LATE-QUATERNARY PALEOENVIRONMENTAL RECONSTRUCTION
OF SAN BENEDETTO DEL TRONTO COAST (CENTRAL ADRIATIC SEA)
BY BENTHIC FORAMINIFERAL ASSEMBLAGES

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ABSTRACT - Detailed analyses carried out on the benthic foraminiferal assemblages of the late-Quaternary core VSB01/7 from the central Adriatic continental shelf, have led to a paleoenvironmental reconstruction of the area. Benthic foraminifera are used as tools to reconstruct the environmental changes that occurred during the Holocene sea-level rise. The statistical analysis singled out four assemblages corresponding to just as many benthic environments that, from the bottom of the core to the top, revealed a deepening trend.

The present ecological distribution of the most frequent taxa is used together with the statistical analysis in order to define the temporal distribution of four different biofacies. From the core bottom to the top, biofacies IV is indicative of a coastal lagoon influenced by fresh-waters and river run-off. Biofacies III shows a facies deepening to a prodelta environment where the river influence is less strong and more marine conditions start to stabilize. Biofacies II represents an infralittoral, vegetated environment abruptly replaced by the modern outer mud-belt environment (biofacies I). On the whole this biofacies shows eutrophic conditions and oxygen stress at the sea floor, as suggested by the occurrence of typical opportunistic species (e.g. Cassidulina carinata, Globocassidulina subglobosa, Bolivina catanensis and Bolivina spathula). In fact, during the sea-level rise the factors that influence the foraminifera distribution the most are the increasing water depth and the proximity of a river run-off system; whereas, during the highstand the foraminifera distribution is influenced by the oxygenation and by the trophic conditions.

Furthermore, a condensed deposition between biofacies II and I is evidenced by the lack of intermediate stages between the infralittoral and the circalittoral assemblages. A paleo-bathymetric reconstruction was also performed in order to reconstruct the sea-level variations.

KEY WORDS: foraminifera, late-Quaternary, Holocene, mud-belt, Adriatic Sea.

INTRODUCTION

The sea-level oscillations particularly influence continental shelf margins which connect the coastal areas to the deeper part of the basins. In the Adriatic Sea, because of the extension of the continental shelf and the shallow depth, these oscillations are very well recorded as demonstrated by numerous studies. During the Last Glacial Maximum the majority of the basin was emersed and an alluvial plain extended up to the middle-Adriatic deep (Asioli, 1996). The flooding of the alluvial plain and the horizontal transfer of the coastal deposits have occurred since 17 kyr, with the post-glacial transgression (Steckler et al., 2007). Furthermore, the Adriatic basin is one of the coastal areas with a major risk, where a sea-level rise may cause damage to human activities and where the trophic unbalance (resulting in algal blooming episodes) has already damaged tourism and fishery activities. Although the last transgression has been well studied from a sedimentological point of view (Trincardi et al., 1994; Correggiari et al., 2001; Gordini et al., 2002; Cattaneo et al., 2003; Steckler et al., 2007), studies concerning the history of the Holocene sea-level (Lambeck et al., 2004) and the relation between Holocene highstand deposits and microfauna are still scarce (Asioli, 1996; Asioli et al., 2001; Morigi et al., 2005).

Within these considerations, in this paper the study of a late-Quaternary core is addressed to reconstruct the environmental changes which occurred in the middle-Adriatic continental shelf during the Holocene sea-level rise. Recent benthic foraminiferal assemblages have been well investigated in the Adriatic basin (Jorissen, 1987,1988; Albani & Serandrei Barbero, 1990; Barmawidjaja et al., 1992; De Stigter et al., 1998; Serandrei-Barbero et al., 1999; Donnici & Serandrei Barbero, 2002; Duijnstee et al., 2004; Panieri, 2006; Albani et al., 2007). Although benthic foraminiferal assemblages have been utilized in the study of the late-Quaternary evolution in the northern part of the Adriatic Sea (Fiorini, 2004; Morigi et al., 2005; Serandrei-Barbero et al., 2005; Curzi et al., 2006; Amorosi et al., 2007), on the other side, they have been poorly employed in the definition of the late-Quaternary continental shelf evolution in the central and southern part of the basin (Jorissen et al., 1993). In this paper benthic foraminifera have been used as a tool for the paleoenvironmental reconstruction because they allowed us to identify typical assemblages, recognizable along the entire Italian coast of the Adriatic Sea under the influence of the Po and Apennines rivers inputs in the
present day as in the past. Preliminary results have been achieved regarding the study of the sea-level rise, the characterization of the different environments related to the facies deepening and the mechanisms of the formation of the mud-belt. Further results could come from the detailed study of the mineralogical component of the sediment and from AMS dates, allowing for the definition of an age model.

GEOMORPHOLOGICAL AND GEOLOGICAL SETTING

The Adriatic Sea is an epicontinental basin orientated NW/SE and located in the central Mediterranean. The western side of the northern and central Adriatic is a foredeep basin formed during the Apennines orogenesis (Royden et al., 1987). During the Pleistocene-Holocene sea-level rise, the alluvial plain that formed during the Glacial period was progressively drowned, resulting in a widening of the Adriatic shelf area (Trincardi et al., 1994; Correggiari et al., 1996; Cattaneo & Trincardi, 1999). The Adriatic basin shows a low axial topographic gradient (ca.0.02°) in the north and a steeper shelf to the south (Cattaneo et al., 2007). The late-Holocene clinoform, on the Adriatic shelf, reaches 35 m in thickness and rests above a regional downlap surface dated ca. 5.5 cal kyr BP (Cattaneo et al., 2003; Ridente & Trincardi, 2005). The central Adriatic is characterized by a narrower shelf compared to that of the Northern Adriatic, and it reaches a maximum depth of 270 m in the Middle Adriatic Depression (MAD) (Ciaubatti et al., 1987). The sediment supply is produced along the western and northern sides of the basin by several rivers located in the eastern Apennines (32.2 x10^6 t yr^-1 of sediments), the Po river catchment (15 x10^6 t yr^-1 of sediments) and the eastern Alpine rivers (3 x10^6 t yr^-1 of sediments). The rivers located south of the Gargano promontory also contribute with 1.5 x10^6 t yr^-1 of sediment supply (Sorgente, 1999; Cattaneo et al., 2003). The drainage area of the eastern Apennines rivers is less than half of that of the Po river, whereas their sediment load is greater: the flood dominated Apennines rivers have the highest sediment yield of the region (Cattaneo et al., 2003). Sediment transport from the Po river delta along the western Adriatic margin is affected by the circulation patterns. The circulation in the Adriatic Sea is characterized by a cyclonic gyre driven by thermohaline currents and is highly variable with seasons (Artegiani et al., 1997; Poulain, 2001). Three water masses are present in the Adriatic Sea (Paschini et al., 1993): the Adriatic Surface Water (AdSW), a superficial temperature-mixed layer (0-30 m), mainly originated by the Po river run-off; the Levantine Intermediate Water (LIW), layer 30-130 m deep; and the Adriatic Deep Water (AdDW), a bottom water, >130 m deep (Orlic et al., 1992; Artegiani et al., 1997). Furthermore, three main components to this circulation can be recognized: river forcing, causing heat loss and low salinity water gain; wind forcing at the surface, producing deep-water masses and seasonal changes in circulation; and Otranto channel forcing that balances the fresh-water discharge and the cooling of the water by introducing warm salty water (Artegiani et al., 1997).

MATERIALS AND METHODS

A foraminiferal analysis was carried out on the sediments from the core VSB01/7 (318 cm length), collected in the central Adriatic Sea near the San Benedetto del Tronto coast (LAT. 42° 52.230' and LONG. 14° 29.1391'; 145.40 m water depth). The core was drilled during the oceanographic cruise “Trenti 2001” (Fig. 1) which was directed towards the localization and characterization of sandy deposits to utilize in the nourishment of eroded littorals. The lithological description of the core is summarized in Fig. 2. Two main lithological units can be recognized: the lower unit (from the bottom to 60 cm) is characterized by fine sands with scarce silty-clayey matrix, the upper unit, from -59 to -40 cm, consists of clayey-silt rich in bioclasts, followed by silty-clay rich in organic matter, from -39 cm to the core top. The preparation of fossil samples followed a standard technique: 32 samples (1 cm thick) were collected at 10 cm intervals and numbered indicating the depth in centimeters from the core top. The sediment was washed over a 63 µm sieve and dried at 50°C. On the >63 µm fraction, quantitative and qualitative analyses of benthic foraminifera were performed. All the samples were split in aliquots containing at least 300 benthic foraminifera, which were subsequently picked, identified and counted. The generic attribution was based on Loeblich & Tappan (1987) and every species was determined on the basis of studies carried out on the Mediterranean benthic foraminifera (Cimerman & Langer, 1991; Sgarrella & Monchamont Zei, 1993; Fiorini & Vaiani, 2001).

Results of quantitative analyses were treated using the statistical software SPSS 12.0.1. The Q-mode Hierarchical Cluster Analysis was performed on the
benthic assemblage in order to define groups of samples attributable to distinct environments. In order to simplify the matrix, only the 26 species more abundant than 5% in at least one sample were considered significant for the statistical analysis (Patterson and Fishbein, 1989; Fishbein and Patterson, 1993). For the Q-mode HCA, distance is given by the squared Euclidean distance and the Ward method is used to calculate the similarities of the new fused clusters (Pielou, 1984; Parker & Arnold, 1999); this hierarchical method is widely used because it is designed to optimize the minimum variance within clusters. Principal Component Analysis (PCA) was carried out taking into account the first two components in order to examine the relationships among the variables.

On the basis of the Recent bathymetrical distribution of the 26 benthic foraminiferal species used for the cluster analysis, a paleo-bathymetric reconstruction was performed in accordance with Morigi et al., 2005. This approach allowed us to calculate the Estimated Water Depth (EWD) for each sample on the basis of this formula:

$$EWD = \frac{\sum (P_x \times MWD_x)}{\sum P_x}$$

where $P_x$ is the percentage of the species in each of the $i$ samples, and $MWD_x$ is the Mean Water Depth of each $x$ species. The MWD was calculated following the database proposed by Jorissen (1988); for some species (e.g. *Epistominella vitrea*) not mentioned in this database, the MWD was calculated taking into account several papers concerning the distribution of Recent foraminifera in the Adriatic Sea (Barmawidjaja et al., 1992; Duijnstee et al., 2004; Serandrei-Barbero et al., 2005; Ernst et al., 2005).

**RESULTS**

A total of 143 benthic foraminifera species, belonging to 65 genera, and 7 planktonic foraminifera species were identified in the studied samples. Planktonic foraminifera are always very scarce and are found only in the upper part of the core. The planktonic foraminiferal assemblage principally consists of *Globigerina bulloides*, *Globigerinoides ruber*, *Orbulina universa* and *Globigerinoides trilobus*.

**Hierarchical Cluster Analysis**

The Q-mode Hierarchical Cluster Analysis (Fig. 3) was performed on the benthic assemblage in order to cluster the samples characterized by similar ecological conditions. Two clusters have been well distinguished: cluster A characterized by circalittoral species and cluster B characterized by infralittoral ones. Cluster B can be furthermore subdivided, although at a different hierarchical level, into three distinct subclusters corresponding to just as many foraminiferal assemblages. In Fig. 4, the
Fig. 3 - Dendrogram resulting from the Q-mode Cluster Analysis. Two clusters (A and B) and three sub-clusters (B1, B2 and B3) are singled out.

downcore distribution of the percentages of the main taxa is plotted along the vertical biofacies distribution.

- Cluster A (from -5 to -65 cm)
  Dominant taxon: *Cassidulina carinata* (9.2-19.9%)
  Accompanying taxa: *Globocassidulina subglobosa* (8.2-16.7%); *Bolivina spathulata* (1.0-15.1%); *Gavelinopsis praegeri* (3.9-7.8%); *Epistominella vitrea* (1.0-7.0%); *Bolivina catanensis* (2.4-8.2%) and *Uvigerina mediterranea* (1.0-7.2%).

A typical circalittoral assemblage composes this cluster. The high values of *C. carinata* and *Bolivina* spp. are typical of an area with high organic flux at the sea floor. In the Adriatic Sea, *C. carinata* is described as a superior competitor for food in oxygen-rich surface microhabitats (De Stigter et al., 1998). Furthermore, the abundance of *Bolivina* spp. could be related to a periodical oxygen-stress due to the organic matter flux. Concerning *E. vitrea*, an infaunal taxon very abundant in muddy sediments, laboratory experiments demonstrated that this species proliferates in eutrophic conditions, but it is negatively influenced by the oxygen depletion (Ernst et al., 2005).

- Cluster B1 (from -75 to -155 cm; -235 cm)
  Dominant taxa: *Cycloforina* spp. (1.9-11.4%); *Neoconorbina* spp. (1.9-9.6%);
  Accompanying taxa: *Miliolinella subrotunda* (2.9-9.5%); *Asterigerinata* spp. (0-10.4%); *Protelphidium granosum* (3.3-5.2%); and *Lobatula lobatula* (2.2-6.6%).

In this infralittoral assemblage epiphytic taxa are dominant. *Cycloforina* spp. (mainly *C. tenuicollis* and *C. villafranca*) are representative of shallow waters. They are commonly found in 5-10 m water depth in the Northern Adriatic (von Daniels, 1970) and on detritic bottoms (Fiorini & Vaiani, 2001). *L. lobatula*, *Neoconorbina* spp. and *Rosalina bradyi* are typical of infralittoral environments with vegetation cover (Langer, 1993; Sgarrella & Moncharmont Zei, 1993). *M. subrotunda* is found in the Venice area, mainly in the gulf zone (Fiorini & Vaiani, 2001) and it also occurs locally as epiphytic (Langer, 1993).

- Cluster B2 (from -165 to -225 cm; from -245 to -255 cm)
  Dominant taxon: *Ammonia parkinsoniana* (8.2-13.4%)
  Accompanying taxa: *P. granosum* (6.9-17.4%); *Elphidium poeyanum* (4.9-13.8%); *Quinqueloculina pygmaea* (3.6-7.3%); *Aubignyna perlucida* (2.7-9.9%) and *Neoconorbina* spp. (0.9-8.7%).

In this cluster *A. parkinsoniana* frequencies are always high and this species dominates the assemblage together with *P. granosum*. *A. parkinsoniana* indicates local fresh-waters run-off in marine settings. *P. granosum* and *E. poeyanum* indicate a marine, well-oxygenated infralittoral environment enriched in organic matter (Jorissen, 1988). *P. granosum* is also abundant in fine sediments and it is recorded in circalittoral muds down to 100 m water depth (Albani and Serandrei Barbero, 1990; Bellotti et al., 1994; Coppa et al., 1994). In the northern Adriatic Sea and at the modern Po delta, similar assemblages are found at 10-20 m water depth (Jorissen, 1988; Albani & Serandrei Barbero, 1990). This assemblage records a high fluvial influence and can be considered as a typical prodelta assemblage (Curzi et al., 2006).

- Cluster B3 (from -265 to -315 cm)
  Dominant taxon: *A. parkinsoniana* (16.0-23.7%)
  Accompanying taxa: *A. perlucida* (11.3-17.9%); *E. poeyanum* (8.5-13.2%); *P. granosum* (3.5-9.4%); *Pseudotriloculina oblonga* (1.9-8.9%); *Haynesina depressula* (1.8-6.3%) and *Ammonia tepida* (1.8-5.4%).

*A. parkinsoniana* and *A. perlucida* are the dominant species occurring in every sample of this cluster with high percentages. Considering the average frequencies, *A. parkinsoniana* increases from 11.3% (Cluster B2) to 20.3% (Cluster B3); *A. perlucida* increases from 4.8% (Cluster B2) to 14.0% (Cluster B3). *A. parkinsoniana*, *A. tepida* and *A. perlucida* live in shallow waters (10 and 20 m water depth) and tolerate low and variable salinity (Jorissen, 1987; Albani & Serandrei Barbero, 1990). *A. tepida* occurs in rich populations in the Venice Lagoon (Serandrei Barbero et al., 1999). *H. depressula* is a common species in Mediterranean lagoons (Murray, 1991). *A. perlucida* points out the presence of a consistent organic matter content. This assemblage is found in the present day in lagoons at the Po river delta and it appears closely related to the Po run-off system.
Fig. 4 - Downcore distribution of the percentages of the main taxa plotted along the vertical biofacies distribution. The biofacies are numbered from the core bottom (biofacies IV) to the top (biofacies I).
Principal Component Analysis

The Principal Component Analysis (Fig. 5) was performed in order to display the main factors that determine the species distribution. The PCA shows three groups of species (X, Y and Z). Considering the frequencies of the species in the samples, the species of group X characterize two clusters (B2 and B3) in the lower part of the core. The species of group Y are very abundant in the samples grouped in Cluster B1, and the species of group Z characterize the upper part of the core corresponding to Cluster A. Considering the ecological preferences of the species, Component 1 (54.7% of variance) has been associated to the water depth. We noticed that group Z, composed of circalittoral species, shows a positive correlation with Component 1, whereas group X, composed of infralittoral species, shows a negative correlation. From group X to group Z an increasing positive correlation is found in conformity with the deepening of the facies observed from the bottom to the top of the core. Component 2 (23.2% of variance) has been associated to the oxygenation of the sea floor (directly proportional correlation) in contrast to the organic matter concentration (inversely proportional correlation). Group Y, mainly represented by epiphytic taxa, shows the highest values for this component, whereas Group Z shows the lowest values because it is represented by species typical of organic-carbon enriched sediments and disoxic substrates. Group X also has a negative correlation with Component 2 because of the organic matter content present in the sediments, probably due to the river run-off. Only T. bocky shows a very low correlation with both components and with all the other species and it cannot be related to any specific condition.

DISCUSSION

A paleoenvironmental reconstruction (Fig. 6) based on the results of the statistical analysis was performed. The cluster analysis and the ecological preferences of the recovered species were used to reconstruct the temporal distribution of four biofacies: each cluster corresponds to a biofacies, a distinct benthic environment inhabited by typical species. From the bottom to the top, the paleoenvironmental evolution recorded in core VSB01/7 is characterized by two main phases: the first phase (biofacies IV, III and II) corresponds to the late-Pleistocene transgression, whereas the second phase (biofacies I) corresponds to the Holocene highstand.

Biofacies IV, which represents the lower part of the core (from the bottom to -260 cm), indicates a brackish environment, probably a coastal lagoon with fresh water...
inputs due to the proximity of a river run-off. This run-off can be attributed to the Tronto river and to the Po river. In fact, the Po river delta was located close to the edge of the Middle Adriatic Deep during the Younger Dryas (Asioli, 1996). The migration towards the north of the Po river delta and also the retrogradation of the Tronto river delta is recorded within biofacies III (from -259 to -160 cm). The low-salinity tolerant species decrease consistently (*A. parkinsoniana* frequencies diminish, *H. depressula* and *A. tepida* almost disappear because of the fresh water source shifting toward the west) and are replaced by marine taxa such as *P. granosum* and *E. poeyanum*. This foraminiferal assemblage records fewer fluvial influences and can be considered as typical of a prodelta area. A further, gradual deepening is recorded within biofacies II (from -159 to -70 cm) that corresponds to a vegetated environment. Some of the species found in this biofacies are mainly found in prairies of phanerogames witnessing a well-oxygenated marine environment with normal salinity conditions.

With the onset of biofacies I (from -69 to the core top) a radical change occurs within the paleoenvironment. The water depth significantly increases and the mud-belt system stabilizes. The presence of species adapted to live in low-oxygenated/eutrophic waters shows the beginning of an alternation between levels with a normal oxygenation at the sea floor and levels characterized by disoxygen conditions. The assemblage is typical of the outer part of the mud-belt, where the sedimentation rate is lower, compared to that of the central part. The faunal turnover, from infralittoral to circalittoral species, happens without any intermediate stage and within 10 cm of sediment. This could be due to the abrupt increase of velocity in the sea level rise, or, more likely, could correspond to a condensed deposition that occurred between the beginning of the Holocene and the maximum flooding surface. The occurrence in the upper part of the core of the modern mud-belt assemblage indicates that the modern circulation patterns stabilize.

A further, gradual deepening is recorded within biofacies II (from -159 to -70 cm) that corresponds to a vegetated environment. Some of the species found in this biofacies are mainly found in prairies of phanerogames witnessing a well-oxygenated marine environment with normal salinity conditions.

The paleo-bathymetric reconstruction carried out in accordance with Morigi et al. (2005) is presented in Fig. 7. The lower part of the core, from the bottom to -69 cm shows a progressive deepening of the facies. According to the biofacies distribution, the bottom of the core shows a shallow environment corresponding to biofacies IV. Starting from biofacies III and II there is first a mild deepening, whose gradualism is abruptly interrupted at -69 cm with the onset of biofacies I. This part of the curve corresponds to the condensed deposition after which, the water depth stabilizes, with some oscillations, on the modern bathymetries corresponding to the environment found today in the outer part of the mud-belt.

**CONCLUSIONS**

The analyses carried out on the benthic foraminifera allowed us to define a paleoenvironmental reconstruction of the core VSB01/7 off the San Benedetto del Tronto coast. This study presents information on late-Quaternary paleoenvironmental changes related to the water depth fluctuations and to the Po river delta migration towards its modern position. The benthic foraminifera assemblages record the evolution from a brackish to a prodelta environment and then from an infralittoral to a circalittoral environment. Four biofacies can be recognized: from the bottom to approximately -160 cm (biofacies IV and III), the infralittoral environment is constantly characterized by the influence of river run-offs. The sequence shows a gradual change from a brackish water environment to a prodelta one and, finally, in biofacies II, a shallow marine environment stabilizes. This gradualism is abruptly interrupted at -69 cm from the core top, when a water depth increment occurs and a renewed circulation of water masses stabilizes bringing about the formation of the mud-belt. The faunal turnover anticipates the lithological change and shows the typical characters of the modern mud-belt assemblage. This preliminary work on core VSB 01/7 shows how the central Adriatic continental shelf preserves a record of the late-Quaternary sea-level changes and shoreline migration. Furthermore, sediments that accumulate on continental margins are useful to investigate the mechanisms of the formation of the mud-belt and to study the eutrophic conditions recorded within this mud wedge through time.

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PLATE I
PLATE II