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Benthic foraminiferal assemblages as tools for paleoenvironmental reconstruction of the early-middle Pleistocene Montalbano Jonico composite section

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KEY WORDS – Benthic foraminifera, Hierarchical cluster analysis, Principal component analysis, Early – middle Pleistocene cyclicity, Basilicata (S. Italy).

ABSTRACT – Quantitative analyses on benthic foraminifera were carried out on the early – middle Pleistocene Montalbano Jonico composite section. Statistical analyses (Hierarchical Cluster Analysis and Principal Component Analysis) were performed to better understand the distributional patterns of the assemblages. Hierarchical Cluster Analysis indicates that a difference between assemblages and benthic foraminiferal distribution exists. The difference and the distribution are related to depth and oxygen content variations, respectively. Results of the PCA – analysis reveals that the greatest correlation with water depth is accounted for by the first axis, while the third and the fifth axes are closely related to oxygen content. In particular, the fifth axis allows the identification of three severe reductions in oxygen content during the periods of sapropel deposition. The Montalbano Jonico composite section deposited during a period of marine regression, registered depth-changes of 500 – 30 m, and was characterized by several shallowing – deepening cycles. The inferred sedimentary cyclicity is believed related to tectono-eustatic forcing in the early Pleistocene, and to eustatically-controlled cyclicity in the middle Pleistocene.

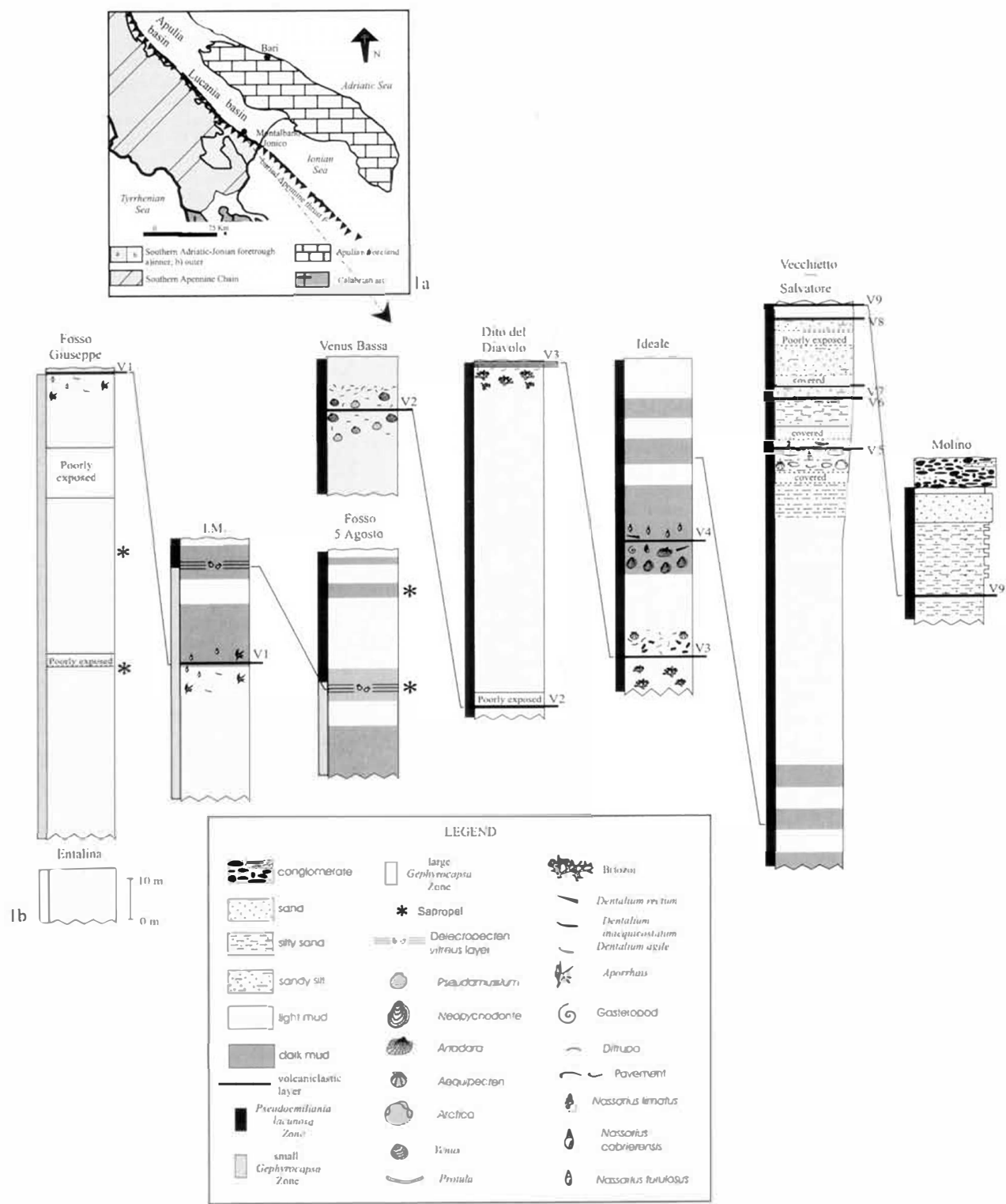
RIASSUNTO – [Ricostruzione paleoambientale della successione infra e mesopleistocenica di Montalbano Jonico sulla base delle associazioni a foraminiferi bentonici] – Indagini quantitative sono state svolte sui foraminiferi bentonici contenuti nella successione infra-mesopleistocenica di Montalbano Jonico (Basilicata, Italia meridionale). Per meglio comprendere i trends distribuzionali delle associazioni sono state condotte due analisi statistiche, l'analisi cluster e l'analisi dei componenti principali. L'analisi cluster ha evidenziato l'esistenza di una differenza sia tra le associazioni a foraminiferi bentonici, sia tra le loro distribuzioni lungo l'intera successione. La differenza nelle associazioni e nella loro distribuzione è imputabile tanto alla batimetria, quanto alla variazione del contenuto di ossigeno al fondo. I risultati dell'analisi dei componenti principali ha evidenziato come la batimetria si rifletta sul primo asse, mentre il contenuto di ossigeno rispettivamente sul terzo e quinto asse. In particolare, il quinto asse ha permesso di riconoscere tre forti riduzioni del contenuto di ossigeno e riconducibili al periodo della formazione dei sapropels. La successione di Montalbano Jonico si è depositata durante una fase di regressione marina; la profondità stimata del bacino di sedimentazione è compresa fra i 500 m e 20-30 m. Numerosi cicli di innalzamento e abbassamento del livello del mare hanno, inoltre, caratterizzato la deposizione della successione, consentendo così di ricostruire una ciclicità continua per il Pleistocene inferiore e medio. Questa ciclicità si pensa possa essere attribuita ad una azione combinata del clima e della tettonica locale, durante il Pleistocene inferiore, e alla sola azione climatica, durante il Pleistocene medio.

INTRODUCTION

The study of benthic foraminiferal assemblages represents an important tool for the paleoenvironmental interpretation of marine sediments. As a matter of fact, several studies have demonstrated that a relationship exists between the distribution of foraminifera and oceanographic properties (Phleger, 1960; Chierici, Busi & Cita, 1962; Blanc-Vernet, 1969; Corliss, 1985; Caralp, 1989; Hermelin & Shimmield, 1990; Murray, 1991; Barmawidjaja *et al.*, 1992; Jorissen *et al.*, 1992). Water depth, oxygen concentration, organic matter, temperature and salinity are important water mass characteristics influencing the faunal composition of the assemblages. Hence, it is thought that changes in foraminiferal assemblages are related to variations in environmental properties. Environmental properties determine the presence of several species of benthic foraminifera if the species are highly responsive to variations in each

of the above mentioned conditions, while other species are completely indifferent to the environmental variations. Changes in the assemblages composition are clearly dependent on the responsiveness of each particular species, the presence of which can be attributed to changes in environmental factors such as depth-range, dissolved oxygen, nutrient input, water temperature and salinity. For this reason, analyses on the composition of benthic foraminiferal assemblages and observations on test morphologies provide information about the properties of the ocean bottom-waters and their variations over time. Knowledge of the modern species distributions in environments, influenced by particular factors (oxygenation, depth, and food), was applied in order to reconstruct the Pleistocene paleoenvironments.

In particular, benthic foraminifera were used to reconstruct paleo-water depth. Many researchers in early studies had used foraminifera as depth indicators (Parker, 1948, 1958; Phleger, 1951, 1956, 1960,



Text-fig. 1 - a) Location of the Lucania Basin and Montalbano Jonico section. b) Selected stratigraphic sections in Montalbano Jonico area: the correlation of the sections has been obtained by means of volcaniclastic layers and fossil assemblages.

1964; Bandy, 1954, 1961; Boltovskoy & Wright, 1976; Douglas, 1979). The marine bathymetric zonation was made on the presumption that some species, or groups of taxa, always occupied the same depth-range. Recently, most available data on foraminifera ecology have demonstrated that depth is not the sole factor responsible for a taxa distribution in marine waters (Denne & Sen Gupta, 1988; Boltovskoy *et al.*, 1991; Jorissen *et al.*, 1992).

It is assumed that benthic foraminiferal abundance is closely linked to levels of dissolved oxygen concentration in the near bottom waters and in the sediment, as well as to the organic matter input from the surface waters (Mullineaux & Lohmann, 1981; Perez-Cruz & Machain-Castillo, 1990; Nolet & Corliss, 1990; Moodly & Hess, 1992; Gooday, 1994; Sen Gupta & Machain-Castillo, 1993; Bergamin *et al.*, 1999; Kaiho, 1999). The change in oxygen concentration at the sediment-water interface and/or in the sediment pore-water plays a role in controlling the composition of benthic foraminiferal assemblages. Therefore, oxygen can be considered the real limiting factor that determines the presence or absence of taxa. Organic flux is also important, as it is a determining factor in the relative abundances of organisms in the assemblages. Nevertheless, organic flux is subordinate to oxygen as soon as the latter starts to be limiting (Van der Zwaan *et al.*, 1999). The modern-day distribution of benthic species, by different oxygen regimes (Jorissen *et al.*, 1992; Gooday & Rathburn, 1999; Bernhard & Bowser, 1999; Schmiedl *et al.*, 2000), is used to reconstruct the existing oxygen conditions that were recorded by the fossil assemblages, for the area from which we have retrieved samples.

In this study, benthic foraminiferal assemblages have been analysed from the early and middle Pleistocene succession, over 450 m in thickness, which crops out in the southern part of the Apennine Foretrench (Basilicata, South Italy) (Ciaranfi *et al.*, 1997; 2001). The aim is to reconstruct the paleoenvironmental conditions, which prevailed during the deposition of Montalbano Jonico sedimentary record by observing the variations in the composition and distribution of the benthic foraminiferal assemblages. A general regressive trend that includes several cycles of sea level rise and fall is evident from previous studies carried out on macrobenthic assemblages, on taphofacies and on sedimentological observations (D'Alessandro *et al.*, 1996; Ciaranfi *et al.*, 1997; 2001). Moreover, the compositional and structural changes of the paleocommunities together with the taphonomic signatures reflect variation in oxygen content, which in turn indicates alternating periods of poor and well-ventilated bottom (or pore) waters.

AREA OF STUDY

The Montalbano Jonico composite section crops out in the Lucania basin, one of the four minor basins

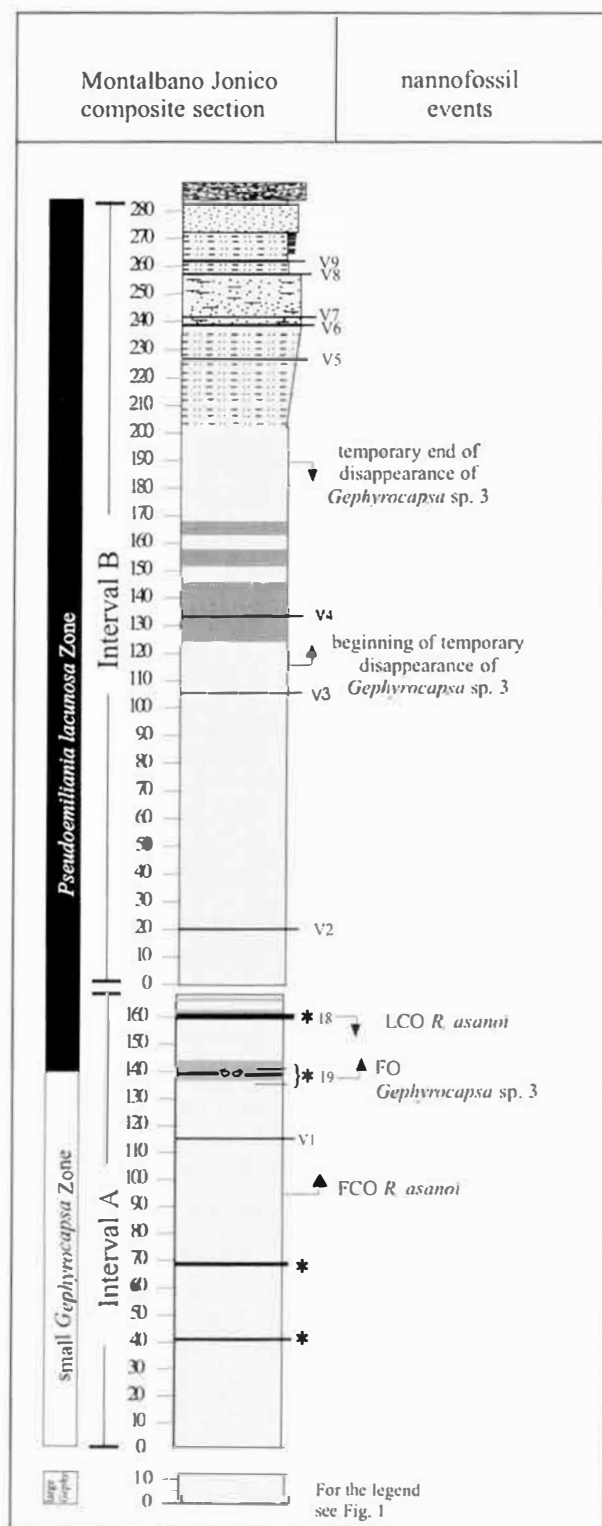
of the Bradano Trough (Casnedi, 1988). The Bradano Trough is located between the external border of the Apennines chain and the internal margin of the Apulia Foreland (Text-fig. 1a). During the late early Pleistocene, the internal portion of the Lucania basin evolved due to a relative sea-level fall caused by the uplifting of the chain. Consequently, an erosional truncation of land areas occurred, up to an almost complete removal of Pleistocene sediments. By contrast, the depocentral areas of the Lucania basin were affected by a strong subsidence that caused a relative sea-level rise. Consequently, a narrow and deep trough was formed, in which the deposition of hemipelagic sediments took place. During the early Pleistocene, the depocentral areas and the foreland border of the Lucania basin were involved progressively in the Bradano Trough evolution caused by the moving eastward of the uplifting Apennines border. During the middle Pleistocene, a generalized shallowing phase took place, causing the exposure of silty-clayey and silty-sand successions.

THE MONTALBANO JONICO COMPOSITE SECTION

In the area of Montalbano Jonico town, several of these exposed successions were studied and some of them were selected and correlated, thus to reconstruct a continuous marine succession (Ciaranfi *et al.*, 1997; Ciaranfi *et al.*, 2001) (Text-fig. 1b). The correlation has been possible through the presence, in each of the selected successions, of volcanoclastic layers, each of them characterized by the presence of macrofossil remains. Therefore, these layers are been used as guide horizons. The volcanoclastic horizons, accumulated by gravity flows, are made up of pure ash or sand, rich in volcanic material and, occasionally, of pumice clasts. The volcanic material is referred to an alkaline undersaturated volcanism, probably coming from a southern Italy source (Ciaranfi *et al.*, 1996).

The Montalbano Jonico composite succession is about 450 m in thickness (Text-fig. 2) and belongs to the "Argille subapennine" Formation. The succession consists, in its low portion (380 m in thickness about), of poorly stratified hemipelagic muds and muddy silts, in which dark gray intervals and four volcanoclastic layers (V1-V4) are observed. In its upper part (70 m in thickness about) the succession consists of stratified sandy silts and silty sands, in which five volcanoclastic layers (V5-V9) are observed. At the top, shelf sands and conglomerates are based in paraconformity. Calcareous nannofossil biostratigraphy refers the succession to the small *Gephyrocapsa* Zone and to the lower part of the *Pseudoemiliania lacunosa* Zone (Marino, 1996; Ciaranfi *et al.*, 1997, 2001).

Montalbano Jonico composite section is interrupted by a gap, a probable missed section, thus eliding part of the section. A lower part, termed "Interval A", and an upper part, termed "Interval B", can be identified.



Text-fig. 2 - Composite section of Montalbano Jonico.

MATERIAL AND METHODS

Approximately 450 samples have been analysed for the quantitative analyses of the benthic foraminiferal assemblages. 300 g of each sample were washed in the laboratory through sieves with sizes of 500 - 250 and 125 μ m. For an easier and quicker counting, the fraction 125 μ m was split, usually three or four times, to obtain an appropriate number of specimens that still reflected the original assemblage. About 300 specimens were counted from each fraction and re-calculated as percentage values. The residue examined consists of taxa distributed in the modern Mediterranean Sea from the lower infralittoral zone (30 m) to the upper bathyal zone (500 m), according to Murray (1991) and Sgarrella & Moncharmont Zei (1993) (Appendix A).

For an improved paleoecological interpretation, two multivariate statistical methods were applied, Hierarchical Cluster Analysis and Principal Component Analysis, by means of SPSS program, version 9.0. 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 these analyses, the taxa having frequency less than 2% are eliminated. In the end, 46 taxa, of the 53 identified, were used.

For the paleobathymetric reconstruction of the sedimentary basin, the formula of van der Zwaan *et al.* (1990) was used:

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

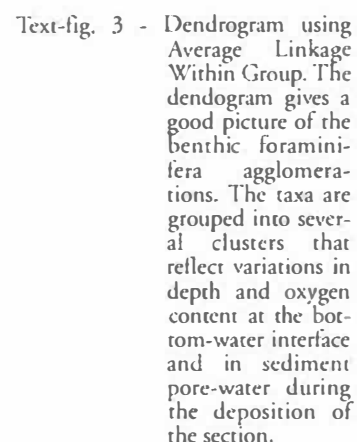
The "%P" represents the percentage of planktonic foraminifera present in the assemblages.

RESULTS

CLUSTER ANALYSIS

The outcome of Hierarchical Cluster Analysis is a dendrogram, a two-dimensional plot, in which benthic foraminifera, with paleoecological similarity, are grouped into a few assemblages representing distinct communities, from which it is possible to draw paleoecological interpretations. In this study, the resulting dendrogram can be divided into two large clusters (Text-fig. 3): Cluster A and Cluster B. Several subclusters can be recognized: subclusters 1, 2 and 3 in Cluster A, and subclusters 4 and 5 in Cluster B.

Cluster A consists of the species *A. beccarii*, *B. elongata*, *C. carinata*, *L. lobatula*, *E. advenum*, *E. crispum*, *C. decipiens*, *P. granosum*, *N. depressulum*, *Q. seminula*, *S. schlumbergeri*, and the taxa *Asterigerinata* spp., *Rosalina* spp. and *Valvulineria* spp. Cluster B includes the species *B. marginata*, *C. ungerianus*, *C. pachyderma*, *C. refulgens*, *G. affinis*, *M. barleanum*,



Subcluster 1 is characterized by the dominance of the species *C. carinata*. *T. angulosa* is also frequent. The other taxa (*Asterigerinata* spp., *L. lobatula*, *A. scalaris* and *O. umbonatus*) are less abundant. Subcluster 2 contains only two forms: *Bolivina* group (including *B. alata* and *B. dilatata*) and *B. spathulata*. The subcluster 3 assemblage groups together taxa such as *Elphidium* group, *Discorbis* spp., *Quinqueloculina* spp., *Pyrgo* spp., *Cornuspira* spp.,

Subcluster 5 consists of the taxa such as *Planulina* spp., *Cibicidoides* spp., *Uvigerina* "costate" group, *Textularia* spp., *Melonis* group, *Lenticulina* spp., and the species *B. nodosaria* and *S. excavata*.

PRINCIPAL COMPONENT ANALYSIS

Among the first five principal components extracted (Text-fig. 4) only 3 are very significant, although all may be useful. In Table 1 the eigenvalues of the first five components are given.

Factor 1 is characterized by high positive loadings for *A. beccarii*, *B. elegans*, *E. crispum*, *E. advenum*, *Q. seminula*, *C. decipiens*, *P. granosum* and *Valvulineria* spp., and significant negative loadings for *S. bulloides*, *Gyroidina* spp. *C. ungerianus*, *C. pachyderma* and *Planulina* spp.

Factor 3 is positively loaded by *C. pachyderma*, *C. refulgens*, *C. ungerianus*, *C. decipiens*, *E. crispum*, *P. granosum* and *E. advenum*, while *Valvulineria* spp., *C.*

Principal component number	eigenvalues	% of Variance	Cumulative %
1	7,321	15,576	15,576
2	3,409	7,253	22,828
3	3,025	6,435	29,264
4	2,399	5,104	34,368
5	2,083	4,431	38,799

Table 1 - Eigenvalues of the five principal components extracted.

carinata, *B. marginata* and *Bolivina* group show the highest negative loadings.

For Factor 5, *Bolivina* gr. and *B. spathulata* show high positive loadings; most of the other taxa display negative loadings.

INTERPRETATION OF DATA

CLUSTER ANALYSIS

Cluster A consists of taxa commonly distributed in modern shallow waters, in the upper circalittoral-lower infralittoral zone (110–30 m, *vide* Sgarrella & Moncharmont Zei, 1993), whereas Cluster B includes forms that are present in modern deep marine waters, from the lower circalittoral zone (200–110 m, *vide* Sgarrella & Moncharmont Zei, 1993) to the upper bathyal zone (lower limit about 500–400 m, *vide* Sgarrella & Moncharmont Zei, 1993). Therefore, a qualitative analysis of the taxa present in Cluster A and in Cluster B indicates that the clusters, apparently, reflect differences in bathymetric zones.

The cumulative plots of Cluster A and Cluster B are displayed in Text-fig. 5. The dominance of the deep assemblage in Interval A supports the suggestion that this part of the succession deposited in rather deep marine water. On the other hand, the dominance of the shallow assemblage in the Interval B suggests deposition of the upper part of the succession in shallow marine water. The shallowing and deepening trends appear to be both cyclic, although their trends as graphed are in the opposite direction. Thus, this analysis provides evidence of quasi-regular and relatively constant sea level changes during the sedimentary deposition.

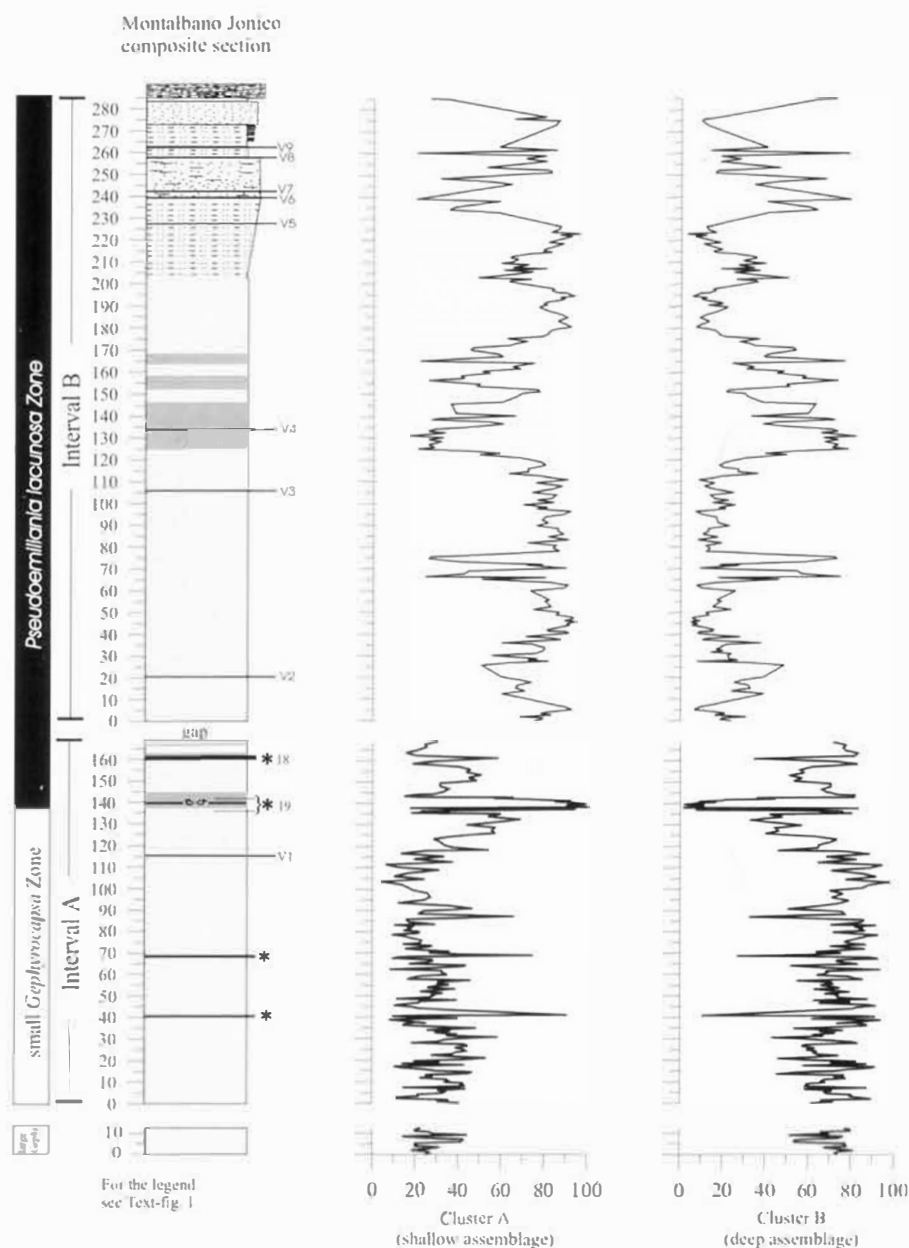
The cumulative plots of the five subclusters reconstructed in the dendrogram (see again Text-fig. 3) are presented in Text-figs. 6a, 6b and 6c, and the discussion follows. Based on a qualitative analysis, the subclusters appear to reflect different oxygen contents at the bottom-water surface and in the sediment pore-water.

C. carinata is considered to belong to the group of the stress-tolerant species (van der Zwaan, 1983).

Component Matrix

	Component				
	1,000	2,000	3,000	4,000	5,000
<i>A. beccarii</i>	.402	-.117	.383	.278	-.032
<i>A. scalaris</i>	-.008	.297	-.016	-.016	-.189
<i>Asterigerinata</i> gr.	.282	.644	-.281	-.152	.206
<i>B. melosaria</i>	-.210	-.050	.380	-.303	.158
<i>Bolivina</i> gr.	-.076	-.239	-.460	.169	.600
<i>B. spathulata</i>	-.105	-.227	-.362	.162	.386
<i>B. castata</i>	-.204	.166	.244	.063	.311
<i>B. elegans</i>	.527	.058	.129	.244	-.106
<i>B. elongata</i>	.120	-.036	.115	.245	.103
<i>B. marginata</i>	-.299	-.001	-.230	-.037	-.100
<i>B. sublimbata</i>	-.245	.082	.005	.086	.149
<i>C. carinata</i>	.468	.068	-.406	-.344	-.205
<i>C. lobatula</i>	.263	.665	-.301	-.320	.088
<i>C. pachyderma</i>	-.489	.300	.385	.073	.148
<i>C. refulgens</i>	-.240	.238	.334	.186	.252
<i>C. ungerianus</i>	-.514	.171	.317	.094	.042
<i>Cornuspira</i> gr.	.275	.079	.018	.213	.123
<i>C. decipiens</i>	.599	.424	-.011	-.080	-.044
DMNS	.243	.726	-.224	-.272	.039
<i>E. advenum</i>	.654	.174	.161	.249	-.060
<i>E. complanatum</i>	.519	-.038	.325	.437	-.033
<i>E. crispum</i>	.669	.153	.210	.336	.003
<i>P. granosum</i>	.590	.016	.175	.383	-.059
<i>G. affinis</i>	-.449	.012	-.088	.248	-.050
<i>G. subglobosa</i>	-.412	-.021	-.279	.259	-.319
<i>Gyroidina</i> gr.	-.627	.118	.012	.289	-.225
<i>H. rhodiensis</i>	-.125	.163	.415	-.196	.351
<i>H. balthica</i>	-.459	-.018	-.145	.197	-.460
<i>Lenticulina</i> gr.	-.150	-.225	.219	-.356	-.121
<i>M. barleanum</i>	-.365	.272	.232	-.094	-.216
<i>M. soldanii</i>	-.385	.037	.462	-.192	-.158
<i>N. depressulum</i>	.372	.196	.028	.418	.114
<i>O. umbonatus</i>	.226	.130	-.029	.096	-.260
<i>P. ariminensis</i>	-.524	.209	.175	.153	-.169
<i>Pullenia</i> gr.	-.471	.298	.385	-.059	.078
<i>Pyrgo</i> gr.	.170	-.003	.261	.060	-.088
<i>Quinqueloculina</i> gr.	.696	-.057	.306	-.034	-.128
<i>Rosalina</i> gr.	.359	.121	.117	-.100	-.013
<i>S. schlumbergeri</i>	.475	.027	.243	-.247	-.145
<i>S. otavata</i>	.002	.086	.362	-.001	.089
<i>S. bulloides</i>	-.665	.209	.198	.150	-.124
<i>S. complanata</i>	.015	-.100	.157	.139	.151
<i>Tectularia</i> gr.	.115	.254	.556	-.366	.104
<i>T. angulosa</i>	.049	.535	.002	.037	-.011
<i>Uvigerina</i> gr.	-.352	-.206	.162	-.345	.128
<i>Valvulineria</i> gr.	.513	.257	-.367	-.259	-.151

Text-fig. 4 - Factor loadings of the taxa on the first, the third and the fifth principal component axes. The significant correlations are in bold type.



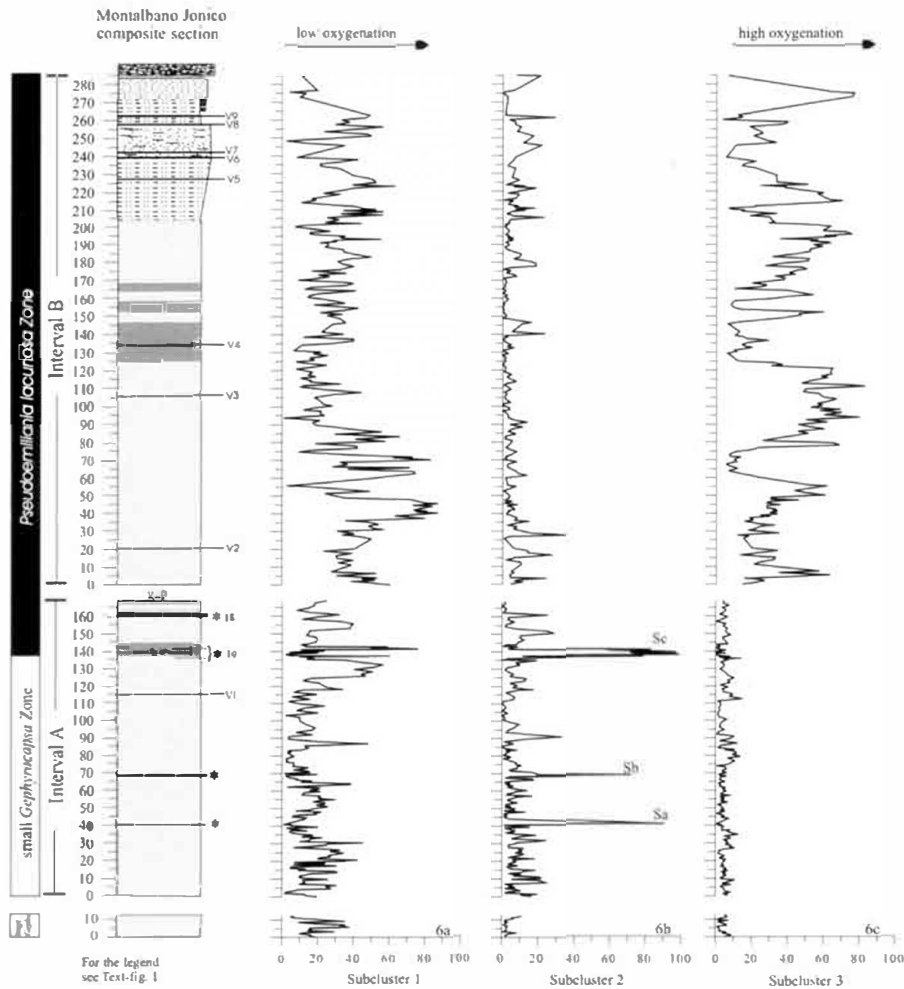
Text-fig. 5 - Cumulative plots of Cluster A and Cluster B. The dominance of the deep taxa (Cluster B) in Interval A suggests deposition in rather deep marine waters. The dominance of shallow taxa (Cluster A) in Interval B suggests deposition in a shallow environment. The sharp passage from deep to shallow could depend on the lack of continuous deposition, corresponding to the gap.

Kaiho (1999) includes this species together with *T. angulosa* among the benthic foraminifera that indicate suboxic sediments (with $O_2 < 1.2$ ml/l). Therefore, subcluster 1 is indicative of an environment characterised by poor oxygenation. The graph of joint frequencies of the subcluster (Text-fig. 6a) shows that the subcluster 1 assemblage exhibits maximum abundances in the middle part of the section and sub-maximum abundances toward the top.

B. alata, *B. dilatata* and *B. spathulata*, reported in the depth range of 600 – 60 m, are indicative of environmental stress, in particular of oxygen-deficiency at the bottom (van der Zwaan, 1983). Kaiho (1994;

1999) considers them typical indicators of dysoxic conditions (with $O_2 < 0.3$ ml/l).

The fossil association of subcluster 2 is distributed throughout the section; its values are consistently less than 20% except for three peaks (labelled Sa, Sb and Sc in Text-fig. 6b). These peaks indicate intervals in which *B. alata* and *B. dilatata* are the sole benthic species that are present with the planktonic species. Some authors (Miller & Lohmann, 1982; Mullins *et al.*, 1985; Quintero & Gardner, 1987; Sen Gupta & Machain-Castillo, 1993) report high values of the genus *Bolivina* (more than 60%), together with planktonic foraminifera, in dysoxic conditions.



Text-figs. 6a, 6b, 6c - Cumulative plots in the three minor subclusters reflecting oxygen variation at the bottom-water surface and in sediment pore-water in shallow marine waters. The opposite direction of change evident in the patterns of subclusters 1 and 3 indicate that oxygen changed frequently during the deposition of the succession. Subcluster 2 reveals three intervals (Sa, Sb and Sc) of severe reductions in oxygen content.

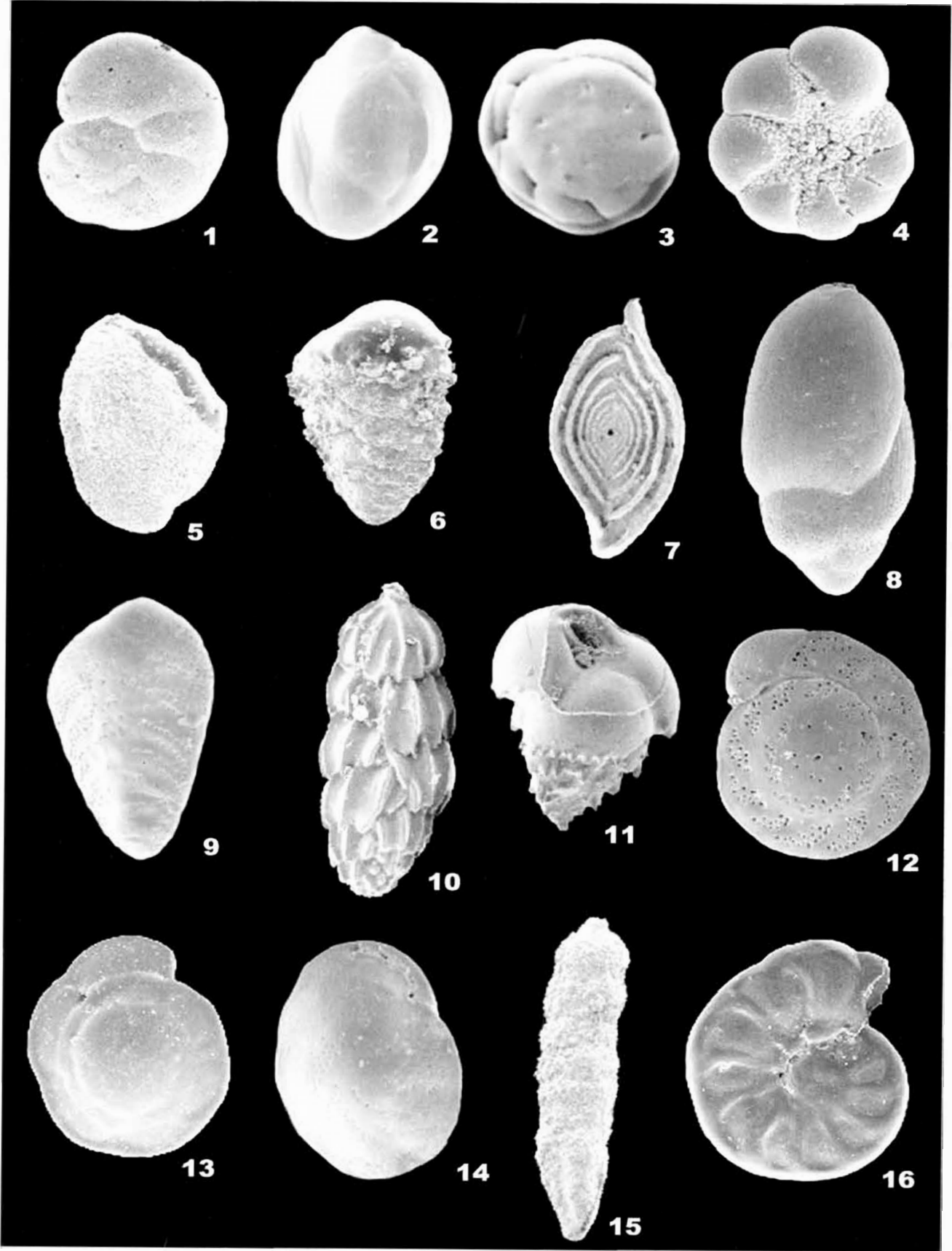
A high-resolution benthic and planktonic foraminiferal investigation connects these intervals to periods of sapropel deposition (Stefanelli *et al.*, in prep.). In particular, the discovery of FO event of *Gephyrocapsa* sp. 3 within the interval Sc (Maiorano *et al.*, submitted), which is entirely closed in the warm isotope stage 25 (Ciaranfi *et al.*, 2001), suggests to consider the sapropel event Sc corresponding to sapropel 19 (sapropel stratigraphy, from Kroon *et al.*, 1998), and to insolation-cycle 90 (1-cycle codification, from Lourens *et al.*, 1996).

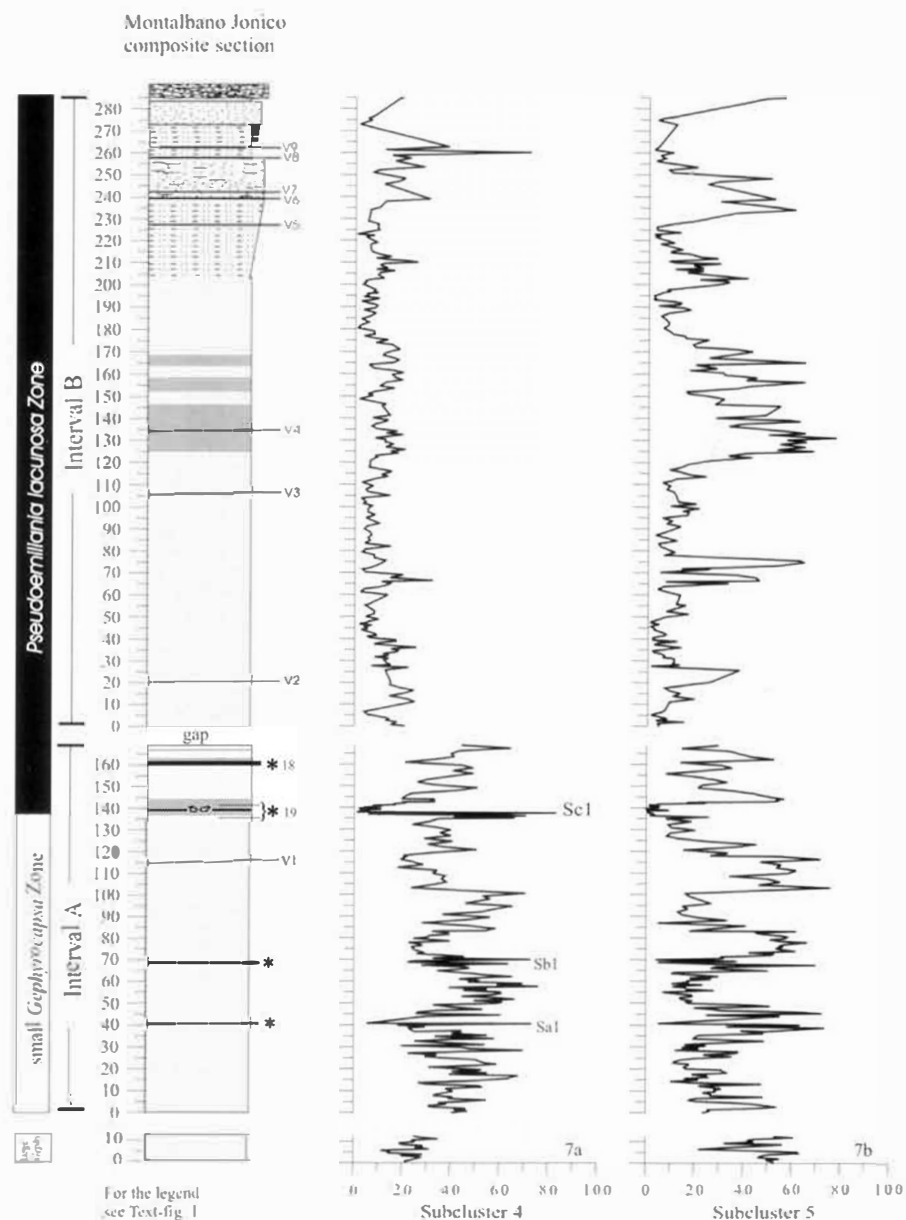
Elphidida, Miliolida and Discorbida, representative of subcluster 3, are common within the infralittoral – upper circalittoral fine sediments. They attain their maximum joint frequency at 50 m depth, and then they decrease, although remaining present, with a low number of specimens down to a 110 m depth. These taxa prefer environments, which are characterized by a minimum of stress, high oxygen content of the bottom-water, and stable salinities. Kaiho (1999) groups them among the high oxyc indicators (with $O_2 > 3,2$ ml/l). Therefore, subcluster 3 is indicative of a

EXPLANATION OF PLATE 1

- Fig. 1 - *Valvulineria* gr. (x 200).
- Fig. 2 - *Quinqueloculina* gr. (x 200).
- Fig. 3 - *Ammonia beccarii* (x 200).
- Fig. 4 - *Protelphidium granosum* (x 200).
- Fig. 5 - *Signoilepsis schlumbergeri* (x 200).
- Fig. 6 - *Textularia calva* (x 200).
- Fig. 7 - *Spiroloculina excavata* (x 200).
- Fig. 8 - *Globobulimina affinis* (x 200).

- Fig. 9 - *Bolivina dilatata* (x 100).
- Fig. 10 - *Uvigerina peregrina* (x 200).
- Fig. 11 - *Bulimina marginata* (x 200).
- Fig. 12 - *Cibicides pachyderma* (x 200).
- Fig. 13 - *Oridorsalis umbonatus* (x 200).
- Fig. 14 - *Cassidulina carinata* (x 200).
- Fig. 15 - *Bigenerina nodosaria* (x 500).
- Fig. 16 - *Hyalinea balthica* (x 200).





Text-figs. 7a, 7b - Cumulative plots of the two subclusters reflect variations in oxygen in deep waters. The subcluster 4 assemblage is considered to more depth-dependent than oxygen-dependent.

shallow and well-oxygenated environment. The graph of joint frequencies shows that the assemblage is abundant in Interval B and manifests a clear cyclic trend (Text-fig. 6c). When this graph is compared to the cumulative plots of subcluster 1, their opposing trends in abundance evidence cyclic oxygen fluctuations in Interval B.

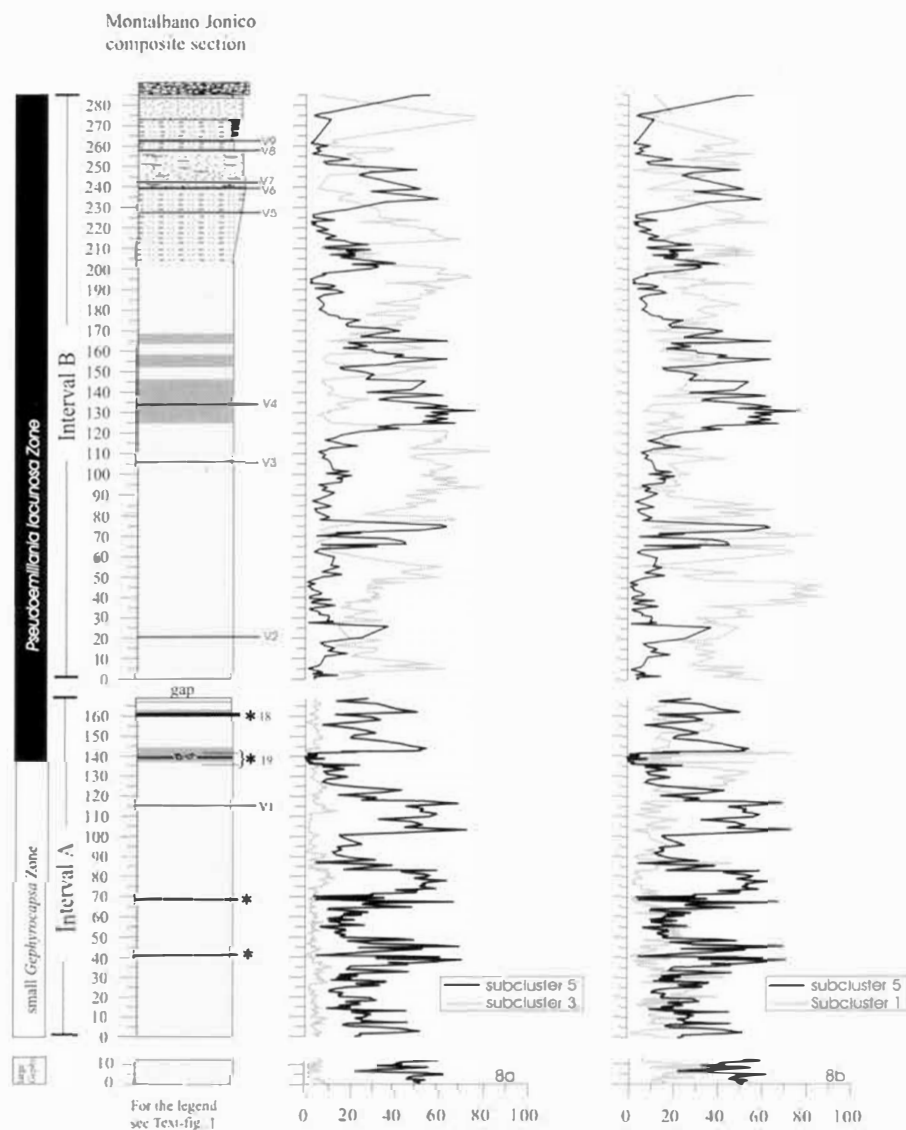
Paleoecological inferences from the subcluster 4 assemblage are less clear because the taxa, commonly distributed in deep waters, are indicative of varying oxygen regimes. Gooday (1994) considered *Gyroidina* sp. as living in well-oxygenated sediments, but Kaiho (1999) inserts it among the taxa preferring suboxic habitats. For some authors (Mullineaux & Lohmann, 1981; Katz & Thunell, 1984) this taxon

seems to prefer oxygen levels intermediate between oxic and suboxic conditions. The same inconsistencies exist for *H. balthica*, *B. marginata* and *G. subglobosa*: Kaiho (1999) inserts them among the forms present in low oxic sediments (with $O_2 > 1.2$ ml/l). *H. balthica* is, generally, related to the glacial period and consequently, to high oxygenation (Ross, 1984). Gooday (1994) inserts *G. subglobosa* among the species preferring a well-oxygenated environment and *B. marginata* in a poorly oxygenated environment. *G. affinis*, an infaunal taxon characteristic of dysoxic sediments (Kaiho, 1999; Jorissen, 1999) is present in the section with the same frequency as the others, excepting two samples (labelled Sb1 and Sc1, in Text-fig. 7a), in which this species is the only benthic

foraminifera present in an assemblage otherwise dominated by planktonic foraminifera. In detail, these intervals are immediately below those rich in *Bolivina* and labelled Sa, Sb and Sc. For several authors (Nolet & Corliss, 1990; Sen Gupta & Machain-Castillo, 1993; Jorissen, 1999), *G. affinis* is the taxon "most closely associated" with the Late Quaternary anoxia in the Mediterranean. They found that it was abundant immediately below, above and/or within sapropel layers. The qualitative analysis carried out on the planktonic foraminifera present in the assemblages, together with presence of *G. affinis*, links these intervals to periods of severe oxygen reduction, i.e. sapropels (Capotondi, pers. comm.). The high-resolution foraminiferal investigation relates these intervals to severest oxygen depletion phases in sapropel formation (Stefanelli *et al.*, in prep.). The cumulative plots show the dominance of

the fossil association of subcluster 4 in Interval A, thus indicating, over all, deep waters. However, the sole presence of taxa with infaunal microhabitat preferences leads to hypothesize low oxygen contents at the bottom.

Subcluster 5 consists of taxa that are indicators, generally, of deep stable marine water, which is rich in oxygen. Among them, *Uvigerina* "costate" group (in particular *U. peregrina*) tolerates stressed oxygen condition (Corliss, 1979b; Verhallen, 1991). The cumulative plots indicate that this assemblage is more abundant in Interval A, and less frequent in the middle part of Interval B, with the exception of two stratigraphic intervals, from 120 m to 165 m, and 225 m to 245 m (Text-fig. 7b). The comparison of the graphs of subcluster 5 and subcluster 3 indicates that the deposition of Entalina, Fosso Giuseppe, IM and Fosso 5 Agosto sections took place in a deep



Text-figs. 8a, 8b - Cumulative plots of subcluster 5, compared with subcluster 1 and subcluster 3. The direction of change of subcluster 5 opposes the direction of change of both subclusters 1 and 3 indicating the regressive trend of the sedimentary basin, the shallowing - deepening cycles, and the variation in oxygen content.

marine environment, while the remaining part of the succession (Venus Bassa, Dito del Diavolo, Ideale, Salvatore, Vecchietto and Molino sections) was deposited in a relatively shallower environment. In both sea level changes (rises and falls) are manifested (Text-fig. 8a). Then the comparison of subcluster 5 with subcluster 1 reveals that fluctuations in oxygen content also occur throughout the entire succession (Text-fig. 8b).

PRINCIPAL COMPONENT ANALYSIS

Elphidium spp. and *Q. seminula* are indicators of shallow marine waters; they are limited to a maximum depth of 100 - 130 m, with the highest frequency at 50 m downwards (Parker, 1958; Chierici *et al.*, 1962; Jorissen, 1988; Sgarrella & Moncharmont Zei, 1993). These taxa prefer well-oxygenated waters, although *C. decipiens* and *P. granosum* (group of *Elphidium* without keel) can tolerate stressed oxygen conditions. *S. bulloides*, *Gyroidina* spp., *C. ungerianus*, *Planulina* spp. and *C. pachyderma* are deep-water taxa; they are present with significant frequencies below depths of 100 - 120 m (Jorissen, 1988; Sgarrella & Moncharmont Zei, 1993). *Gyroidina* spp. is present below 150 - 200 m (Wright, 1978). *Cibicidoides* sp. is reported from 50 - 70 m downwards, but it is common in bathyal muds. *S. bulloides* occurs from 65 m downwards, but it is more frequent at depths greater than 120 m. *P. ariminensis* is abundant below 200 m.

Therefore, the taxa showing positive Factor 1 loadings, apparently, indicate a shallow marine environment (the upper circalittoral-lower infralittoral zone), while the taxa with negative loadings are indicative of deep marine waters (the lower circalittoral - upper bathyal zone). The graph of the sample scores of this factor (Text-fig. 9a) indicates that Interval A deposited in a deep marine environment, whereas Interval B deposited in a shallower environment. However, within both environments, several shallowing - deepening cycles are still detected, which confirms the results inferred from Hierarchical Cluster Analysis.

Cibicidoides spp. and *Elphidium* spp., loaded positively with Factor 3, have a preference for well-oxygenated sediments, the former in deep waters and the latter in shallow waters. *Valvulineria* spp., *B. marginata*, *B. alata* and *C. carinata*, loaded negatively, are infaunal taxa commonly present in poorly oxygenated environments, ranging from suboxic to dysoxic (Bergamin *et al.*, 1999; Kaiho, 1999).

Since Factor 3 is loaded by opposing indicators of oxygen, then this factor may be indicative of variations in bottom water oxygenation. The sample scores of Factor 3 (Text-fig. 9b) show an evident cyclic variation of oxygenation throughout the succession, which concurs with Hierarchical Cluster Analysis results. In the lowermost part of Interval B, from 35 m to 50 m, the sample scores of Factor 3 show the widest phase of "high" oxygenation.

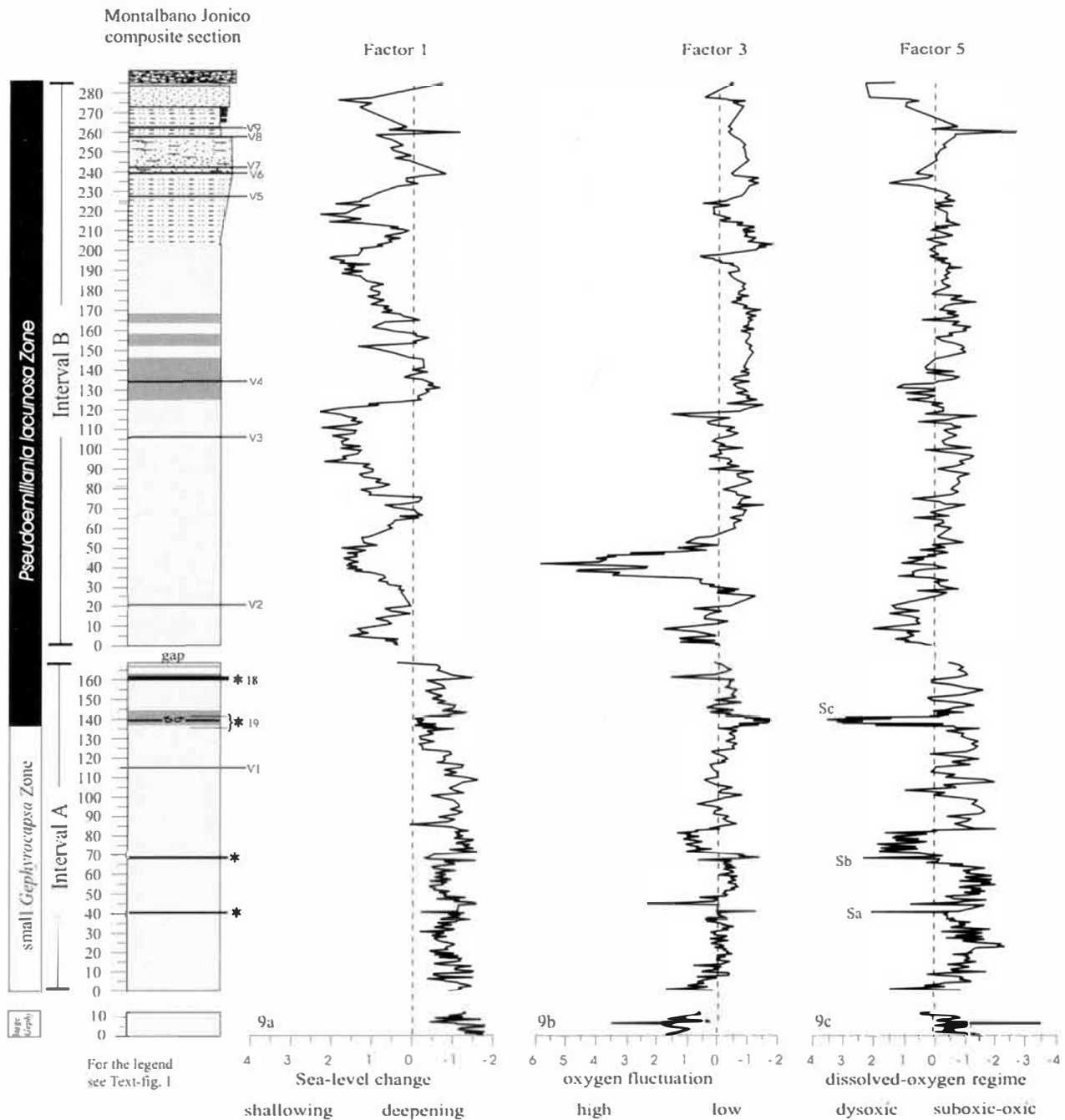
Focusing on the distribution patterns of the species in this stratigraphic portion, the presence of *Asterigerinata* spp. and *L. lobatula* is noteworthy, since these taxa are totally absent in the rest of Interval B. Murray (1991) reports *Asterigerinata* spp. and *L. lobatula* in the seagrass assemblages of whole Mediterranean at depth of 2 - 4 m. Therefore, in this part of Interval B, the sedimentary basin records its strongest regressive phase (Ciaranfi *et al.*, 2001). So, it is most likely that the presence of these displaced taxa, in addition to the others, could have distorted Factor 3 and amplified the signal.

Bolivina group and *B. spathulata*, loaded negatively with Factor 5, are dysoxic indicators, while most of the other taxa, loaded positively, are present in varying oxygen regimes, ranging from suboxic to oxic. On the basis of these data, Factor 5 seems to be indicative of extreme stressed oxygen conditions: in fact, the dysoxic peaks, clearly visible in the sample scores, occur at levels corresponding to the sapropel events Sa, Sb and Sc, evidenced in Hierarchical Cluster Analysis (Text-fig. 9c). The sapropel events Sa1, Sb1 and Sc1 are not identified because they have a different benthic faunal composition, being dominated by *G. affinis*.

Factor 2 and Factor 4 components have no clear significance since they are loaded, both positively and negatively, with taxa that are indicators of different environmental conditions. These components might indicate the interplay between depth and oxygenation: it is not possible to separate the influences of depth from oxygen or *vice versa* on the benthic foraminiferal assemblages during the deposition of the succession. The taxa that display high negative and positive loadings with Factor 2 and Factor 4, respectively, live in shallow and deep waters regardless of the levels of oxygenation. In Text-fig. 10, the sample scores of Factor 2 and Factor 4 are compared with the sample scores of Factor 1 and Factor 3. Factor 2, in Interval A, manifests a pattern similar to Factor 3, but opposite to Factor 1 (highlighted by thick line). Thus Factor 2 reflects, in the lower part of the succession, oxygen variations. In contrast, in Interval B, Factor 2 is of little or no significance for the paleoenvironmental reconstruction (marked by the thin line). Factor 4, in the Interval B, shows a trend similar to Factors 1 and 3 (denoted by the thick line), and thus reflects both depth and oxygenation, even if in the uppermost 50 m Factor 4 trends in the opposite direction to Factor 3. In Interval B, Factor 4 is of little or no significance for the paleoenvironmental reconstruction (marked by the thin line).

Consequently, if Factors 2 and 4 are indicators of the interplay between depth and oxygenation, then there is, presumably, a strong influence of depth on the distribution of benthic foraminifera in Interval B, while in Interval A oxygen plays the stronger role.

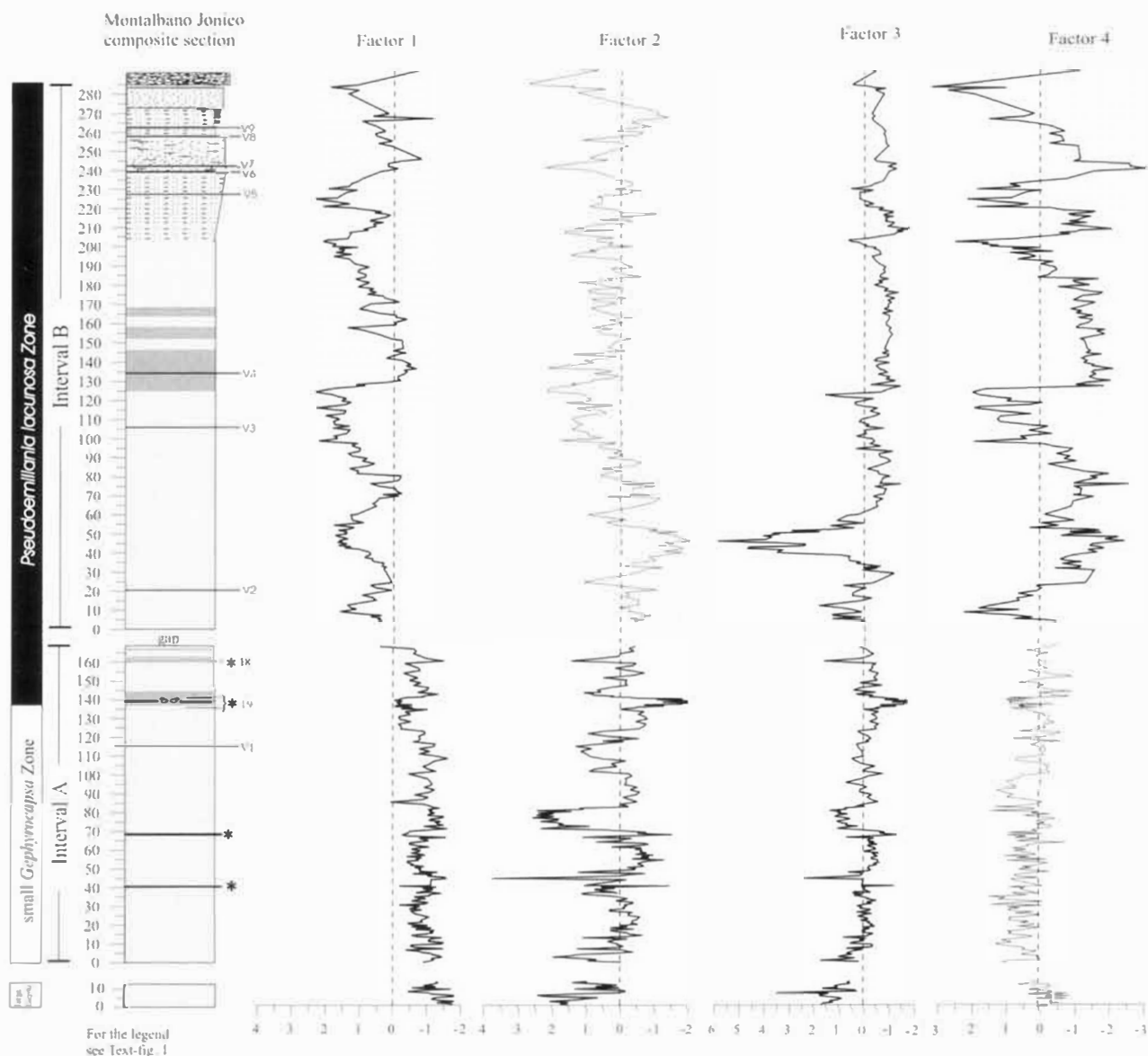
The calculated results according to the formula of van der Zwaan *et al.* (1990) support the already inferred shallowing trend of the succession, from the



Text-figs. 9a, 9b, 9c - The sample scores of the three factors extracted in Principal Component Analysis. Factor 1 is related to depth, Factor 3 and Factor 5 to oxygen. Factor 1 records rise and fall in sea level, which is more marked in Interval B. Factor 3 records cyclic oxygen fluctuation, which is more marked in the upper part of the succession. Factor 5 records intervals of severe oxygen reduction Sa, Sb and Sc, almost evidenced by the cumulative plots of subcluster 2.

bottom towards the top (Text-fig. 11). Interval A deposited in a deep marine environment with a depth-range of 500-100 m, which corresponds to the upper bathyal – lower circalittoral zone. Interval B deposited in a shallow environment, with a depth – range of 100-30 m corresponding to the upper circalittoral - lower infralittoral zone. *Entalina* results to

be the deepest section, with a depth range of 600-300 m. The shallowing – deepening cycles are less apparent in the cumulative plots, than in Hierarchical Cluster Analysis and in the PCA – analysis. Probably, the rises and falls in sea level may have been on the order of only 20-30 m, which is too small to be recorded by changes of the P/B ratio.



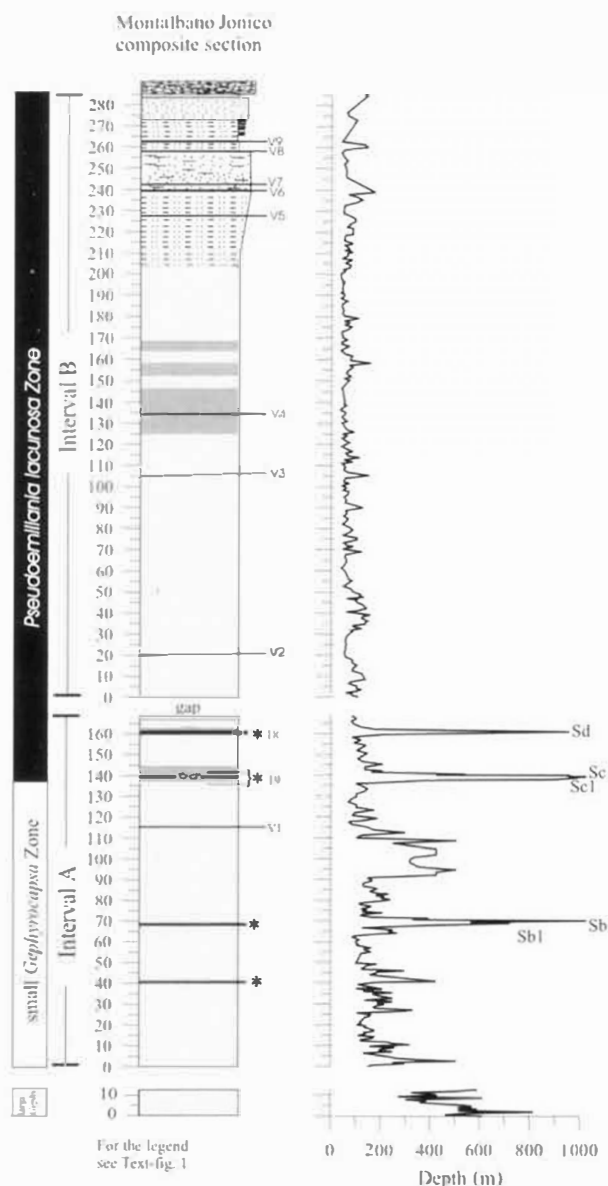
Text-fig. 10 - Factor 2 and Factor 4 are compared with Factor 1 and Factor 3. The trend of Factor 2 in Interval A is similar to Factor 3, but the inverse of Factor 1. Factor 4, in Interval B, shows a trend similar to Factor 1 and Factor 3. Factor 2 and Factor 4 may be related to an interplay between the influence of depth and oxygen upon the benthic foraminiferal assemblages.

The sapropel layers S_b and S_c, as well as a fourth layer, S_d, which was not evidenced in Cluster and PCA analyses, are also visible. In interval S_d, the benthic foraminiferal fauna are extremely rare (only 74 individuals counted, 51 of which belong to genus *Bolivina*) and planktonic foraminifera dominate the assemblage. Probably, the scarce presence of benthic taxa has made it difficult for this layer to be discerned in the statistical analyses. The discovery of LCO event of *Reticulofenestra asanoi* in this interval (Maiorano *et al.*, submitted), which is entirely closed in the warm isotope stage 23 (Ciaranfi *et al.*, 2001), suggests to consider the sapropel event S_d corresponding to sapropel 18 (sapropel stratigraphy, from Kroon *et al.*,

1998), and to insolation-cycle 88 (I-cycle codification, from Lourens *et al.*, 1996).

DISCUSSION

Two principal marine domains, the upper bathyal – lower circalittoral zone and the upper circalittoral zone, are defined on the basis of the benthic foraminifera faunal composition. The predominance of deep benthic foraminifera in Interval A indicates its deposition in the deeper domain. The predominance of shallow benthic taxa in Interval B indicates a shallower depositional environment. Within this setting, the Entalina section represents the deepest part of the

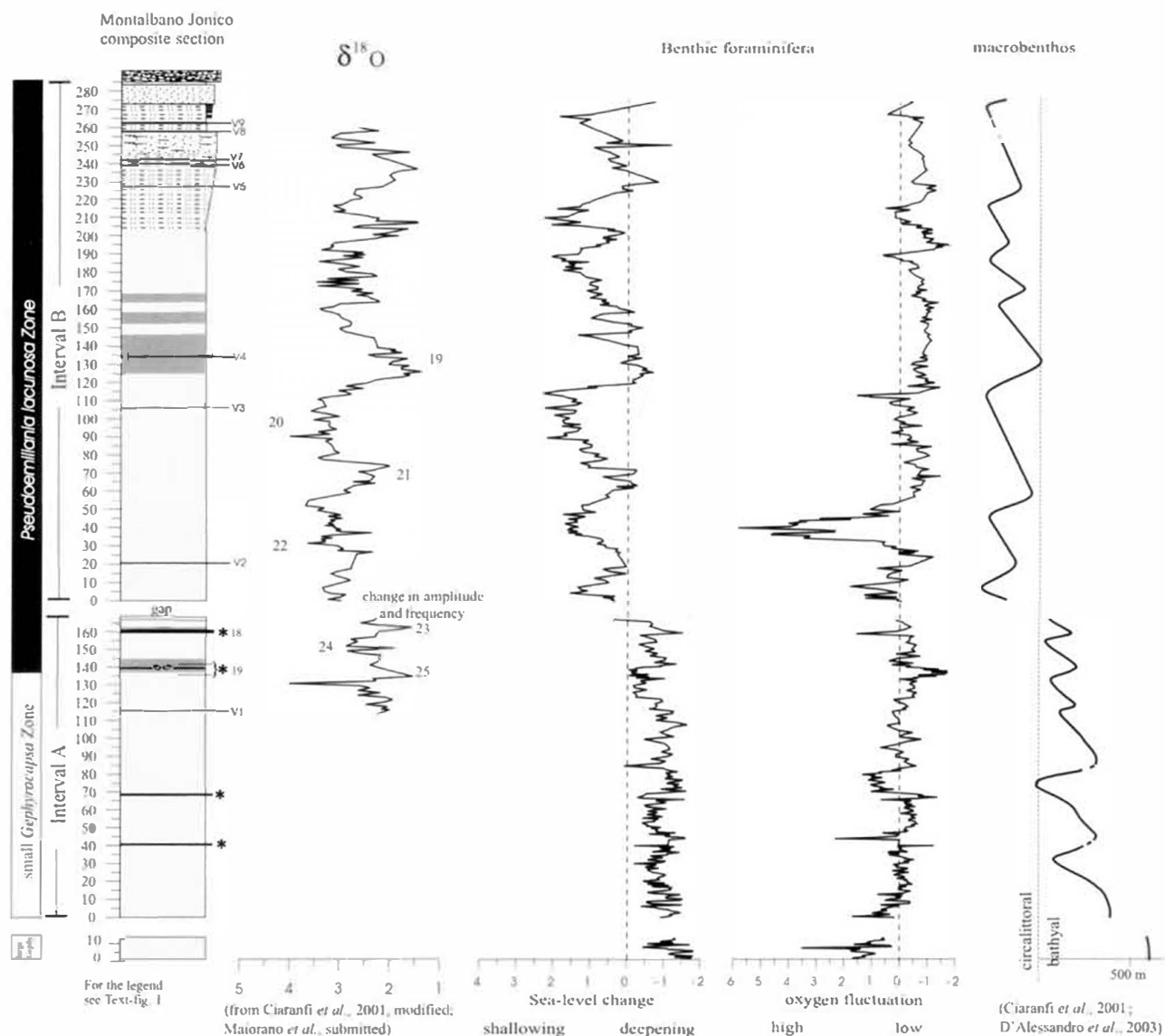


Text-fig. 11 - The paleobathymetric reconstruction of the sedimentary basin, in which the succession was deposited. The graphed trend indicates the regressive evolution of the sedimentary basin, with depth – changes from 500 m to 50 m, and the intervals of sapropel deposition (Sb1, Sb, Sc1, Sc and Sd).

Montalbano Jonico composite succession, while the Venus Bassa section represents the beginning of the shallowing trend. The passage from deep to shallow waters appears abrupt, but this interpretation may depend on the lack of continuous deposition represented by the gap. Principal Component Analysis indicates that changes in sea-level occurred several times during deposition of the section, evidencing regular alternations between shallowing and deepening phases. Concurrently, there is an alternating dominance of the oxic and suboxic indicators, which is interpreted as

a cyclic variation in oxygen content at the bottom-water interface, and in the sediment pore-water. In the deep part of the succession, severe oxygen depletions are recorded and interpreted as sapropel events because of the dominance of certain opportunistic species.

Depth and oxygen show cyclic trends throughout the whole section, which is evident in the graphs derived from the Cluster and PCA analyses, but most clearly represented in Factors 1 and 3. Cyclicality seems more marked in Interval B than in Interval A. The cyclicality observed in Montalbano Jonico composite section could be related to different patterns of climatic and sea-level change, in the early and middle Pleistocene times, since the lower deposits are in the “small” *Gephyrocapsa* Zone and the upper deposits lie entirely within the *Pseudoemiliania lacunosa* Zone. The early Pleistocene is, in fact, characterized by low amplitude glacial/interglacial cycles, while the middle Pleistocene shows periods of high amplitude $\delta^{18}\text{O}$ fluctuations, with longer and more marked glacial/interglacial cycles. As reported in the literature, a striking change in the amplitude and frequency of glacial-interglacial cycles occurs around the oxygen isotope stages 22 and 23 (Shackleton & Opdyke, 1973). In the oxygen isotope record for the section (Ciaranfi *et al.*, 2001), partially numbered (Maiorano *et al.*, submitted), stage 23 is recorded immediately below the gap and stage 22 immediately above it (Text-fig. 12). Benthic invertebrate communities also record the sedimentary cyclicality in the section. Benthic invertebrates recognize two fourth-order cycles (Interval A and Interval B), which appear to tectono-eustatic causes. However, in Interval B the climate signal appear to prevail over the tectonic signal (Ciaranfi *et al.*, 1997; 2001; D'Alessandro *et al.*, 2003). The benthic foraminiferal and oxygen isotope record, when compared with the benthic invertebrate record, confirms this hypothesis. In Interval B, the shallowing phases correspond to high oxygen and “cold” stages, whilst the deepening phases correspond to low oxygen and “warm” stages. In Interval A the patterns are less clear because the cycles have smaller amplitudes. However, oxygenation levels and sea-level fluctuations show inverse correlations: the shallowing phases correspond to low oxygenation. This phase shift could be related to tectonic pulses tightly linked to changes in the geodynamic regime in the evolution of Apennine Foretrench during the early Pleistocene (Ciaranfi *et al.*, 1979). Therefore, the cycles in the deep part of the section are believed to be tectono-eustatic in origin (Ciaranfi *et al.*, 1997). The $\delta^{18}\text{O}$ variations might be caused not only by temperature changes, but also by changes in major river inputs. Several sedimentological signals of episodic mass transports have been recorded in this part of succession. This could explain the two different phases (“warm” and “cold”) that correspond to the low oxygenation phase found at the base of isotope record, immediately above V1.



Text-fig. 12 - The oxygen isotope record that is presently available for Montalbano Jonico section. The striking change in the amplitude and frequency of the climate changes occurs at stages 22 and 23, in accordance with the literature. The sedimentary cyclicity of the section is also interpreted by macrobenthos paleocommunities. The integration of the data allows us to relate cyclicity to tectonoclastic causes, in Interval A, and to glacio-eustatic control, in Interval B.

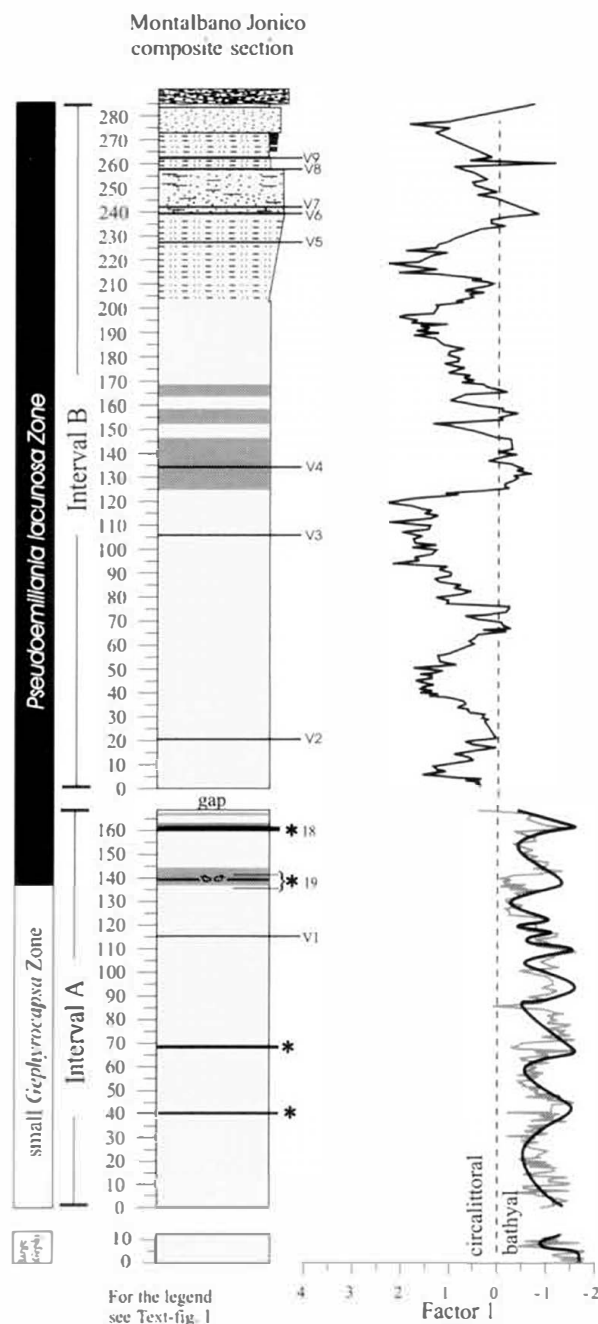
It is interesting to note that benthic foraminifera, in the stratigraphic intervals corresponding to the sapropels, record a shallowing phase. On the contrary, benthic invertebrates record a deepening phase. The signal of Factor 1 could, probably, have been distorted by the influence of oxygen. Since of the severe oxygen reduction at the time of sapropel formation, all the benthic foraminifera disappeared, with the exception of *Bolivina* and *Globobulimina*. This hypothesis is consistent with the interpretation that Factors 2 and 4 represent a strong influence of oxygen during the deposition of the deep part of the Montalbano Jonico composite section.

Finally, the consideration of oxygen influence on

the bathymetry, in association with the observations on benthic foraminiferal faunal composition, have allowed the extraction of a final curve of paleodepth for Interval A of the Montalbano Jonico composite section, marked by the black line in Text-fig. 13.

CONCLUSIONS

Hierarchical Cluster Analysis and Principal Component Analysis are two good methods for the extrapolation of detailed information from a large, multivariate and heterogeneous data set. These methods, applied to the study of the early-middle Pleistocene benthic foraminiferal assemblages, have



Text-fig. 13 - Curve of paleodepth extrapolated for Interval A, by studying the benthic foraminifera faunal composition.

allowed the reconstruction of the paleoenvironmental features of Montalbano Jonico composite section.

Data analysis shows primarily the strong dependence of benthic foraminifera upon depth and oxygen concentration. These two parameters regulated both faunal composition and the distribution of the assemblages in the studied section. The most striking change in faunal composition is recorded at the tran-

sition from the lower circallittoral zone to the upper circallittoral zone. The shallow taxa, at about 100-110 m of depth, replace the deep taxa thus highlighting the changes in depositional environment.

Variations in faunal benthic composition are also recorded when the oxygen regimes changed. Drastic variations are recorded when the oxygen content fell to 0.3 ml/l: many taxa disappeared and only the opportunistic species, generally two or three, survived.

Benthic foraminifera have recorded the cyclic change of these environmental parameters during the deposition of the early - middle Pleistocene sedimentary succession. Together with oxygen isotope and benthic invertebrate records, benthic foraminifera showed that in the first 180 m of the succession, the cycles could well have been caused by tectono-eustatic changes, while in the upper part the cycles may be related to eustatically controlled cyclicity.

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APPENDIX A

List of the benthic foraminifera recognized in the Montalbano Jonico composite section.

1. *Ammonia beccarii* (Linneo, 1758) [Pl. 1, Fig. 3, x 200]
2. *Amphicoryna scalaris* (Batsch, 1791)
3. *Asterigerinata* gr. Within this taxonomic group are included *Asterigerinata mamilla* (Williamson, 1858) and *Asterigerinata adriatica* Haake, 1977.
4. *Bigennerina nodosaria* (d'Orbigny, 1926) [Pl. 1, Fig. 15, x 500]
5. *Bolivina* gr. Within this taxonomic group are included *Bolivina dilatata* Reuss, 1850 [Pl. 1, Fig. 9, x 100] and *Bolivina alata* (Seguenza, 1862)
6. *Bolivinita quadrilatera* (Schwager, 1866)
7. *Bolivina spathulata* (Williamson, 1858)
8. *Bolivina subspinescens* Cushman, 1922
9. *Buccella granulata* (Di Napoli Alliata, 1952)
10. *Bulimina costata* d'Orbigny, 1852
11. *Bulimina* cf. *Bulimina elegans* d'Orbigny, 1826
12. *Bulimina elongata* d'Orbigny, 1846
13. *Bulimina marginata* d'Orbigny, 1846 [Pl. 1, Fig. 11, x 200]
14. *Bulimina sublimbata* Panizza, 1967
15. *Cassidulina carinata* Silvestri, 1896 [Pl. 1, Fig. 14, x 200]
16. *Lobatula lobatula* (Walker & Jacob, 1798)
17. *Cibicidoides pachyderma* (Rzehak, 1886) [Pl. 1, Fig. 12, x 200]
18. *Cibicides refulgens* de Montfort, 1808
19. *Cibicidoides ungerianus* d'Orbigny, 1846
20. *Cornuspira* gr. Within this taxonomic group are included: *Cornuspira carinata* (Costa, 1856) and *Cornuspira involvens* (Reuss, 1850)
21. *Criboelphidium decipiens* (Costa, 1856)
22. *Dentalina* gr. Within this taxonomic group are included: *Dentalina* spp. (most representative are *Dentalina legumini-formis* (Batsch, 1791) and *Dentalina inflexa* (Reuss, 1866)). *Saracenaria italica* (DeFrance, 1824), *Nodosaria* spp. (rare) and *Marginulina* spp. (rare)
23. *Elphidium advenum* (Cushman, 1822)

24. *Elphidium complanatum* (d'Orbigny, 1839)
 25. *Elphidium crispum* (Linneo, 1758)
 26. *Globobulimina affinis* (d'Orbigny, 1839) [Pl. 1, Fig. 8, x 200]
 27. *Globocassidulina subglobosa* (Brady, 1881)
 28. *Gyroidina* gr. Within this taxonomic group are included: *Gyroidina neosoldanii* (Brotzen, 1936) and *Gyroidina umbunata* (Silvestri, 1898)
 29. *Hanzawaia rhodiensis* d'Orbigny, 1839
 30. *Hyalinea balthica* (Schroeter, 1783) [Pl. 1, Fig. 16, x 200]
 31. *Hoeglundina elegans* (d'Orbigny, 1826)
 32. *Lenticulina* gr. Within this taxonomic group are included: *Lenticulina orbicularis* (d'Orbigny, 1826), *Lenticulina calcar* (Linneo, 1758) and *Lenticulina inornata* (d'Orbigny, 1846)
 33. *Melonis barleanum* (Williamson, 1858)
 34. *Melonis soldanii* (d'Orbigny, 1846)
 35. *Nonion depressulum* (Walker & Jacob, 1798)
 36. *Oridorsalis umbonatus* (Reuss, 1851) [Pl. 1, Fig. 13, x 200]
 37. *Orthomorphina stainforthi* (Pecornig, 1955)
 38. *Planulina ariminensis* d'Orbigny, 1826
 39. *Protelphidium granosum* (d'Orbigny, 1846) [Pl. 1, Fig. 4, x 200]
 40. *Pullenia* gr. Within this taxonomic group are included: *Pullenia bulloides* (d'Orbigny, 1846) and *Pullenia quinqueloba* (Reuss, 1851)
 41. *Pyrgo* gr. Within this taxonomic group are included: *Pyrgo depressa* (d'Orbigny, 1826) and *Pyrgo bulloides* (d'Orbigny, 1826)
 42. *Quinqueloculina* gr. This taxonomic group is predominantly dominated by *Quinqueloculina seminula* (Linné, 1758) [Pl. 1, Fig. 2, x 200]
 43. *Reussella spinulosa* (Reuss, 1850)
 44. *Rosalina* gr. Within this taxonomic group are included: *Rosalina floridana* (Cushman, 1915), *Rosalina globularis* d'Orbigny, 1826, *Rosalina brady* (Cushman, 1915) and *Discorbis* spp.
 45. *Signoilopsis schlumbergeri* (Silvestri, 1904) [Pl. 1, Fig. 5, x 200]
 46. *Spiroloculina excavata* d'Orbigny, 1846 [Pl. 1, Fig. 7, x 200]
 47. *Sphaeroidina bulloides* d'Orbigny 1826
 48. *Stainforthia complanata* (Egger, 1893)
 49. *Stilostomella* gr. This taxonomic group is represented exclusively by *Stilostomella monilis* (Silvestri, 1872)
 50. *Textularia* gr. Within this taxonomic group are included: *Textularia calva* Lillicker, 1935 [Pl. 1, Fig. 6, x 200] and *Textularia soldanii* Fornasini, 1883
 51. *Trifarina angulosa* (Williamson, 1858)
 52. *Uvigerina* "costate" gr. Within this group are included: *Uvigerina mediterranea* Hofker, 1932 and *Uvigerina peregrina* Cushman, 1923 [Pl. 1, Fig. 10, x 200]
 53. *Valvulineria* gr. [Pl. 1, Fig. 1, x 200] Within this taxonomic group are included: *Valvulineria complanata* (d'Orbigny, 1846) and *Valvulineria bradyana* (Fornasini, 1900).
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