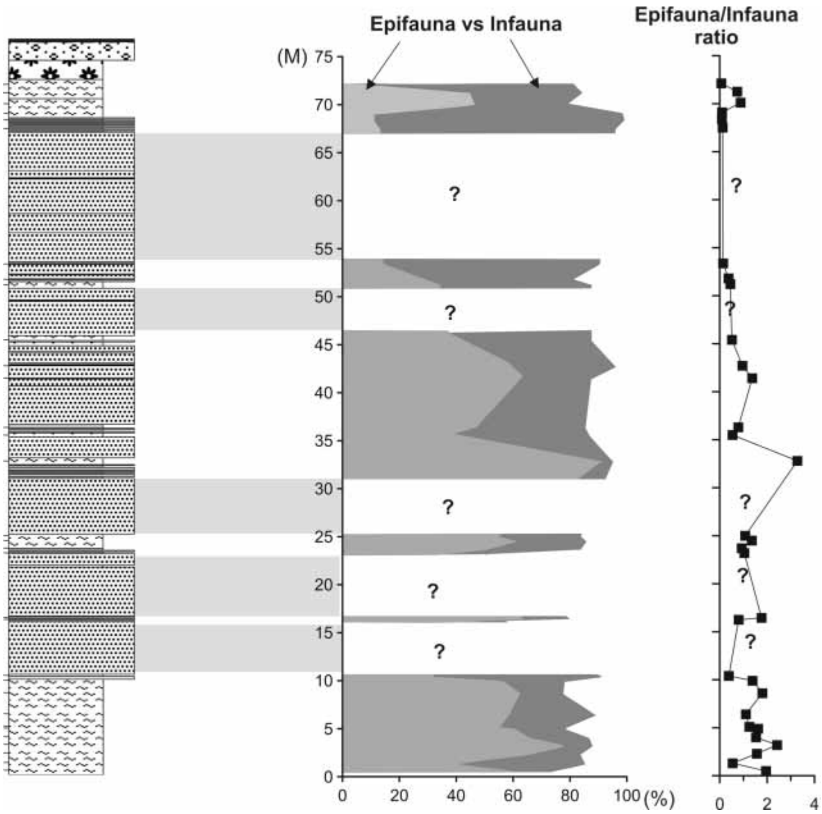

Fig. 9. Distribution patterns of the microhabitat preferences in the succession and distribution of epifauna/infauna ratio. (?) indicates inadequate data due to the existence of thick turbidite beds of Facies 3 (no sampling). See Figure 2 for legend.

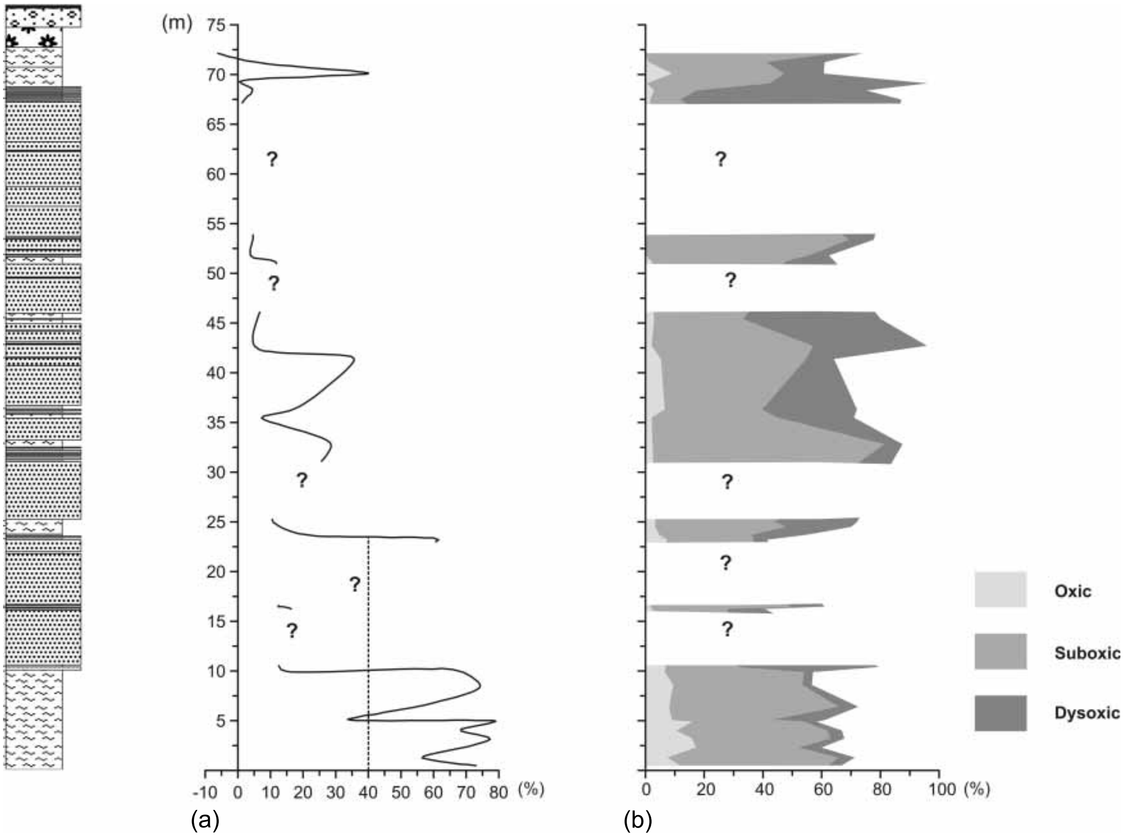

Fig. 10. (**a**) Bottom water oxygenation and (**b**) benthic foraminiferal morphogroups from the Ag. Giannis section. Benthic Foraminifera Oxygen Index (BFOI) values between 39 and 100 correspond to oxygen concentrations >3 ml l^{-1}. BFOI values from -6 to 39 correspond to oxygen concentrations from 1.5–3 ml l^{-1}. (?) indicates inadequate data due to the existence of thick turbidite beds of Facies 3 (no sampling). See Figure 2 for legend.

taxon can also be found at abyssal depths (Corliss, 1979). *Cibicidoides* spp. has an upper depth limit within the middle bathyal in the Gulf of Mexico (Pflum & Frerichs, 1976). Additionally, *C. ungerianus* and *C. kullenbergi* are very abundant deep-water taxa below 100–120 m (Jorissen, 1988; Sgarrella & Moncharmont Zei, 1993).

From 9.9 m to 53.37 m, where turbidite deposits prevail, the palaeodepth assignment is difficult due to the possibility of reworking of the specimens. However, the high abundance and good preservation of the low-diversity *V. complanata–Globobulimina* spp. assemblage, in combination with the absence of benthic foraminifera typical of shallow-water environments (e.g. *Ammonia beccarii*, *Elphidium* spp.), supports an outer-shelf environment setting.

Finally, in the upper part of the succession, the *B. alata* assemblage indicates deposition in the upper bathyal zone, as also suggested by high abundances of *B. spathulata/dilatata*, *B. costata* and *Globocassidulina subglobosa*. *G. subglobosa* is a cosmopolitan species present in a wide bathymetric range and in different water masses (e.g. in the Gulf of Mexico, *G. subglobosa* occurs in the upper bathyal zone; Pflum & Frerichs, 1976).

Bulimina costata is recorded to be one of the dominant species representative of upper middle bathyal (610–914 m) biofacies in the Gulf of California (Bandy, 1961). In the Peru–Chile Trench area of the southeastern Pacific, it was found at depths of 150–2000 m, with greatest abundances occurring from 500 m to 1500 m (Ingle *et al.*, 1980). In the Gulf of Mexico, it ranges from 100 m (Bandy & Chierici, 1966) to 1676 m (Pflum & Frerichs, 1976) but is most common in upper and bathyal zones. In the Sigsbee Plain and Mississippi Fan, it is a common component of the *Bolivina–Brizalina* facies along the middle and lower slope (Poag, 1981).

DISCUSSION

The Lower Tortonian deposits of the Ag. Giannis section on Gavdos Island consist of hemipelagic marls interbedded in thick turbidite-like sandy deposits. The increased thickness of litharenitic sands upward in the section reflects strong terrigenous influence (runoff-related turbidites). Therefore, the action of gravity and downslope sediment transport cannot be understated.

In this record, the percentage of planktonic foraminifera over the total assemblages is considerably high. This indicates the presence of an open-marine environment. From the plot of Figure 11, it is evident that percentage values of planktonic foraminifera are fairly consistent, indicating relatively undisturbed sediments. The absence of anomalously low percentage planktonic values indicates either that material transported to the study area arrived in amounts small enough such that values of percentage planktonics were not affected, or that the material was displaced from a location of similar depth characterized by comparable abundances. However, the reduction in benthic

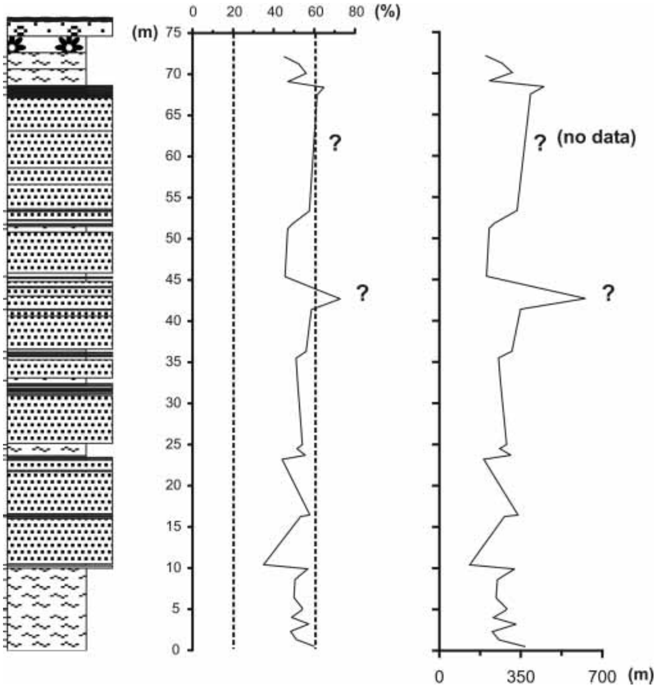

Fig. 11. Plankton/benthos ratio and palaeodepth curve (right) obtained for the studied section. (?) indicates inadequate data due to the existence of thick turbidite beds of Facies 3 (no sampling). See Figure 2 for legend.

foraminifera in the sandy intervals, in combination with the high abundance of the planktonic forms, may be explained by the fact that these layers have been intensively winnowed by bottom currents. Hence, the fine-grained organic detritus and other possible adequate food for benthic foraminifera would have been washed away, thus preventing the small benthic organisms from thriving under these conditions. Nevertheless, this kind of habitat can be favourable for some specialized endobenthic forms (*V. complanata–Globobulimina*) that take advantage of the food supplied by the strong bottom currents.

Ecosystem evolution

Major differences in diversity, community structure, feeding and habitat preferences are observed among benthic foraminiferal assemblages across the Ag. Giannis section.

The composition of the pre-turbidite assemblage (first 9.9 m of the section) is characterized by high diversity and numerous different morphotypes. Sessile suspension feeders, such as *Cibicidoides ungerianus* and *C. kullenbergi*, occur together with infaunal detritus feeders. All ecological niches were occupied, signifying that the oxygen penetration within the sediment column reached several centimetres (Loubère, 1997) and the redox zone was deep.

The interval from 9.9 m to 53.37 m is composed mostly of turbidite-like sediments. The thriving pre-turbiditic assemblage was drastically reduced. Only some sediment-dwelling foraminifera (*V. complanata–Globobulimina* spp.) could keep pace with burial and survived by utilizing organic matter in the turbidite layer. The microfaunas of this interval are less diversified, with a minimum diversity value at 42.7 m, the percentage values of the epifaunal component show a diminishing trend with small-scale fluctuations and the assemblage is enriched in the infaunal component, indicating a high trophic profile (Zahn *et al.*, 1986). The positive peak of the *V. complanata–Globobulimina* spp. assemblage indicates high bottom productivity due to the increased input of nutrients from the continent (maybe river-induced) (e.g. Van der Zwaan & den Hartog Jager, 1983).

Above the turbiditic sands, from 53.37 m to 72.12 m, an oligotypic assemblage (*Bolivina alata* assemblage) prevails. This ‘recolonization’ fauna is composed mostly of infaunal forms that are mobile and may take advantage of the small amounts of organic matter which comes to the seafloor during and after the turbidites. Epifaunal benthic forms are represented only by small numbers in the sediments deposited after the turbidites.

It is interesting to note that this low diversity assemblage includes a number of new species, which have not been observed in the abundant and highly-diversified pre-turbidite faunas. Among these are *Bolivina alata*, *Globocassidulina oblonga* and *Uvigerina gaudrynoides*. The increase of *Bolivina* is linked to poorly oxygenated bottoms and a fine-grained sedimentation setting.

In a short interval, at 70.1 m, the repopulation of the nutrient-rich substrate by the low-diversity *Bolivina alata* assemblage is replaced by species (the shallow infaunal *Valvulineria*, *Uvigerina* and the epifaunal *Cibicidoides* spp.) that are able to occupy a wider range of ecological niches. This repopulation process and the increase in diversity values is suggestive of an improvement in oxygen content in the bottom water, causing a temporary deepening of the redox zone.

The palaeoenvironmental conditions of the Ag. Giannis section reflect the biotic recovery of the benthic ecosystem after a period of intense turbidity activity. The vertical evolution of the benthic foraminiferal assemblages indicates a succession from (a) a pre-disturbance deposit to (b) a disturbance deposit followed by (c) the post-disturbance deposit (*sensu* Alve, 1999). According to Alve (1999), units (a) and (c) may contain *in situ* fossils, whereas (b) will be either unfossiliferous (there are 13 barren samples) or contain transported fossils (although they may contain post-disturbance, infaunal taxa which utilize organic matter in the turbidite layers (Rathburn & Corliss, 1994)).

CONCLUSIONS

Palaeoecological relationships between benthic foraminifera and environmental factors were analysed in the Lower Tortonian hemipelagic marls and turbidite-like sands of the Ag. Giannis section, Gavdos Island, Greece.

Considerable differences in diversity, community organization, feeding and habitat preferences are detected among benthic foraminiferal assemblages below, across and above the turbiditic episodes.

Prior to the deposition of turbiditic sands, the benthic foraminiferal assemblage (*Uvigerina striatissima* assemblage) is indicative of a certain environmental stability, as characterized by relatively minor fluctuations in measured faunal parameters. This stability was disrupted by the recurrent deposition of turbiditic sands. Some specialized endobenthic forms, such as *Valvulineria complanata* and *Globobulimina* spp., could keep pace with high sedimentation in this high-energy regime, taking advantage of the food supplied by the strong bottom currents.

A remarkable pattern that can be interpreted as evidence of faunal recovery characterized the sea floor following the deposition of turbiditic sands. A new assemblage of opportunistic taxa (*Bolivina alata* assemblage) initiated the process of recolonization. The reduction in the dominance of *Bolivina* spp. and the reappearance of both infaunal and epifaunal taxa reflects the ongoing recovery of the benthic ecosystem.

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Epifaunal taxa

Anomalinoides spp., *Cassidulina laevigata*, *Cibicides* spp., *Cibicidoides* 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 gaudrynoides*, *Uvigerina peregrina*, *Uvigerina striatissima*.

Oxic indicators

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

Suboxic indicators

Bulimina aculeata, *Bulimina costata*, *Cassidulina carinata*, *Cassidulina laevigata*, *Dentalina* spp., *Globocassidulina oblonga*, *Globocassidulina subglobosa*, *Gyroidina soldanii*, *Gyroidinoides neosoldanii*, *Hoeglundina elegans*, *Lenticulina* spp., *Melonis* spp., *Nonion* spp., *Oridorsalis umbonatus*, *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.

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