

Foraminiferal sequence eco-biostratigraphy of the Middle-Early Late Miocene, Potamos Section from Gavdos Island, Greece

With 6 figs and 3 tabs

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Abstract

Extremely well preserved fossil floras, evaluated by plant taxonomy and leaf physiognomy, from the Potamos Section, Gavdos Island, Greece are well dated to the Middle- and early Late-Miocene by mid- to outer-shelf assemblages of planktonic and benthonic foraminifera.

The essentially parallel trends in the dominating benthic groups – epifaunal *Cibicides* and infaunal *Bolivina* and *Uvigerina* allow us to identify at least two nutrient-rich events. These two events are characterized by low specific diversity in the plankton and a high abundance of the planktonic species *G. bulloides*. Among the benthos, infaunal species increase in abundance.

Planktonic upwelling indicator *G. bulloides* and many delicate *Bolivina* spp., together with a higher planktonic ratio and a relatively low benthic diversity, indicate cooler, if not deeper, depositional environments.

The fluctuating differences in relative abundances between inner and outer neritic taxa can be quantified as a curve, enabling the recognition of possible sequences with boundaries implied at the peaks in inner neritic forms. In some levels, collapse in P/B ratio, decrease in deep water benthics and increase in elphidiids, may indicate the existence of sequence boundaries.

Key words: foraminifera, Miocene, productivity, sea-level.

Kurzfassung

Gut erhaltene Floren, deren Taxonomie und Blatt-Physiognomie beschrieben wurde, des Potamos Profiles, der Insel Gavdos in Griechenland, können mittels charakteristischen marinen mittel- bis äußeren Schelf-faunen von planktonischen und benthonischen Foraminiferen in das Mittel- bis frühe Ober-Miozän eingestuft werden.

In diesem Profil treten zwei nährstoffreiche Ereignisse auf, die durch die epifaunale *Cibicides*- und die infaunale *Bolivina* / *Uvigerina*-Vergesellschaftung charakterisiert werden. Die beiden Ereignisse werden durch die niedrige Diversität des Planktons mit Massenaufreten von Individuen von *G. bulloides* charakterisiert, während im Benthos die infaunalen Arten in ihrer Häufigkeit zunehmen.

G. bulloides, als ein planktonischer „upwelling“ Indikator und delikate Bolivinen, eine hohe Plankton-Rate und eine relativ geringe Diversität des Benthos, weisen auf kühlere, eventuell tiefere Ablagerungsbedingungen hin.

Die relativen Häufigkeiten von Taxa des inneren und äußeren Neritikums werden kurvenmäßig erfasst und erlauben die Zuordnung zu möglichen Sequenz-Grenzen mit Häufigkeitsmaxima von Formen des inneren Neritikums. In einigen Niveaus kollabiert die P/B-Rate, das Tiefwasser Benthos nimmt ab und Elphidien nehmen an Häufigkeit zu, welche ebenfalls auf diese Sequenz-Grenzen hinweisen.

Schlüsselworte: Miozän, Foraminiferen, Produktivität, Meeresspiegel

Introduction

Many studies indicate that benthic foraminiferal abundance and distribution data are useful for interpreting the paleobathymetry of sediments (e.g. BUZAS & GIBSON 1973, VAN MORKHOVEN et al. 1986, OLSSON & WISE 1987, OLSSON 1991). Benthic organisms are environmentally sensitive and generally inhabit relatively narrow ranges of environmental conditions. The distribution of benthic organisms is controlled by both biotic and abiotic parameters. Primary abiotic factors affecting benthic foraminiferal distributions include salinity, temperature, substrate type, dissolved oxygen content, nutrient supply and current strength (KOUTSOUKOS & HART 1990). Important biotic factors include the interrelationships among organisms. The complex interplay of these abiotic and biotic factors controls the distribution of benthic foraminifera. Therefore, benthic foraminiferal taxa show definite specific environmental preferences that can be used to reconstruct past environments. In general, open marine middle-outer neritic to upper bathyal environments have high benthic foraminiferal diversity (BUZAS & GIBSON 1973). In addition to benthic foraminiferal distributions, numerous studies show a link between benthic foraminiferal habitats and test morphology (e.g. LIPPS 1976, 1982, 1983, KOUTSOUKOS & HART 1990). Moreover, many studies have concluded that variations in benthic foraminiferal assemblages can be used to assess water-depth changes within and between sequences (e.g. BROWNING et al. 1997). Within a sequence, changes in benthic foraminiferal assemblages should obey Walther's Law of Facies. During a transgression, the populations living on the outer shelf occur stratigraphically above those living on the inner shelf.

The purpose of this paper is to use the benthic foraminiferal assemblages in the >125 µm size fraction from the early Late Miocene Potamos Section in Gavdos Island to reconstruct water-depth changes throughout this interval. The benthic foraminifera from the Potamos Section are generally well preserved and highly abundant.

Material and methods

The Potamos section, which is 112.5 m thick, is located in the northeastern part of the Gavdos island, along the Potamos bay (fig. 1). It is mainly composed of alternations of whitish to grayish-bluish marls and sands. Upwards these beds change into shale and sand alternations with significant presence of *Chlamys latissima* and *Gryphaea (Crassostrea) gryphoides crassissima* exposed in a distinct bed. In the uppermost levels of the Potamos section *Heterostegina* sands, followed by red soils, top the deposits.

Fifty-eight samples were collected at two meters intervals, except in some cases, where recovering was not possible. The samples were screen-sieved in 125 µm mesh.

As regards benthic and planktonic foraminifera,

qualitative analysis was performed on all samples. Some samples resulted barren. Therefore twenty-six samples showed a foraminiferal content, which was sufficient for the quantitative analysis. At least 300 specimens per sample were counted following the modern standard methods.

In each sample foraminifera were identified at specific level, after Foraminiferi Padani (AGIP, 1982), LOEBLICH & TAPPAN (1989) and CIMERMAN & LANGER (1991) and all specimens were counted. The relative abundance of each species was determined. For each sample, dominant and accessory species were defined according to their relative abundance. An estimation of the species diversity was performed using the following parameters: number of species, number of specimens, Shannon-Wiener species diversity index (H), equitability index (BUZAS 1979). In addition, the Fischer α -index (FISHER et al. 1943), which shows the relationship between the number of species and the number of individuals in an assemblage, and the dominance, are also reported for all the samples. P/B ratios, which can be regarded variously as a measure of deposition depth, a paleoproductivity index or as a measure of preferential loss of planktonics by dissolution, were also calculated. Paleobathymetry was calculated for each sample by introducing P/B ratio based on epifaunal species in the equation of VAN DER ZWAAN et al. (1990). For this paper the bathymetric zonation of VAN MORKHOVEN et al. (1986) is used: 0–30 m is inner neritic, 30–100 m is middle neritic, 100–200 m is outer neritic and 200–600 m is upper bathyal.

Infauna versus epifauna percentages – by reference to their modern representatives – were used as indicators of paleoproductivity and upwelling. Strictly speaking, epifauna refers to living either on the sediment surface or else on a firm substrate, such as a shell or other structure. If the sediment is soft, the distinction between epifaunal and shallow infaunal may be negligible. Because of this problem CORLISS (1991) extended the use of the term epifaunal to include the forms living 1 cm below of the sediment surface. This method has been followed by other authors (BARMAWIDJAJA et al. 1992) who extended the epifaunal term down to 2 cm. However, although it may be convenient to apply this method, it may lead to confusion or erroneous conclusions. For instance, living *Ammonia beccarii* is rarely seen at the sediment surface as it lives just below the sediment-water interface and is therefore considered to be infaunal. However, BARMAWIDJAJA et al. (1992) described this species as “apparently epifaunal”. Even infaunal taxa are not consistently present at the same depth in different areas (CORLISS & VAN WEERING 1993, JORISSEN 1999) because the control of their position in the sediment, which is mainly dependent on food availability/type, sediment porewater and geochemistry, varies both spatially and temporally. Anyway, LINKE & LUTZE (1993) point out that foraminiferal microhabitats should not be classified according to static concept, but should be regarded as a dynamic adaptation to optimize food acquisition.

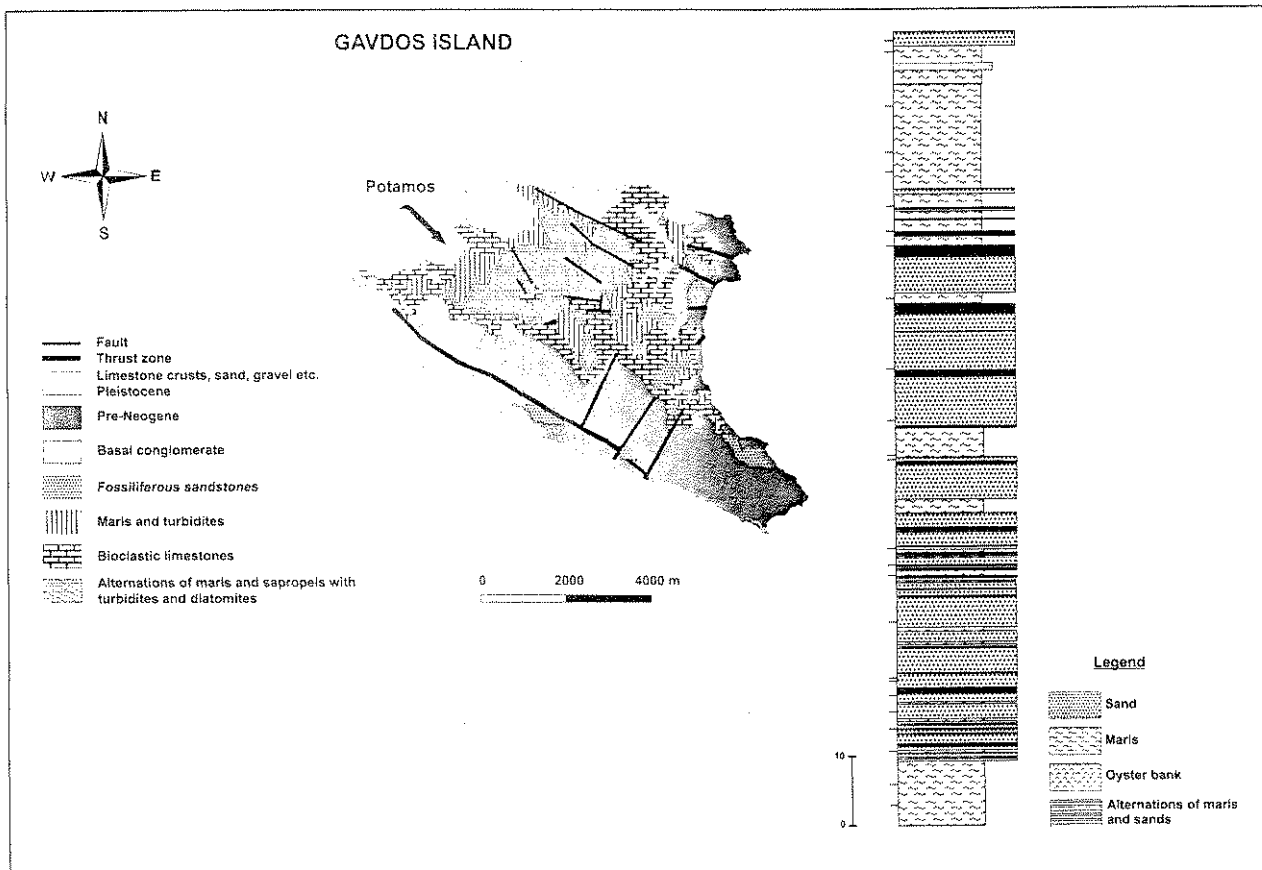


Fig. 1: Location map and lithostratigraphical column of the Potamos Section.

In addition, benthic foraminiferal changes have been used to assess water-depth changes within the sequence. McGOWRAN & LI (1996) used abundance contrasts between inner and outer neritic faunas to define third-order events in the Miocene sequences from the Lakes Entrance Oil Shaft, finding a plausible correlation between the local biofacies and global eustatic and isotopic events (see also LI & McGOWRAN 1997). A similar exercise was performed here to detect paleodepth changes in Potamos Section by selecting forms representing inner and outer neritic groups and calculate their abundance differences. Under this respect, the trends in their abundance differences from objective counts of taxa, could imply sea level changes.

Discussion of data

The relative frequency of the main planktonic and benthic species is shown in figures 2 and 3. For simplicity, several planktonic or morphotypes are lumped together, although they were counted separately.

1. Biostratigraphy

The biostratigraphic analysis of the section is based on the qualitative and semi-quantitative analysis of the planktonic foraminifera (fig. 2).

We identified 17 planktonic foraminifera categories.

Taxon abundance is expressed as percentage of the total assemblage. The distribution pattern of the most significant taxa is described in order to obtain a detailed planktonic foraminifera biostratigraphic framework for Potamos section. Taxa having biostratigraphic significance in our record are *Globigerinoides obliquus*, *Globorotaloides falconarae*, *Globorotalia partimlabiata* and the neogloboquadriniids.

The species *Globigerinoides obliquus* and *Globorotalia apertura* were counted and plotted together as the preservation was poor in several samples. This group is continuously present in our record, in high percentages, showing a significant decrease in the middle part of the section, from 55 to 75 m, occurring in low numbers. From the base of the section, *G. obliquus* occurs regularly. The distribution pattern of the group suggests that the section biostratigraphically starts above the First Regular Occurrence (FRO) of *G. obliquus*, dated at 11.478 Ma (FORESI et al. 1998, 2002b, SPROVIERI et al. 2002, HILGEN et al. 2000, 2003b). This fact is enhanced by the real absence of *G. subquadratus*, which Last Common Occurrence (LCO) is reported at 11.54 Ma and marks the Serravallian/Tortonian boundary (TURCO et al. 2002, HILGEN et al. 2003a). Specimens identified as *G. subquadratus* exist only at the first 3 m of the section, and may represent a 3-chambered variant of *Globigerinoides obliquus*.

Neogloboquadrina group was identified in all the

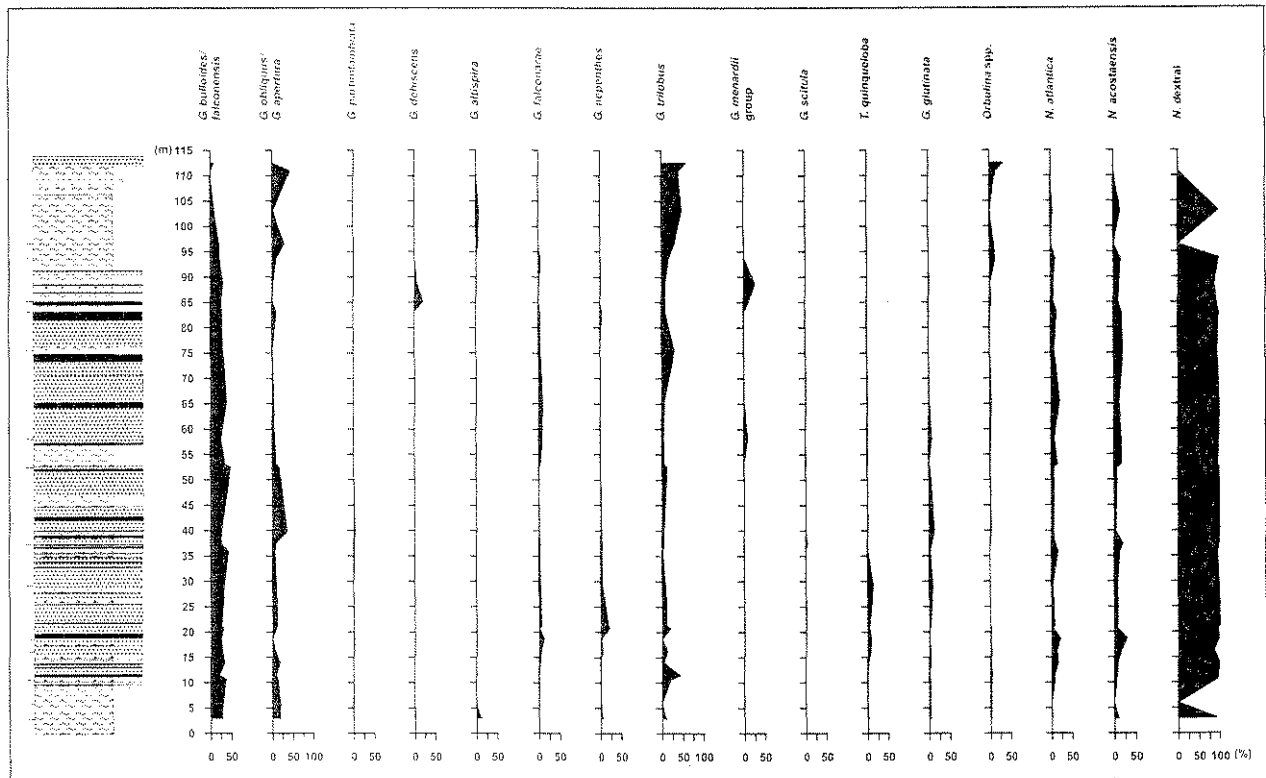


Fig. 2. Relative frequencies of the selected planktic foraminifera from the Potamos Section.

samples. Two types of this group were distinguished, *N. atlantica* and *N. acostans*. *Neogloboquadrina acostans* comprises forms with 4–5 chambers in the final whorl. Representatives identified as the 4-chambered type of HILGEN et al. (2000) were also included in the *N. acostans* following the taxonomic concept of FORESI et al. (2002a). Their higher abundances are recorded in the middle part of the section.

Specimens identified as *N. atlantica* correspond to the forms described as *N. continua* by DERMITZAKIS (1978), *N. atlantica praeatlantica* by FORESI et al. (2002a, b), and the small size *N. atlantica* of HILGEN et al. (2000). *N. atlantica praeatlantica* first occurs at the astronomical age of 11.78 Ma (HILGEN et al. 2000, FORESI 2002a) and vanishes within the *Globigerinoides extremus* Zone of FORESI et al. (1998) (FORESI et al. 2002b) and according to HILGEN et al. (2000), its Last Regular Occurrence (LRO) is recorded around 10.48 Ma.

Large size specimens of *N. atlantica* were also recognized in our record, in particular, at the middle part of the section and are identical to large-sized *N. atlantica* of HILGEN et al. (2000) and described as *N. atlantica atlantica* of FORESI et al. (2002a,b). In the Mediterranean, the First Occurrence (FO) of *N. atlantica atlantica* has been dated at 11.16 Ma (Tremi Island, FORESI et al. 2002b) and according to HILGEN et al. (2000), in Monte Gibliscemi section, the large sized specimens of *N. atlantica* are present between 11.121 and 10.850 Ma and in Monte dei Corvi section between 11.137 and 10.832 Ma (HILGEN et al. 2003b).

Both types in our record are recorded from the base of the section and occur continuously up to the top. The curve of *N. atlantica* shows an upward decrease, in particular at the last 25 m, whereas *N. acostans* increases from the 60 m upwards. From the base of their distribution up to the top, the coiling of neogloboquadriniids is persistently right (more than 80%). HILGEN et al. (2000) reported this event in Gibliscemi, ranging from 11.178 Ma to 10.011 Ma. In Tremi Island the right coiling starts at 11.25 Ma.

Globorotalia partimlabiata occurs in small percentages up to the top of the Section. The distribution pattern of this taxon is not continuous showing one major increase at the interval between 30 to 50 m and a less prominent one at around 20 m of the section. FORESI et al. (2002a) reported the Last Occurrence (LO) of this species at 11.8 Ma. According to their taxonomic concept, this level represents the actual LO of the species yet they observed less typical representatives at higher levels, which they labeled *G. cf. partimlabiata*. According to HILGEN et al. (2000), *G. partimlabiata* occurs up to 9.91 Ma.

In the record studied, specimens of *G. partimlabiata* are comparable with the *G. cf. partimlabiata* forms of FORESI et al. (2002a) and can be included in the morphological variation of *G. partimlabiata* of HILGEN et al. (2000).

Globorotaloides falconarae and *Catapsydrax parvulus* were counted together as specimens identified in our record are variable in size, ranging from small, typical to *C. parvulus*, to large sized. In the Mediterranean, the small-sized type of *G. falconarae* is indistinguishable from *C. parvulus* (HILGEN et al. 2000). This taxon is continuously present in

the section, being more abundant from 55 to 85 m and it shows an important influx at 23 m.

Globigerina bulloides/falconensis is the most abundant species in all the samples showing an overall decrease at the top part of the section. Concerning other species, *T. quinqueloba*, is abundant up to 35 m of the section and then the species exists in low numbers, *G. glutinata* is abundant up to 65 m and then decreases significantly, whereas *Orbulina* spp. exists in low abundances up to 90 m and then it shows two major influxes at 94 and 112 m of the section. The species *G. dehiscens*, *G. altispira*, *G. menardii* and *G. scitula* occur sporadically showing some influxes in the record, which can be used for regional correlations. *Globigerinoides trilobus* occurs continuously showing an upward increase, whereas *G. nepenthes* decreases upwards.

The planktonic foraminifera analysis discussed above, reflects that the studied sequence ranges in absolute ages from 11.178 to 10.01 Ma according to the distributional range of *Neogloboquadrina* types, the coiling of this group and the regular occurrence of *G. obliquus*.

2. Benthic foraminifera

The fluctuations of the benthic foraminifer assemblages allowed us to distinguish the following intervals (fig. 3):

- 0–55 m: The benthic assemblage is characterized by high percentages of *Cibicides* sp. in the lower part. *Valvulineria complanata*, *Gyroidina soldanii* – *Gyroidinoides neosoldanii* and *Globobulimina* sp. become common at the top of the interval. *Oridorsalis umbonatus*, *Nonion boueanum*, *Pullenia bulloides*, uvigerinids and buliminids-bolivinids are also present, in small numbers.
- 55–110 m: The benthic assemblage shows a decreasing diversity, it is oligotypic and it is mainly composed of bolivinids-buliminids that peak at 65,5 m. At the base there is a peak of *O. umbonatus*. Finally, *Globobulimina* sp., *P. bulloides* and uvigerinids peak in the lower limit of this interval.
- 110–112,5 m: Bolivinids-buliminids show a general decrease. *Globobulimina* sp. has a peak at around 90 m and uvigerinids display high percentage values.

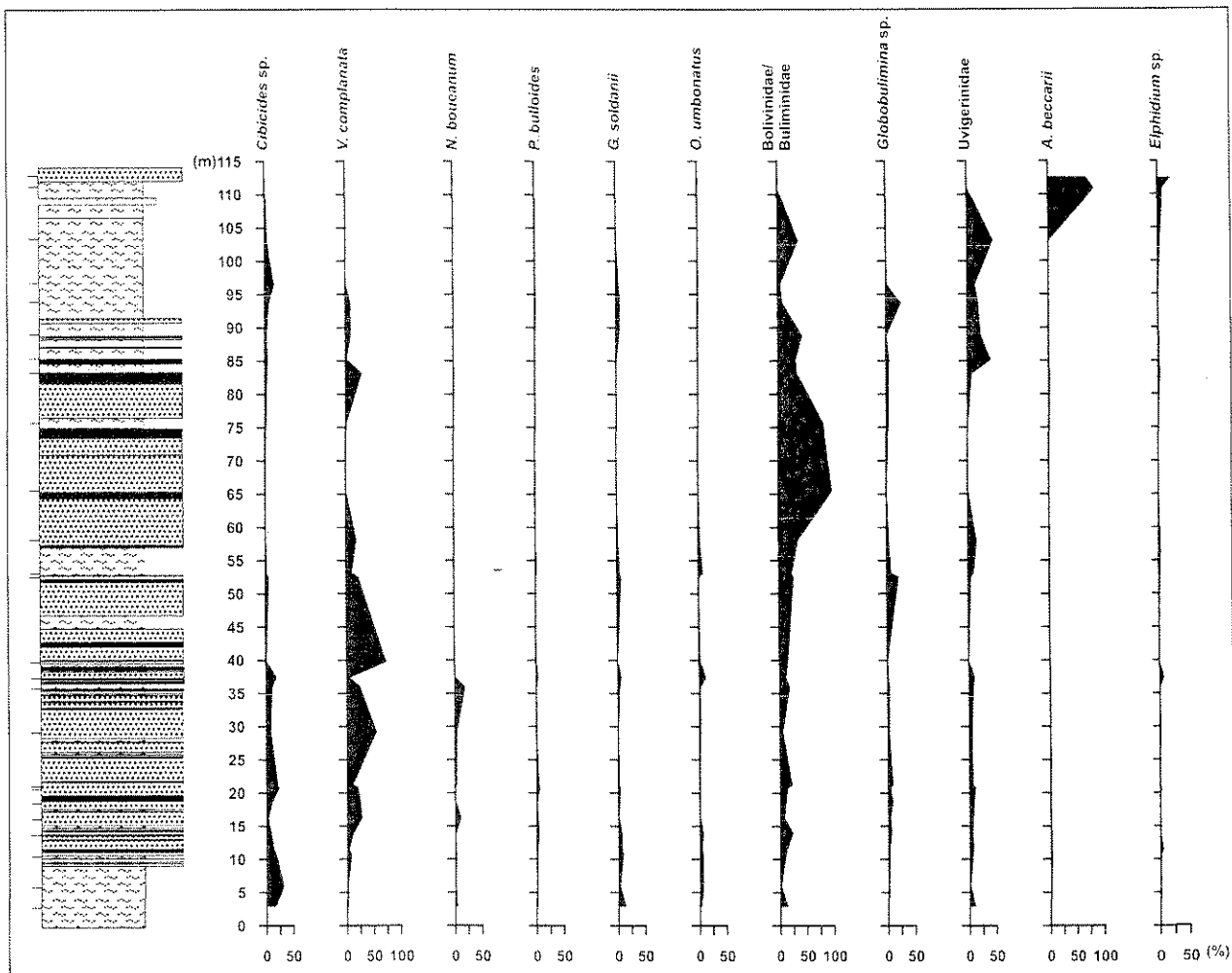


Fig. 3. Relative frequencies of the selected benthic foraminifera from the Potamos Section.

In the upper part, *G. soldanii*-*G. neosoldanii* and *V. complanata* decrease. The last 2,5 m are characterized by *A. beccarii* (84,7%) and *Elphidium* sp. (23,4%).

3. Species diversity and dominance trends

The general faunal characteristics expressed by Fischer- α index, Shannon diversity, Dominance and Equitability show predictable patterns (tab. 1). These indices are in accordance with the faunal abundance pattern implying that high diversity corresponds with low dominance and low equitability. Low-diversity assemblages, dominated by one or a few species, tend to occur in stressed environments, whereas a normal marine environment would be indicated by a relatively diverse association. In the latter case, dominance, expressed as the percentage of the most abundant taxon, is usually found to be relatively low (VAN DER ZWAAN & JORISSEN 1991, SEN GUPTA & MACHAIN-CASTILLO 1993).

Values of Fischer- α < 5 generally indicate brackish or hypersaline marginal environments but may also indicate normal marine environments with a high dominance of a single species. According to Shannon index, values > 2,1 indicate normal marine environments.

In the studied record, species numbers range from 8 to 40 per sample and Fischer- α diversity values range from 1,69 to 14,35. At 39,8 m, 65,5 m, 75,6 m, 110,9 m and 112,5 m, low values of Fischer- α index suggest some deviation from the norm of the paleoenvironmental parameters.

The benthic foraminiferal record shows at first (from 3 to 37,4 m) high abundance and diversity suggesting low levels of ecological stress, as commonly met in relatively stable and well ventilated deep-sea environments. An abrupt decrease of diversity, tagged by an increase in dominance, at 29,25 and 39,8 m, is due to the peak occurrence of *V. complanata* (53,8% and 72,9% respectively),

a shallow infaunal species, tolerant of low oxygen values, which responds to a high food level at the sediment-water interface (JORISSEN 1987, 1988, VAN DER ZWAAN & JORISSEN 1991). The same stands for the intervals at 65,5 and 75,6 m, where peak occurrences of *B. spathulata* (50% and 73,2% respectively) indicate high organic content and dysoxia (VAN DER ZWAAN 1982, JONKERS 1984, KATZ & THUNELL 1984, MURRAY 1991, VERHALLEN 1991, JORISSEN et al., 1992, KAIHO 1994, LOUBÈRE 1996, 1997, KOUWENHOVEN et al. 1999).

In the uppermost part (110,9 and 112,5 m), the section is characterized by low diversity values and high dominance trend. The abundance of *A. beccarii* is very high (84,7% and 70,2% respectively) indicating an estuarine environment of low environmental quality.

4. P/B ratio and Paleobathymetry

Bathymetric estimation is essential in any paleoenvironmental analysis. Two independent methods have been used to estimate the water depth during the deposition of the Potamos Section: a) the P/B ratios (100P/P+B), where P is the planktonic foraminifera and B is the benthic foraminifera and b) the bathymetric distribution of the Potamos benthic foraminiferal assemblages in the present day Mediterranean.

a) P/B ratio

Plankton/Benthos ratios are well known in the modern ocean: they characterize different water columns (from the deep/lower bathyal/abyssal plain to the shallow inner shelf).

In the studied succession, P/B ratio values vary from 41,16% to 78,95% (fig. 4A), apart from the uppermost part of the section, at 110,9 and 112,5 m, where P/B ratio is 7,2% and 10,33% respectively.

Table 1: Benthic foraminifera faunal parameters from the Potamos Section.

HEIGHT	3	6	10,7	11,5	13,95	16,32	18,72	20,8	21,2	29,25	35,9	37,4	39,8
Taxa	39	21	31	40	37	18	17	28	32	22	20	27	11
Individuals	203	129	137	242	203	133	51	132	252	201	107	213	116
Dominance	8,7	16,6	7,1	8,1	14,2	26,7	23,5	18,7	13,4	53,8	23,9	11,8	72,9
Shannon index	3,32	2,53	3,20	3,31	3,08	2,25	2,40	2,95	2,91	1,85	2,49	3,02	1,10
Equitability	0,90	0,83	0,93	0,90	0,85	0,78	0,85	0,89	0,84	0,60	0,83	0,92	0,46
Fischer-a	14,35	7,12	12,49	13,65	13,25	5,61	8,93	10,87	9,72	6,30	7,26	8,19	2,99
HEIGHT	52,5	53,1	58,1	65,5	75,6	83,1	85,2	88,8	93,7	96,5	103,1	110,9	112,5
Taxa	14	29	26	8	13	22	19	17	30	34	13	10	11
Individuals	125	249	129	188	220	193	332	200	287	254	256	232	249
Dominance	22,2	16,4	22,6	50	73,2	28,9	40,5	37,6	26,4	10,8	41	84,7	70,2
Shannon index	2,17	2,86	2,62	1,43	1,03	2,24	1,89	2,15	2,52	3,10	1,57	0,56	0,84
Equitability	0,82	0,85	0,80	0,69	0,40	0,72	0,64	0,76	0,74	0,88	0,61	0,24	0,35
Fischer-α	4,04	8,50	9,81	1,70	3,02	6,40	4,38	4,44	8,44	10,55	2,89	2,13	2,36

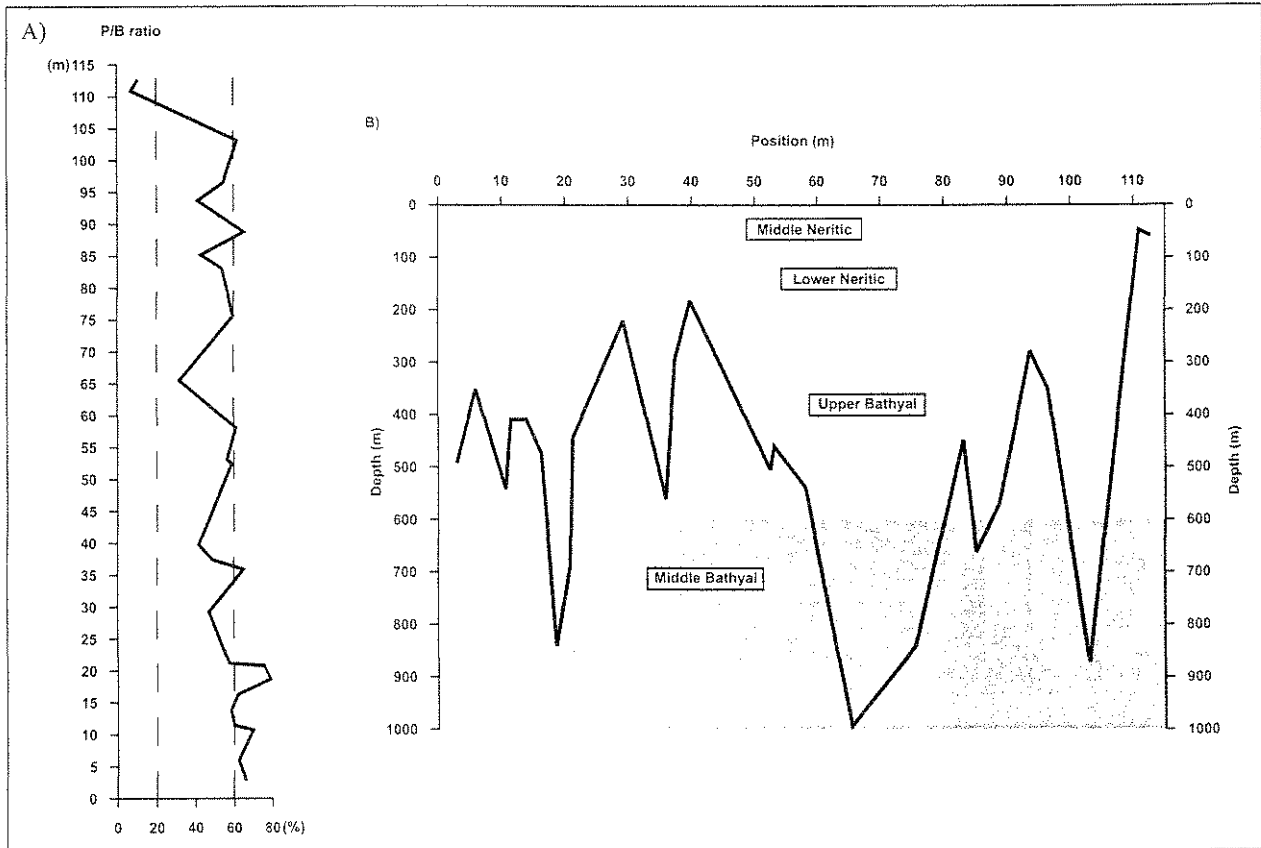


Fig. 4. A) P/B ratio distributional pattern of the studied succession of the Potamos Section. B) Depth reconstruction of the studied sequence of the Potamos Section.

Therefore, in the Potamos Section, we identify an inner shelf environment (values not exceeding 20%) corresponding to 110,9 and 112,5 m, which yield the shallower assemblage, and a slope to outer shelf environment (values between 20–60%).

An improved P/B ratio, worked out by VAN DER ZWAAN et al. (1990), estimates paleowater depth (D) directly in meters. According to this model, paleoproductivity is measured by the number of planktonic foraminifera (P), whereas organic flux reaching the bottom is measured by the number of benthic foraminifera excluding inbenthic species. The correction for inbenthic species is necessary because they are independent of the organic matter that rains down from the euphotic layer by having an unlimited food resource in the sediment (DE RIJK et al. 1999, WILSON 2003). The advantage of this method is that it gives paleowater depth directly in meters, which is readily usable in basin modeling and it corrects for minor changes in productivity by excluding inbenthic species.

The application of VAN DER ZWAAN et al. (1990) expression indicates that (fig. 4B) at 3 m of the studied record, the sea was already 480 m deep. After small-scale fluctuations during the deposition of the following 15 m of sediment, a maximum water depth was reached, which was over 840 m. Until 39,8 m, it gradually shallows to 182 m followed by a gradual deepening with a peak of a 1000 m paleo-water depth at 65.5 m. Up to 103 m, the

depth of deposition remains rather deep with smaller and larger scale fluctuations in paleo-water depth. An abrupt shallow interval of 50 m terminates the studied section. This coincides with the higher sand content.

However, this approach must be used cautiously in view of the fact that P/B ratios are a measure of paleodepth under certain restrictions (ADELSECK & BERGER 1975, VAN DER ZWAAN et al. 1990): indications of paleoenvironmental stress at the time of deposition and (partial) dissolution of faunas prohibit the use of P/B ratios in this sense.

b) Depth-related species

Because the assemblages recorded from the Potamos Section consist of species that are alive today, paleobathymetries have been also estimated through a direct comparison with water-depth ranges seen in their present-day counterparts. References we used include general studies (e.g. VAN MORKHOVEN et al. 1986, MURRAY 1991) and a selection of papers concerning the Mediterranean Sea (e.g. PARKER 1958, TODD 1957, BANDY & CHIERICI 1966, CITA & ZOCCHI 1978, WRIGHT 1978, VENEC-PEYRE 1984, JORISSEN 1987, CIMERMAN & LANGER 1991).

Table 2 summarizes depth-diagnostic benthic foraminiferal taxa selected among those having common or abundant occurrences in the Potamos Section. Paleobathymetric zones correspond in nomenclature and definition

Table 2: Paleobathymetric list of regularly occurring species.

HEIGHT	3	6	10,7	11,5	13,95	16,32	18,72	20,8	21,2	29,25	35,9	37,4	39,8	52,5	53,1	58,1	65,5	75,6	83,1	85,2	88,8	93,7	96,5	103,1	110,9	112,5	SHELF	UPPER BATHYAL	MIDDLE BATHYAL	LOWER BATHYAL				
TAXA																																		
<i>A. beccarii</i>																																		
<i>A. planorbis</i>								✓																										
<i>A. stelligerum</i>	✓							✓																										
<i>B. alata</i>								✓																										
<i>B. dilatata</i>				✓																														
<i>B. punctata</i>	✓																																	
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<i>C. laevigata</i>																																		
<i>Elphidium</i> sp.																																		
<i>G. neosoldanii</i>																																		
<i>G. soldanii</i>																																		
<i>Globbulimina</i> sp.																																		
<i>L. rotulata</i>																																		
<i>O. umbonatus</i>																																		
<i>P. bulboides</i>																																		
<i>P. quinqueloba</i>																																		
<i>P. wulferstorfi</i>																																		
<i>R. siphonogeneroides</i>																																		
<i>S. carinata</i>																																		
<i>U. cyl. gaudynoides</i>																																		
<i>U. peregrina</i>																																		
<i>U. rutile</i>																																		
<i>U. sriatissima</i>																																		
<i>V. complanata</i>																																		

to those by VAN MORKHOVEN et al. (1986) and BERGGREN & MILLER (1989). The depth range chart goes in accordance with the results extracted from the formula used for the calculation of the paleodepth, which means that the benthic foraminiferal assemblages are indicative of an upper to lower bathyal environment. An abrupt shallow interval of 50 m terminates the studied section. Indeed, abundant shallow-water species as *A. beccarii* and elphidiids suggest inner neritic paleodepths with upper water limits that may ultimately reach the emergence (BARBIERI & ORI 2000). This, in accordance with the anomalously low percent planktic values (fig. 4A) indicates either the existence of a sedimentation gap or the strong influence of relative sea-level changes.

5. Identification of sequence boundaries

The paleoenvironmental analyses of benthic foraminiferal faunas and the paleobathymetric relationships in the Potamos section serve as a means for recognizing sequence boundaries— an aspect of sequence biostratigraphy (LOUITT et al. 1988, 1997, OLORIZ et al. 1995, MCGOWRAN & LI 1996, MILLER et al. 1998, HOLLAND 1999). By referring to their modern habitat preferences, we selected benthic foraminifera representing inner and outer neritic groups and calculated their abundance differences (i.e. outer minus inner neritic). The trend in their abundance differences gives a hint on the local sea level changes: Outer neritic species increase with increasing water depth while

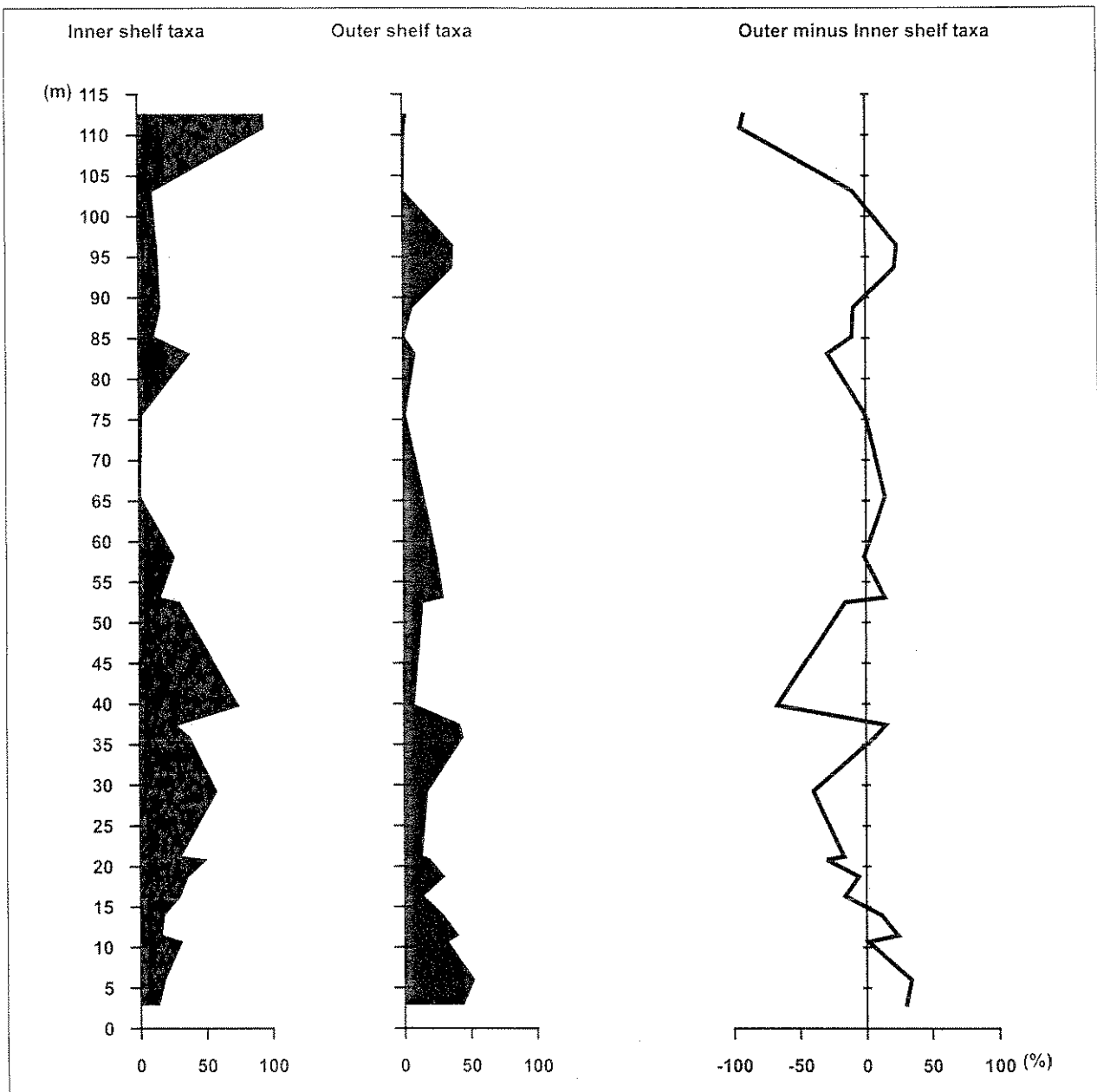


Fig. 5: Abundances of the major groups of inner and outer neritic taxa through the Potamos Section. Changes in their abundance generate a curve depending on the composition of the “inner neritic” category. The curve is consistent with the possibility that it is reflecting changes in sea-level.

Table 3: Microhabitat preference of regularly occurring species

Epifauna-Shallow infauna (living shallower than 2 cm in the sediment)	Deep infauna (living deeper than 2 cm in the sediment)
<i>Ammonia beccarii</i> (Linné)	<i>Amphicoryna scalaris</i> (Batsch)
<i>Asterigerinata planorbis</i> (d'Orbigny)	<i>Bolivina alata</i> (Sequenza)
<i>Anomalinoidea</i> sp.	<i>Bolivina dilatata</i> (Reuss)
<i>Cibicides dutemplei</i> (d'Orbigny)	<i>Bolivina punctata</i> d'Orbigny
<i>Cibicidoides kullenbergi</i> (Parker)	<i>Bolivina reticulata</i> Hantken
<i>Cibicides lobatulus</i> (Walker & Jacob)	<i>Bolivina spathulata</i> (Williamson)
<i>Cibicidoides pseudoungerianus</i> (Cushman)	<i>Bolivina tortuosa</i> Brady
<i>Cibicides</i> sp.	<i>Bulimina aculeata</i> d'Orbigny
<i>Cibicidoides ungerianus</i> (D'Orbigny)	<i>Bulimina costata</i> d'Orbigny
<i>Cibicides refulgens</i> de Montfort	<i>Cassidulina laevigata</i> d'Orbigny
<i>Cibicidoides wuellerstorfi</i> (Schwager)	<i>Globobulimina</i> sp.
<i>Gyroidinoides neosoldanii</i> (Brotzen)	<i>Globocassidulina subglobosa</i> (Brady)
<i>Gyroidina soldanii</i> Brotzen	<i>Hoeglundina elegans</i> (d'Orbigny)
<i>Heterolepa dertonensis</i> (Ruscelli)	<i>Nonion boueanum</i> (d'Orbigny)
<i>Lenticulina gibba</i> (d'Orbigny)	<i>Pullenia bulloides</i> (d'Orbigny)
<i>Lenticulina rotulata</i> (Lamarck)	<i>Pullenia quinqueloba</i> (Reuss)
<i>Oridorsalis umbonatus</i> (Reuss)	<i>Praeglobobulimina ovata</i> (d'Orbigny)
<i>Spiroloculina</i> sp.	<i>Praeglobobulimina pupoides</i> (d'Orbigny)
<i>Valvulineria complanata</i> (d'Orbigny)	<i>Textularia</i> sp.
	<i>Uvigerina cyl. gaudryoides</i> Lipparini
	<i>Uvigerina longistriata</i> Perconig
	<i>Uvigerina peregrina</i> Cushman
	<i>Uvigerina pygmaea</i> d'Orbigny
	<i>Uvigerina rutila</i> Cushman
	<i>Uvigerina striatissima</i> Perconig

inner neritic forms become common in shallow-water environments approaching sequence boundaries. Therefore, high negative values suggest more neritic forms, which suggest shallower paleodepth and vice versa. The lows in these inferred sea level changes could represent sequence boundaries (fig. 5).

Our data suggest that a sequence boundary lies at 110,9 m of the studied succession, in which the peak in inner neritic forms in combination with the very low P/B ratio enable us the recognition of a possible sequence boundary. Sequence boundaries should be at shallowing events and epifaunal peaks, whereas infaunal peaks should indicate burial of organic carbon, i.e. deeper quieter water as well as upwelling.

However, the inferred boundaries may only represent proxies to actual sequence boundaries, which should be drawn on erosional or other physical surfaces, because we did not sample the surfaces at which the actual sequence boundaries may occur. Therefore, the sequence boundaries inferred from biofacies should be tuned on physical and sedimentological grounds.

6. Infauna vs Epifauna

The benthic assemblage has been also divided into two major ecological categories, infauna and epifauna, based on habitat preferences of their recent representatives (tab. 3), (JORISSEN et al. 1995, BUZAS et al. 1993, CORLISS 1985, CORLISS & CHEN 1988, BARMAWIDJAJA et al. 1992).

A plot of their relative abundances (fig. 6) shows the

epifaunal component dominating the benthic community in total numbers except in four intervals, where the infaunal component rises more significantly.

Infaunal foraminifera prefer nutrient-rich, low oxygen, muddy environments, and their high abundances usually are indicative of eutrophication in the water column (MURRAY 1991).

Oxygen-poor, nutrient-rich conditions are more typical of colder or deeper waters, and may occur in shallower sites with upwelling influence. Other mechanisms, which may produce a similar effect, include large-scale runoff that produces a brackish water lid and ultimately a high nutrient level.

Therefore, the infaunal concentrations in Potamos Section are likely to be due to a eutrophic and oxygen-poor environment that was driven by either local upwelling or a strong river discharge or both.

Data at present are inadequate in distinguishing which environmental factor played a primary role; nor can we dismiss the suggestion that the Potamos basin became a semi-enclosed basin that effectively enhanced dysaerobic or eutrophic activities.

In order to sort out which environmental factor makes the infauna flourish we used a quantified profile of the spinose *Globigerina bulloides* group (fig. 6).

Globigerina bulloides is a cold water form which may occur in high numbers in upwelling regions in low and mid-latitudes (see HEMLEBEN et al. 1989). Its abundant presence in these areas with prevailing warm climate is largely due to nutrient-rich, upwelling waters (PRELL &

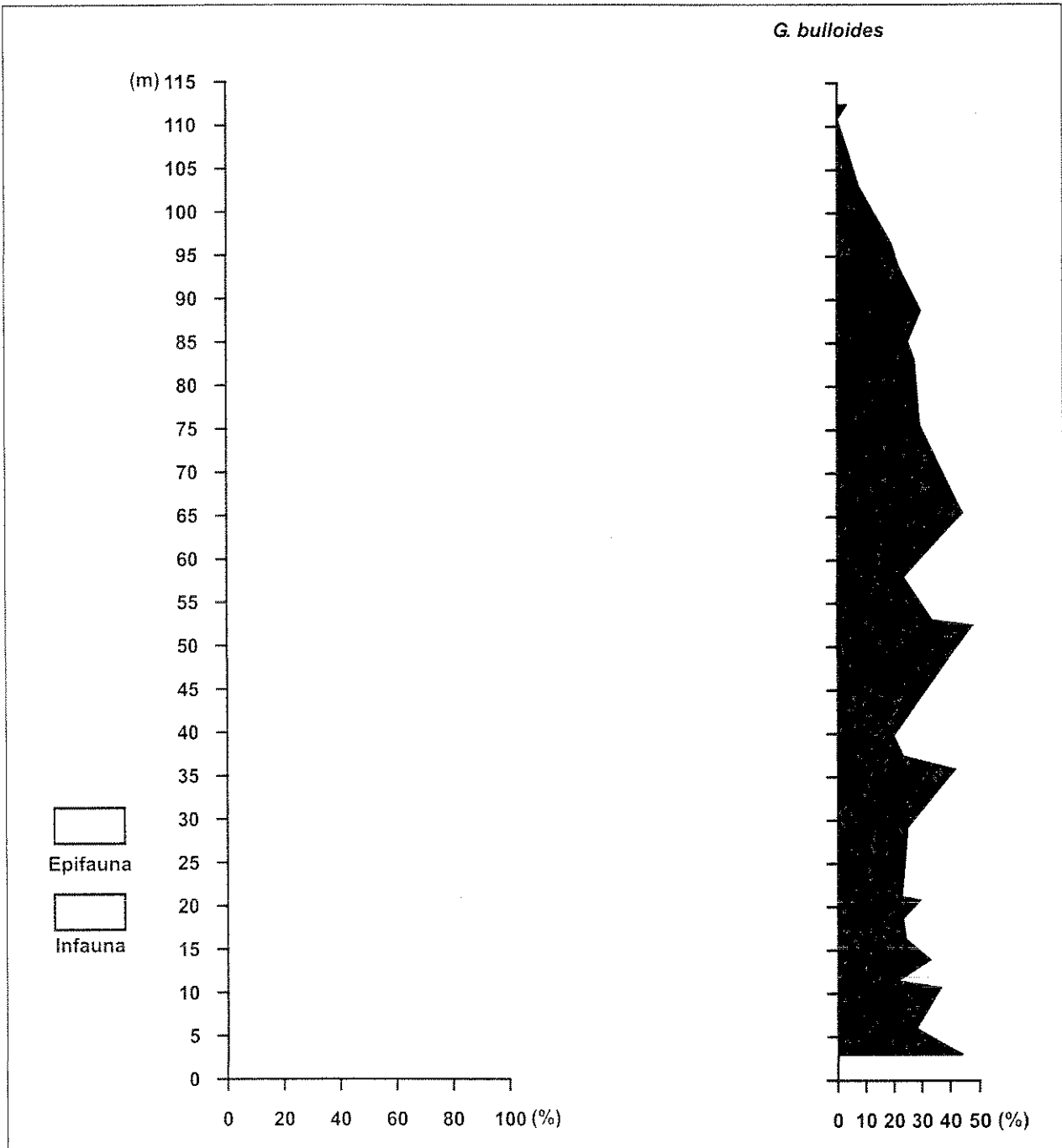


Fig. 6. Benthic foraminiferal microhabitat preferences compared with the quantified profiles of *G. bulloides*.

CURRY 1981, RAO et al. 1989, KROON 1991, CURRY et al. 1992, NAIDU & MALMGREN 1996, GUPTHA et al. 1997). That is, increased numbers of the *G. bulloides* group may indicate a cooler water-mass, but it could also indicate a more fertile water-mass. However, from this species alone, it is not clear whether the signal obtained was due to climatic cooling or upwelling. To separate them, we need benthic profiles as an out group.

The profile of *G. bulloides* shows small-scale fluctuations, with variations of ten percent in relative abundance and quite broad decline in the uppermost part of the section. Among several peaks in the *G. bulloides* curve,

two are more significant in terms of concurrence with other upwelling indices (infaunal benthos), at 35,9 and 65,5 m. Indeed, in these two levels, the benthic signal – high dominance, low diversity and relatively small, thin-shelled specimens – suggest that the planktonic signal has an upwelling component and is not simply due to cooling. Upwelling cold currents may have favored the cooling and sinking of surface waters with the subsequent upward mixing of nutrient-rich intermediate waters (ROHLING & BIGG 1998, SIERRA et al. 2003). We, therefore, suggest the establishment, in these parts of the section, of a small upwelling cell, probably as a result of wind strengthening.

Palaeoenvironmental reconstruction

The sequence through Potamos Section in Gavdos Island is well exposed and apparently continuous in the resolution of our samples. Deposition, estimated by benthic and planktonic foraminiferal paleodepth proxies, occurred at the upper bathyal to lower bathyal zone, apart from the uppermost part of the succession which has been deposited in the middle neritic zone.

This abrupt change of paleodepth, at the last 2,5 m of the sequence, implies either the existence of a stratigraphical gap or the abrupt elevation of the relative sea level. According to ZELLERS (1995), major fluctuations (>200 m) in paleobathymetry are mainly the result of basement uplift/subsidence and sediment loading. Indeed, the sequence biostratigraphic approach, which is broadly defined as the analysis of microfossil distribution patterns in sediments or rocks for the purpose of recognizing unconformity bounded units, was used to predict a sequence boundary at 110,9 m of the succession. The fluctuating differences in relative abundances between inner and outer neritic taxa can be quantified as a curve enabling the recognition of possible sequences with boundaries implied at the peaks in inner neritic forms.

In 110,9 m, collapse in P/B ratio, decrease in deep water benthics, increase in elphidiids, may indicate the existence of a sequence boundary.

On the basis of the available ecological information on benthic foraminifera, a preliminary palaeoenvironmental reconstruction of the study area can be inferred.

The benthic foraminifera, in the lower portion of the section show moderate diversity and abundance. This part of the section consists of high abundances of *Cibicides* sp., while *G. soldanii*-*G. neosoldanii* and *Globobulimina* sp. are found in lower frequency values. These abundant occurrences in combination with the frequency patterns of *O. umbonatus* would be indicative of a well-oxygenated benthic environment (MIAO & THUNELL 1993). The relatively high abundance of *P. bulloides* in this part of the section may be associated with areas of low productivity in the surface waters and therefore low flux of organic matter to the sea floor (BURKE et al. 1993). On the other hand, *G. neosoldanii* has a propensity for the transition between normal marine and oxygen-depleted conditions. This species seems to be excellent marker of organic matter and doesn't tolerate strong ecological stress due to long periods of very low oxygen levels (MULLINEAUX & LOHMANN 1981, DE STIGTER et al. 1998).

This assemblage is almost entirely replaced by a low diversity assemblage of opportunistic species with low equitability, indicating that the environment became unstable (at 29,25 m, 39,8 m, 65,5 m, 75,6 m, 110,9 m and 112,5 m).

Indeed, the peak occurrence of *O. umbonatus* in combination with *V. complanata* at 29,25 and 39,8 m, is correlated with high percentages of organic matter and low oxygen concentration in the sediment (BURKE et al. 1993, MACKENSEN et al. 1985, RATHBURN & CORLISS 1994). In par-

ticular, *V. complanata* shows significant peak abundances in the studied record (at 29,25, and 39,8 m) reflecting a high labile organic flux to the sea floor (VAN DER ZWAAN & JORISSEN 1991, SEN GUPTA & MACHAIN-CASTILLO 1993).

In addition, representatives of the infaunal bolivinids-buliminids and *Globobulimina* sp., known to become more prominent in stressed environments, are well presented in the middle part of the section (65,5 m and 75,6 m), indicating adaptation to high-organic carbon and low oxygen conditions of deep infaunal microhabitats (MURRAY 1991). According to PHLEGER & SOUTAR (1973), CARALP (1989) and GOODAY (1993), benthic assemblages dominated by *Bolivina* typify low oxygen environments with a sustained flux of organic matter in regions of high productivity, often associated with intense upwelling.

Finally, in the upper part of the section, at 110,9 m, a dramatic change takes place. High relative abundance of *A. beccarii* (84,7%) and an overall benthic foraminiferal abundance decline indicates that an estuarine environment offered suitable conditions for this species. However, we are not sure whether the increasing abundance of *A. beccarii* reflects increasing eutrophication and/or hypoxia, or whether increasing temperatures also played a role. The abundance of this species may reflect low environmental quality due to high nutrient influx from a river (GUSTIANINI et al. 2004). In the Gulf of Mexico and Chesapeake Bay, recent increases in relative abundance of *A. beccarii* have been linked to increased hypoxia/anoxia or due to regional warming (HASLETT 2001). Moreover, in the laboratory, *A. beccarii* needs temperatures at bottom >17 °C, in order to reproduce successfully (THOMAS et al. 2000).

The Potamos Section is marked by the abundant occurrence of *G. bulloides*, a subpolar species that in modern Mediterranean Sea occurs in significant abundances during the winter (PUJOL & VERGNAUD GRAZZINI 1995). Furthermore, the frequency curve of *G. bulloides* indicates a warming trend upward. This trend is not gradual but it is punctuated by more intense cold episodes. In these cold fluctuations, the benthic assemblage suggests cold and productive waters (bolivinids-buliminids) as well as the planktonic assemblage, dominated by *G. bulloides*, a species probably related to fertility conditions (ROHLING et al. 1993).

The presence of infaunal and low oxygen tolerant species such as *Globobulimina* spp. points to a decrease of the oxygen content into the deepest sediment levels inhabited by the infaunal benthic foraminifera. The essentially parallel trends in the dominating benthic groups – epifaunal *Cibicides* and infaunal *Bolivina* and *Uvigerina* allow us to identify at least two nutrient-rich events.

These two events are characterized by a low specific diversity in the plankton and a high abundance of the planktonic species *G. bulloides*. Among the benthos, infaunal species increase in abundance.

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