



Ostracod assemblages from Holocene subsurface deposits of modern Po Delta: a palaeoenvironmental proxy record

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ABSTRACT - Benthic ostracod analyses performed on a 40 m long core (Core 1) enabled a detailed facies characterization and palaeoenvironmental reconstruction of the Late Pleistocene-Holocene deposits buried beneath the modern Po Delta. On the basis of relative abundance categories and hierarchical cluster analyses carried out on a presence-absence matrix composed of 23 samples and 22 ostracod species, four ostracod assemblages were identified. Assemblages 1 (*Palmoconcha turbida*), 2 (*Pontocythere turbida* and *Semicytherura acuticostata*) and 3 (*Semicytherura incongruens* and *Leptocythere ramosa*) correspond to three different shallow marine subenvironments, whereas assemblage 4 (*Pseudocandona albicans*) is indicative of a freshwater-oligohaline setting. Core 1 ostracod distribution patterns pointed out that several palaeoenvironmental oscillations occurred during the last glacial-interglacial period in the study area.

Above an alluvial plain succession completely barren in microfossils and assigned to the last glacial interval, a transgressive-regressive sequence of Holocene age was deposited. Organic-rich paludal deposits containing assemblage 4 developed during the first phase of transgression. Following the sea-level rising trend, marine sedimentation reached the core site around 6,000 cal. yr BP, as documented by the deposition of washover and transgressive barrier sands containing few valves of transported ostracods. A highly diversified shallow marine ostracod fauna (assemblage 2) was found within the overlying inner shelf deposits formed during the last transgressive-early regressive interval.

Upwards, an abrupt change of ostracod fauna occurred at the transition to prodelta deposits. The lower prodelta succession is characterized by an alternate record of two marine fluvial-influenced assemblages (assemblages 1 and 3), suggesting the development of an unstable prodelta environment subject to frequent river discharge oscillations during the first phases of deltaic progradation. On the contrary, a very scarce ostracod fauna is found within the upper prodelta succession probably due to the outstanding rates of sedimentation that affected the study area after the Ficarolo avulsion (last ca. 600 cal. yr BP).

RIASSUNTO - [Record paleoambientale delle associazioni a ostracodi dei depositi olocenici del delta del Po] - Le associazioni ad ostracodi bentonici presenti nei depositi di sottosuolo delle attuali pianure deltizie-costiere sono un ottimo strumento di indagine per la ricostruzione dell'evoluzione paleoambientale tardo quaternaria-olocenica delle suddette aree. In questo lavoro sono riportati e discussi i risultati ottenuti dall'analisi dell'ostracofauna del sondaggio a carotaggio continuo Core 1 profondo 40 metri e ubicato nella porzione meridionale dell'attuale piana deltizia del Po, in prossimità della foce del Po di Tolle.

Quattro associazioni ad ostracodi bentonici sono state distinte sulla base di analisi semiquantitative (categorie di abbondanza relativa) e dei dendrogrammi ottenuti tramite Cluster analysis, eseguite su una matrice presenza-assenza composta da 23 campioni e 22 specie. Le associazioni 1 (*Palmoconcha turbida*), 2 (*Pontocythere turbida* e *Semicytherura acuticostata*) e 3 (*Semicytherura incongruens* e *Leptocythere ramosa*) corrispondono a tre differenti subambienti di mare basso, mentre l'associazione 4 (*Pseudocandona albicans*) è tipica di ambiente dulcicolo-oligoalino. La distribuzione delle associazioni entro la successione in esame ha consentito di riconoscere i principali passaggi di facies e le oscillazioni paleoambientali avvenute durante l'ultimo ciclo glaciale-interglaciale nell'area del delta del Po.

Alla base del sondaggio sono presenti depositi di pianura alluvionale completamente sterili e sviluppatasi durante l'ultimo periodo glaciale. Il brusco passaggio a depositi palustri di retrobarriera contenenti un'ostracofauna dulcicolo-oligoalina (associazione 4) segna l'inizio della trasgressione olocenica avvenuta attorno ai 9.900 anni calibrati fa. La successiva transizione a depositi di spiaggia, datati a circa 6.000 anni calibrati fa e contenenti poche valve rimaneggiate di ostracodi marini, avviene in risposta ad un rapido spostamento verso terra delle facies deposizionali indotto dalla progressiva risalita del livello marino. Il momento di massima trasgressione e le prime fasi regressive sono registrati dalla deposizione delle sovrastanti argille di piattaforma interna, contenenti un'associazione ad ostracodi ricca e diversificata, indicativa di un ambiente di mare basso scarsamente fluvio-influenzato (associazione 2).

Una netta variazione nel contenuto in ostracodi è registrata in corrispondenza del passaggio da depositi di piattaforma interna a depositi di prodelta, segnando l'inizio di una intensa fase di progradazione deltizia. Due associazioni marine fluvio-influenzate (associazione 1 e associazione 3) sono presenti nella successione, litologicamente omogenea, di prodelta. Le associazioni 1 e 3 sono indicative di due differenti subambienti di prodelta soggetti ad un diverso grado e tipologia di influenza fluviale soprattutto in termini di idrodinamismo, apporto sedimentario e materia organica. Nell'intervallo stratigrafico inferiore della successione di prodelta il record alternato delle associazioni 1 e 3 suggerisce dunque lo sviluppo di un ambiente deposizionale complesso caratterizzato da frequenti variazioni nell'apporto fluviale durante le prime fasi di costruzione del delta del Po. La porzione superiore della successione di prodelta presenta invece una scarsa ostracofauna. Una tale povertà di ostracodi nel record sedimentario è compatibile con gli elevati tassi di sedimentazione che hanno caratterizzato l'area del delta del Po circa 600 anni calibrati fa, in seguito alla riorganizzazione del sistema fluviale avvenuta dopo la Rotta di Ficarolo.

INTRODUCTION

During the last years an increasing interest in the application of benthic ostracods to monitor coastal areas evolution is steadily growing. Thanks to a wide environmental distribution (almost all of the available

aquatic habitats) and a well-known high ecological sensitivity, ostracods can be considered useful bioindicators of water quality and a powerful tool to reconstruct past coastal environments as well (Rosenfeld et al., 2000; Holmes & Chivas, 2002; Frenzel & Boomer, 2005; Matzke-Karasz et al., 2007).

Many studies carried out on modern ostracod assemblages evidenced that their spatial distribution patterns are controlled by a combination of several environmental variables as salinity, temperature, pH, substrate, turbidity, food availability and oxygen content among the most important (Masoli, 1968; Colalongo, 1969; Bonaduce et al., 1975; Breman, 1975; Athersuch et al., 1989; Montenegro & Pugliese, 1996; Ruiz et al., 2000; Holmes & Chivas, 2002; Pascual et al., 2008).

In freshwater, brackish and fully-marine settings, the ecology and palaeoecology of ostracods are intensively used to obtain objective and reliable palaeoenvironmental information. Particularly, in high unstable marginal marine settings ostracod analyses show a large potential use in palaeoenvironmental and palaeoclimatic reconstructions. Very useful information regarding Late Quaternary relative sea-level oscillations were recently inferred by an accurate analysis of the fossil ostracod fauna recorded within worldwide coastal successions (Lachenal, 1989; Barra, 1991; Pugliese & Stanley, 1991; Barbieri et al., 1999; Mazzini et al., 1999; Guernet et al., 2003; Ricci Lucchi et al., 2006; Reeves et al., 2007; Viehberg et al., 2008).

Mixed ostracod and benthic foraminiferal assemblages were frequently used to refine, mainly in terms of water depth and salinity, facies characterization of Late Pleistocene-Holocene deposits recorded beneath Mediterranean deltaic areas as the Po Plain (Amorosi et al., 2003, 2004), the southern Po Delta (Bondesan et al., 2006), the Arno Plain (Aguzzi et al., 2007; Amorosi et al., 2009) and the Ombrone Delta (Carboni et al., 2002). In these fossil sequences peculiar biofacies changes provided evidences of cyclic sedimentation patterns including continental, brackish and marine deposits driven by relative sea-level and climatic oscillations occurred at different time scales. Besides, the study of ostracod fauna guaranteed a detailed facies analysis also within paralic successions including oligohaline-freshwater deposits where benthic foraminifers are usually scarce or absent.

Recently, Amorosi et al. (2008) reconstructed the Late Quaternary stratigraphic architecture of modern Po Delta combining sedimentological, micropalaeontological (benthic foraminifers and ostracods) and geochemical investigations, carried out on three 40 m-long cores (cores 1-3), one of which (Core 1) is the object of this study.

In response to the rapid sea-level rise occurred during the Late Pleistocene-early Holocene period, a ca. 7 m-thick transgressive succession (transgressive system tract-TST) developed above an unconformable surface capping alluvial deposits dated to the last glacial age. This transgressive succession is composed of back-barrier deposits and inner shelf clays rich in microfossils (benthic foraminifers and ostracods).

Upwards, a thick vertically stacked pattern of prodelta, delta front, and delta plain deposits (up to 27 m) composed the highstand systems tract-HST, mainly formed during the recent phases of modern Po Delta progradation. Changes in microfossil assemblages allowed distinguishing inner shelf from prodelta deposits and identifying the maximum flooding surface-MFS within a homogeneous shallow marine succession.

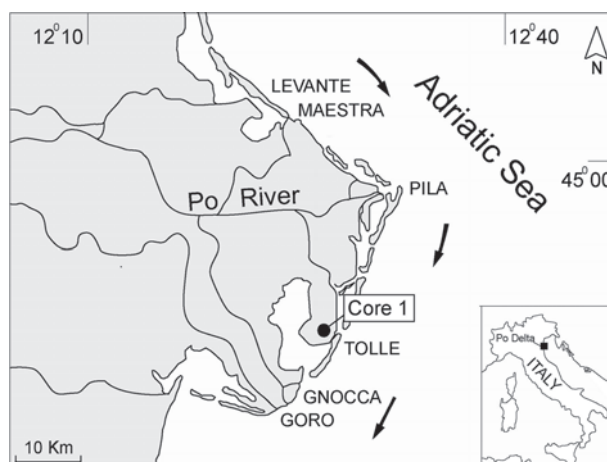


Fig. 1 - Location map of Core 1. Black arrows represent present-day Northern Adriatic surficial circulation patterns.

This paper reports in detail the ostracod fauna of Core 1 drilled in the southern part of modern Po delta plain (Fig. 1), to verify the large potential of ostracod studies in high-resolution palaeoenvironmental reconstructions even at a small-scale of investigation.

Specific aim of this work is to evidence the linkage existing between the core distribution patterns of ostracod assemblages and the fluvial discharge oscillations occurred during the Po Delta evolution and recorded within Core 1 shallow marine succession.

MATERIAL AND METHODS

The 40 m long Core 1 was drilled in the southern portion of modern Po delta plain, close to the present shoreline (ca. 300 m west) in proximity of Po Tolle channel mouth (Fig. 1). The wireline perforation system guaranteed an undisturbed core stratigraphy and a very high recovery percentage (> 90%).

A detailed description of sedimentological features and facies characterization of Core 1, along with the report of the main micropalaeontological data (benthic foraminifers and ostracods), were reported by Amorosi et al. (2008).

A total of 124 samples for micropalaeontological analyses were collected along the entire length of the cored succession. Within fine-grained deposits (clay and silt) the sampling density was very high (five samples per meter), while it becomes substantially lower within sands and overconsolidated intervals where well-preserved microfossils are usually scarce (Carboni et al., 2002; Amorosi et al., 2003; Bondesan et al., 2006).

Approximately 150-200 g of each sample were dried at 60 °C for eight hours and washed with water or water plus hydrogen peroxide (35% vol.), in case of very cohesive sediments. Successively, each sample was wet sieved through sieves of 63 µm (240 mesh) and dried again for 24 hours. The microfossil content (ostracods and benthic foraminifers) of all samples was observed under a binocular microscope and described in Amorosi et al. (2008). Rossi & Vaiani (2008) focused on the foraminiferal content of Core 1, while a more detailed

picture of ostracod assemblages is reported in this work.

Thirty-seven samples containing a well-preserved ostracod fauna were dry sieved through sieves of 125 µm to concentrate adult valves and avoid problems about the specific attribution of juveniles of the first moult stages. The size fraction >125 µm was qualitatively analyzed and the identification of species was determined on the basis of several reference works as Müller (1894), Bonaduce et al. (1975), Breman (1975), Athersuch (1978), Athersuch et al. (1989), Henderson (1990), Guernet et al. (2003), and Meisch (2000).

On the twenty-three samples containing relatively abundant valves (more than 10 valves), semiquantitative analyses were performed using three categories of relative abundance (abundant = >30%; common = 10-30% and scarce = <10%), following the method adopted by Aguzzi et al. (2007) for a comparable and coeval fossil ostracod fauna recorded beneath the Arno coastal plain.

On the basis of these abundance categories and hierarchical cluster analyses carried out on a presence-absence matrix composed of 23 samples and 22 ostracod species, four ostracod assemblages were defined. The palaeontological statistical program PAST (PAleontological STatistic ver. 1.55 by Hammer et al., 2007) was used to process cluster analyses. Dice similarity coefficient, recommended for presence-absence microfossil data (Hammer et al., 2007), was used both for the R-mode and Q-mode cluster analyses providing important information about ostracod community structure and core sample groups, respectively.

Ecological significance and palaeoenvironmental interpretation of ostracod assemblages relied upon specific papers (Bonaduce et al., 1975; Athersuch et al., 1989; Lachenal, 1989; Yassini & Jones, 1995; Meisch, 2000; Anadón et al., 2002; Smith & Horne, 2002) and the spatial distribution patterns of ostracods in the modern Adriatic Sea reported by Colalongo (1969) and Breman (1975).

Further information were also provided by comparison with the ostracod fauna recorded within the Late Quaternary successions buried beneath present-day deltaic areas as Po Plain (Amorosi et al., 2003, 2004), inner Po Delta (Bondesan et al., 2006) and Arno coastal plain (Aguzzi et al., 2007).

CORE 1 OSTRACOD ASSEMBLAGES: COMPOSITION AND ENVIRONMENTAL SIGNIFICANCE

Twenty-two species of autochthonous benthic ostracods were identified within the fine-grained

deposits of Core 1. The Core 1 ostracod distribution patterns along with species abundance categories are reported in Fig. 2. A poorly diversified ostracod fauna,

	15.40	16.70	17.15	17.30	17.90	18.50	18.95	20.05	21.10	21.60	22.05	22.45	22.68	23.45	23.65	24.65	25.08	25.20	25.40	25.60	25.80	26.05	26.40	26.60	26.80	28.60	28.80	28.90	31.90	33.20	33.40	34.10
OSTRACOD SPECIES																																
<i>Cardona candida</i> (O.F. Müller, 1776)																																
<i>Cardona neglecta</i> (Sars, 1887)																																
<i>Pseudocardona albicans</i> (Brady, 1868)																																
<i>Callistocythere flavidofusca</i> (Ruggieri, 1950)																																
<i>Carinocythereis whitei</i> (Baird, 1850)																																
<i>Cistacythereis turbida</i> (G.W. Müller, 1894)																																
<i>Cytheretta adriatica</i> (Ruggieri, 1952)																																
<i>Cytheridea neapolitana</i> (Kollmann, 1960)																																
<i>Cytherois fischeri</i> (Sars, 1866)																																
<i>Cytheroma variabilis</i> (G.W. Müller, 1894)																																
<i>Leptocythere bacescoi</i> (Rome, 1942)																																
<i>Leptocythere ramosa</i> (Rome, 1942)																																
<i>Loxoconcha agilis</i> (Ruggieri, 1967)																																
<i>Loxoconcha exagona</i> (Bonaduce et al., 1976)																																
<i>Palmoconcha turbida</i> (G.W. Müller, 1912)																																
<i>Pontocythere turbida</i> (G.W. Müller, 1894)																																
<i>Pterygocythereis siveteri</i> (Athersuch, 1978)																																
<i>Sagmatocythere versicolor</i> (G.W. Müller, 1894)																																
<i>Semicytherura acutostata</i> (Sars, 1866)																																
<i>Semicytherura incongruens</i> (G.W. Müller, 1894)																																
<i>Semicytherura sulcata</i> (G.W. Müller, 1894)																																
<i>Xestoleberis communis</i> (G.W. Müller, 1894)																																

Tab. 1 - Benthic ostracods distribution in the core samples containing an autochthonous ostracod fauna (x: recorded species). Core samples are expressed in core depth meters. Core samples with a scarce ostracod fauna are highlighted in grey. The taxonomy is based on Bonaduce et al. (1975), Breman (1975), Athersuch (1978), Athersuch et al. (1989), Henderson (1990), and Meisch (2000). Bibliographical references are given in these papers.

mainly composed of *Palmoconcha turbida*, *Semicytherura incongruens* and *Leptocythere ramosa*, characterizes the samples collected at ca. 11-27 m core depth interval. On the contrary, a more diversified assemblage dominated by *Pontocythere turbida* and *Semicytherura acuticostata* is found within samples

collected at ca. 27-29 m core depth. Few species belonging to *Candona* and *Pseudocandona* genera are recorded at 31-34 m core depth within organic-rich clays. Tab. 1 summarizes core sample distribution of autochthonous ostracod species along with taxonomic references. Samples collected from the sandy deposits

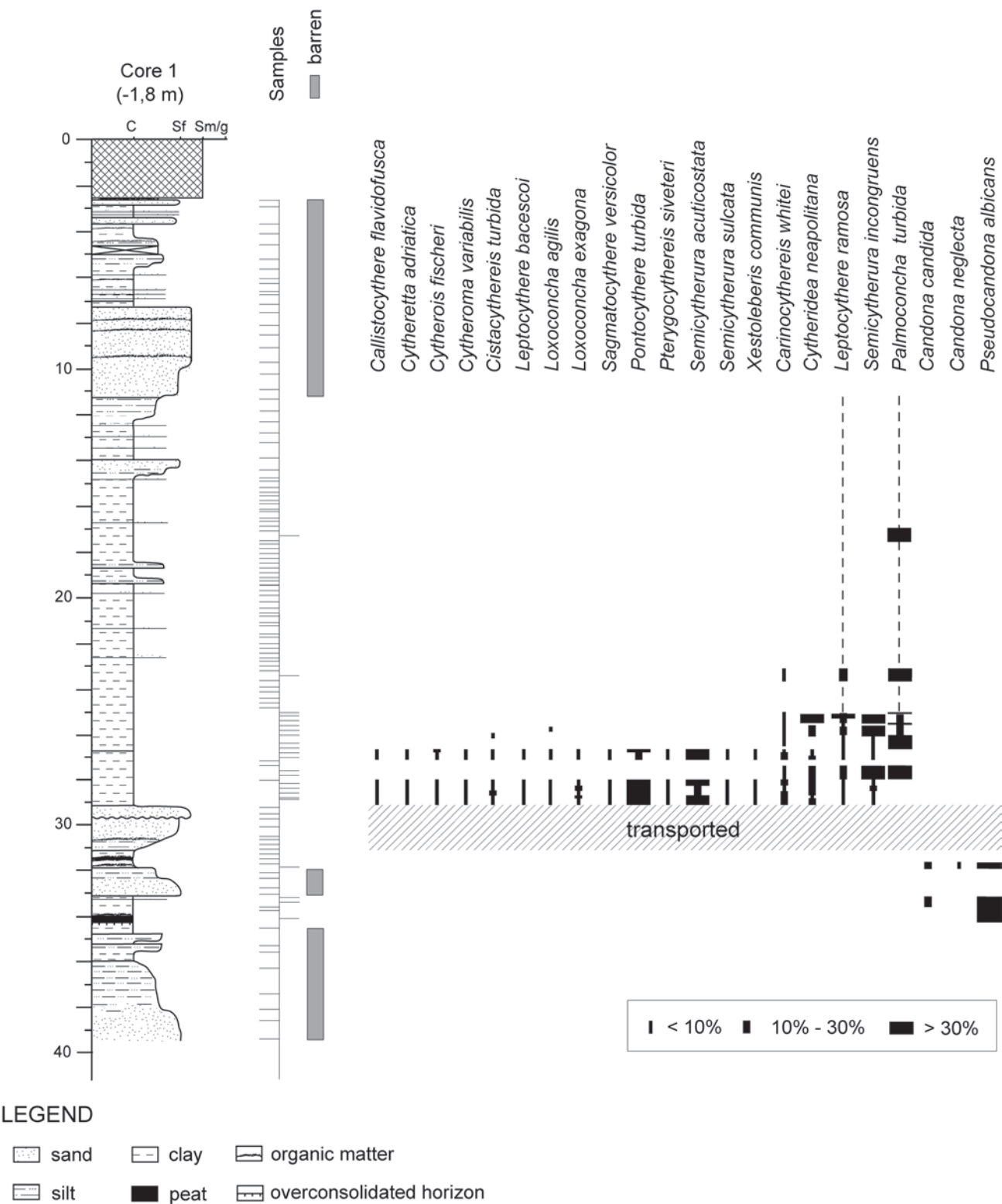


Fig. 2 - Vertical distribution patterns of benthic ostracods in Core 1. Species relative abundances (reported as abundances categories) within each sample containing a countable ostracod fauna are shown. Dotted lines indicate scattered valves. Samples statistically analyzed are shown on the right of the sample column, while barren samples and those containing scarce or transported ostracods are reported on the left.

of Core 1 are barren or characterized by few transported valves of ostracods (Fig. 2) and for this reason are not reported in Tab. 1.

Throughout the cored succession ostracods abundance is generally low (usually less than 40 valves for sample). Particularly, fourteen samples collected from the upper part of prodelta succession (25-11 m core depth) showed a very scarce ostracod fauna (Fig. 2) composed of less than 3 valves.

R-mode cluster analysis performed on the twenty-three samples containing more abundant valves produced a dendrogram composed of three clusters and one separated species (Fig. 3a), corresponding to four different ostracod assemblages described below.

Cluster C shows no similarity with the other clusters as well the separated species *Palmoconcha turbida*, while Clusters A and B seem to be rather similar (Fig. 3a). However, Clusters A and B are reported and discussed in text as separated associations because the R-mode cluster analysis was performed on a presence-absence dataset.

The sample groups obtained performing Q-mode cluster analysis (Fig. 3b) are consistent with the faunal assemblages.

Assemblage 1-*Palmoconcha turbida*

Dominant species: *Palmoconcha turbida* (G.W. Müller, 1912).

Assemblage 1 is characterized by an overwhelming dominance of *Palmoconcha turbida* that is reported as a separated species by the R-mode dendrogram (Fig. 3a).

Few valves of *Leptocythere ramosa* and *Carinocythereis whitei* are also found in association with *Palmoconcha turbida*, indicating a very low specific diversity.

Samples including assemblage 1 are grouped in the Cluster Qa (Fig. 3b).

In the Northern Adriatic Sea, the highest percentages of *Palmoconcha turbida* were recorded within scattered samples collected in proximity of Po Tolle and Po Goro-Gnocca river mouths around 10-20 m water depth (Colalongo, 1969; Breman, 1975).

Generally, a similar but more diversified assemblage is found in the southern prodelta area of the Po Delta up to 25 m water depth on a fine-grained (silty clay) organic-rich substrate (Breman, 1975).

Recently, remarkable abundances of *Palmoconcha turbida* were also found within the Holocene prodelta succession recorded beneath the present Arno coastal plain (Aguzzi et al., 2007).

The dominance of a shallow marine species usually recorded in the Adriatic Sea at water depth less than 20 m (Bonaduce et al., 1975) and tolerant to relatively low oxygen conditions (Bodergat et al., 1998; Ruiz et al., 2005) suggests a proximal prodelta setting, characterized by frequent river discharge fluxes and seasonal dysoxic conditions. Such unstable complex environment affected by the dynamic interaction between waves and river fluxes probably induces the development of the observed oligospecific ostracod fauna, capable of withstanding elevated fluvial discharge rates and a high hydrodynamic gradient.

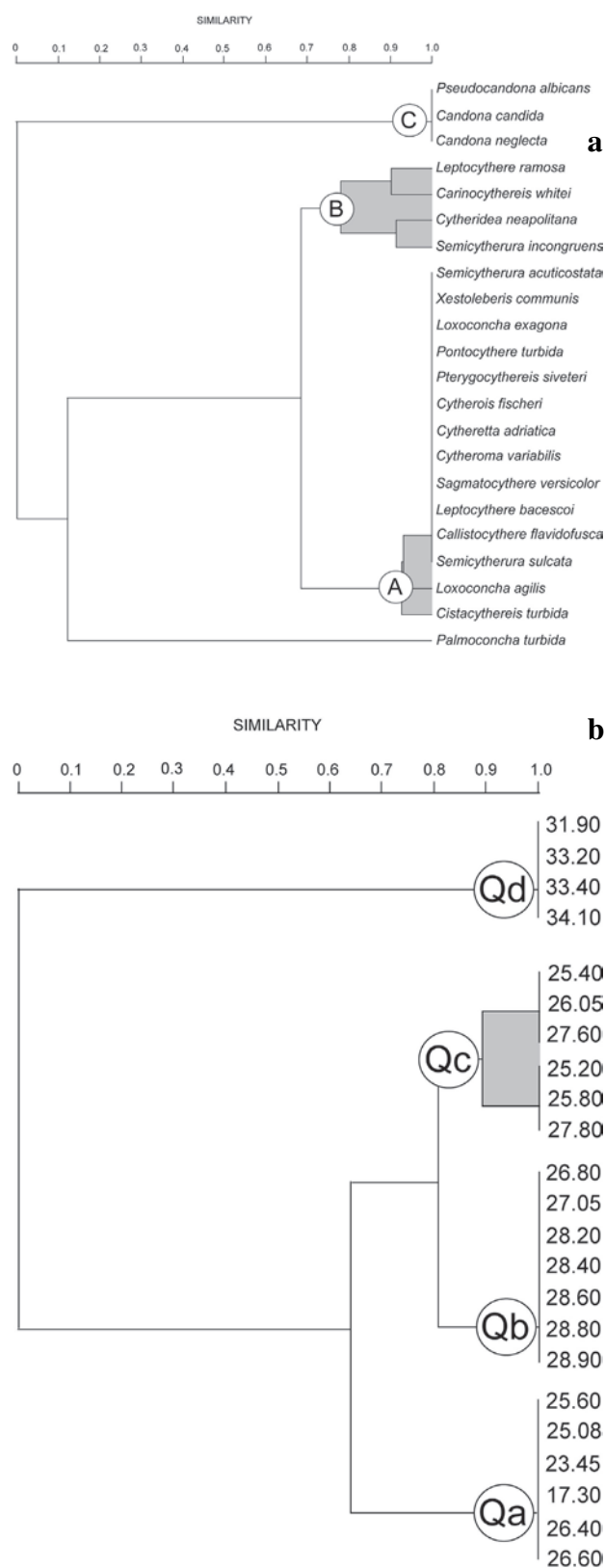


Fig. 3 - Dendrogram classifications resulting from hierarchical cluster analysis performed on a presence-absence matrix. Dice similarity coefficient is used for both R-mode and Q-mode analyses. a) Ostracod assemblages produced by R-mode analysis; b) sample associations produced by Q-mode analysis. The grey areas highlight species (a) or samples (b) belonging to the same cluster.

Assemblage 2-Cluster A

Dominant species: Pontocythere turbida (G.W. Müller, 1894); *Semicytherura acuticostata* (Sars, 1866).

Assemblage 2 shows the highest diversified ostracod fauna recorded throughout the entire cored succession. Among all the species composing assemblage 2 (reported in Cluster A, Fig. 3a), *Pontocythere turbida* and *Semicytherura acuticostata* are usually the most abundant.

Samples including assemblage 2 are grouped in the cluster Qb (Fig. 3b).

At present, a similar high-diversified ostracod fauna is found north of the modern Po Delta (north of Po Pila mouth) where the influence of Po River runoff products is relatively low (Colalongo, 1969; Breman, 1975). The highest percentages of *Pontocythere turbida* are encountered at about 20-30 m water depth within sandy samples containing low organic matter percentage (Zone C in Colalongo, 1969; Biofacies IIb in Breman, 1975).

A comparable fossil ostracod fauna was found within the transgressive-early regressive inner shelf deposits recorded beneath the contiguous Po Plain area (Amorosi et al., 2003, 2004).

The variety and composition of assemblage 2, characterized by remarkable amounts of littoral and sublittoral marine species, suggest a shallow marine environment slightly or not influenced by river discharge.

Assemblage 3-Cluster B

Dominant species: Semicytherura incongruens (G.W. Müller, 1894); *Leptocythere ramosa* (Rome, 1942).

Assemblage 3 consists of two dominant species (*Semicytherura incongruens* and *Leptocythere ramosa*) with the subordinate occurrence of *Carinocythereis whitei*, *Cytheridea neapolitana* (Cluster B in Fig. 3a) and *Palmoconcha turbida*.

Cluster Qc groups the core samples containing assemblage 3 (Fig. 3b).

In the Northern Adriatic Sea, a similar ostracod fauna characterized by high percentages of *Semicytherura incongruens*, *Leptocythere* spp. and *Palmoconcha turbida* is found in the prodelta area of Po Delta on a fine-grained substrate at a water depth generally less than 25 m (Colalongo, 1969; Breman, 1975).

South of Po Pila mouth the decreasing abundances of *Palmoconcha turbida* are paralleled by a relative increase of *Semicytherura incongruens* and *Cytheridea neapolitana*, following a bathymetric and organic matter gradient (Breman, 1975). According to this trend, *Cytheridea neapolitana* reaches remarkable percentages within muddy samples collected from the intermediate-deep infralittoral zone of the Adriatic Sea (Bonaduce et al., 1975; Breman, 1975).

Thus, the composition and a higher specific diversity suggest that assemblage 3 reflects a slightly deeper and food-enriched prodelta setting respect to assemblage 1.

Assemblage 4-Cluster C

Dominant species: Pseudocandona albicans (Brady, 1868).

Assemblage 4 consists of ostracods belonging to genera *Pseudocandona* and *Candona*. *Pseudocandona albicans* is the dominant species and *Candona candida* and *C. neglecta* are encountered as subordinate species.

Samples containing assemblage 4 are grouped in the cluster Qd (Fig. 3b).

Pseudocandona albicans is reported as a mesothermophilic and mesohalophilic species, preferring stagnant or slow flowing waters as well as *Candona candida* (Henderson, 1990; Meisch, 2000). However, specimens of *Pseudocandona albicans* have been recorded living in a variety of habitats as streams, ponds and lakes throughout Europe, Asia and North America (Henderson, 1990).

An ostracod assemblage similar to assemblage 4 is reported from several European shallow water lakes, ponds and swamps (Colizza et al., 1987; Henderson, 1990; Melis et al., 1995), indicating that assemblage 4 is consistent with a freshwater-oligohaline depositional setting.

CORE 1 OSTRACOD RECORD

In correspondence of Core 1 area, a metric clay-sand alternation of organic-rich deposits is recorded above a 6 m-thick alluvial succession completely barren in microfossils and assigned to the last glacial period (Amorosi et al., 2008; Rossi & Vaiani, 2008).

Between 34-31 m core depth a freshwater-oligohaline ostracod fauna (assemblage 4) is encountered within the organic clayey layers, suggesting the development of a backswamp environment during the early Holocene period (9,875-9,340 cal. yr BP; radiocarbon dates from Amorosi et al., 2008) (Fig. 4).

Few valves of poorly preserved *Cyprideis torosa*, *Semicytherura* spp. and *Loxoconcha* spp. characterize the overlying washover sands (31-30 m core depth). This mixed brackish-marine ostracod fauna is interpreted as transported from nearby environments and possibly reflects the transition from a back-barrier to a shoreface depositional setting triggered by the rapid beach-barrier landward migration.

An erosional surface evidenced by a veneer of mollusk shells marks the lower boundary of the overlying transgressive barrier sands (30-29 m core depth), containing abraded valves of *Semicytherura* spp. and *Loxoconcha* spp. (Amorosi et al., 2008).

The overlying marine clays (ca. 29-27 m core depth) contain a rich and high-diversified ostracod fauna mainly belonging to assemblage 2 (Fig. 4). The dominance of littoral and sublittoral marine species, as *Pontocythere turbida* and *Semicytherura acuticostata*, usually found in the Northern Adriatic sandy platform at 20-30 m water depth (Colalongo, 1969; Breman, 1975), suggests the development of an inner-shelf environment slightly or not influenced by Po River discharge.

However, two samples collected at 27.80 m and 27.60 m core depth show a different ostracod association (assemblage 3). The dominance of shallow-water species (*Semicytherura incongruens*, *Leptocythere ramosa*, and *Palmoconcha turbida*), commonly found in the modern Po prodelta area (Colalongo, 1969; Breman, 1975), indicates a local increase of fluvial influence probably related to a delta lobe switching occurred around 4,700 cal. yr BP (radiocarbon age from Amorosi et al., 2008) (Fig. 4).

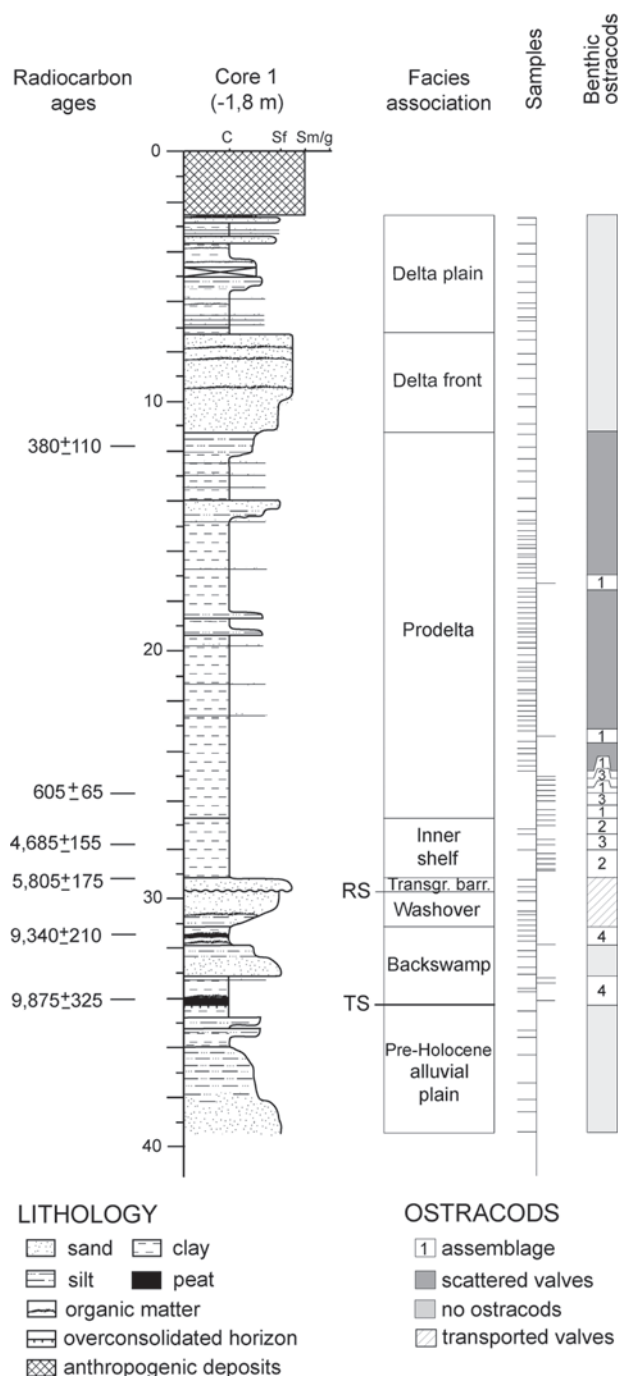


Fig. 4 - Stratigraphy and vertical distribution of ostracod assemblages 1-4 in Core 1. TS: Transgressive surface, RS: Ravinement surface (stratigraphy after Amorosi et al., 2008). Ages are reported as calibrated years BP. Samples statistically analyzed are shown on the right of the sample column, while barren samples and those containing scarce or transported ostracods are reported on the left.

Upwards, a thick and continuous prodelta succession is recorded between 26.60-11 m core depth (Fig. 4). An alternate record of two fluvial-influenced shallow marine assemblages (assemblages 1 and 3) characterizes the lower prodelta succession between 26.60-25 m, suggesting the development of a prodelta environment subject to frequent river discharge oscillations. Such complex palaeogeographic reconstruction is consistent with the relative sediment-starved conditions (about 3 m of sediments in more than 4,000 years) that affected the study area between ca. 5,000-600 cal. yr BP (Amorosi et al., 2008).

Within the upper prodelta succession (25-11 m core depth) very few scattered valves of *Palmoconcha turbida* and *Leptocythere ramosa* are observed. Unique exception is represented by two samples collected at 23.45 m and 17.30 m core depth that show a typical assemblage 1 ostracod fauna (Fig. 4), suggesting the establishment of a proximal prodelta environment.

The low number of valves recorded within the upper prodelta succession is likely related to the high sedimentation rates (ca. 14 m of fine-grained sediments in less than three centuries) that affected the study area between ca. 600-380 cal. yr BP (radiocarbon dates from Amorosi et al., 2008) (Fig. 4).

Upcore, no ostracods are encountered within the delta front sands and the overlying delta plain deposits recording the most recent stages of modern Po Delta progradation (Fig. 4).

OSTRACODS AS PROXIES OF CORE 1 PALAEOENVIRONMENTAL CHANGES

Core 1 ostracod distribution patterns record the main palaeoenvironmental changes that occurred during the last glacial-interglacial period in the modern Po Delta area, inducing the formation of a transgressive-regressive depositional cycle.

At the beginning of the Holocene age a rapid sea-level rising trend led to the inundation of the alluvial plain formed during the last glacial period and the development of a transgressive surface-TS (Amorosi et al., 2008). The first depositional record of Holocene transgression is represented by the back-barrier organic-rich deposits containing assemblage 4 (Fig. 4), that suggests the development of a paludal setting (backswamp) characterized by freshwater-oligohaline conditions not tolerated by benthic foraminifers.

Successively, the deposition of washover and transgressive barrier sands characterized by a transported ostracod fauna evidences the onset of marine transgression in the core area. These sandy depositional facies are separated by an erosional surface dated around 6,000 cal. yr BP and interpreted as a wave ravinement surface-RS (Amorosi et al., 2008).

During the late transgressive-early regressive period (ca. 5,500-900 cal. yr BP after Rossi & Vaiani, 2008) an inner shelf environment slightly or not influenced by fluvial discharge developed as recorded by assemblage 2 (Fig. 4). Moreover, the concomitant occurrence of the most open marine ostracod and foraminiferal (Rossi & Vaiani, 2008) associations indicates that the peak of transgression, along with the maximum landward

position of palaeoshoreline, was reached during the deposition of the inner shelf succession.

A momentary increase in river runoff, maybe related to a minor delta lobe switching, is promptly recorded by ostracods between 28-27 meters core depth (Fig. 4), according to the foraminiferal fauna that indicates a local increase of fluvial influence (Rossi & Vaiani, 2008).

This early and brief phase of deltaic sedimentation seems to anticipate the establishment of a typical prodelta depositional setting, marked by an abrupt change in the ostracod fauna, where littoral and sublittoral species are replaced by shallow marine ostracods able to tolerate high amount of river runoff products.

Although detailed autoecological studies in modern environments are still to be undertaken on several marine species, spatial distribution patterns of Northern Adriatic ostracods appear to be mainly controlled by substrate, food supply and hydrodynamicity (Colalongo, 1969; Breman, 1975). These environmental factors are strongly influenced by the interaction between the total amount of Po river runoff, the Adriatic surficial circulation patterns and the location of the main active channel mouths.

During the first stages of Po Delta progradation two prodelta subenvironments, corresponding to a different degree and typology of fluvial influence, developed in the core area. The repetitive record of assemblages 1 and 3 within the lower prodelta succession reflects the alternating development of a proximal and a slightly deeper, food-enriched prodelta setting, respectively.

This palaeoenvironmental reconstruction based on Core 1 ostracod record is consistent with the complex palaeogeographic evolution that affected the Po Delta area between ca. 3,000-900/800 cal. yr BP. Indeed, during this period several generations of cusped deltas developed across the Po Plain and induced frequent lateral shifts of the active river mouths, decreasing the environmental stability of prodelta area (Correggiari et al., 2005).

On the contrary, the scarce ostracod fauna found within the upper prodelta succession indicates the establishment of new stressed environmental conditions induced by the very high sedimentation rates that affected the study area after the Ficarolo avulsion between ca. 600-380 cal. yr BP (Fig. 4). At present, very low ostracod population densities were found near the active mouths of Po Delta (Colalongo, 1969) and Rhône Delta (Kruit, 1955), where elevated river discharge fluxes induce turbidity and high hydrodynamic conditions.

Thus, the incapacity of benthic ostracods to tolerate elevated sedimentation rates probably prevents the identification within the Core 1 succession of marginal mud-belt deposits, clearly recognized by benthic foraminifers between ca. 25-20.50 m core depth (Rossi & Vaiani, 2008).

According to the rapid progradation of Po Delta system (Correggiari et al., 2005; Rossi & Vaiani, 2008), the occurrence of assemblage 1 within two samples collected at 23.45 m and 17.30 m core depth maybe indicates the incoming end of mud-belt sedimentation and the establishment of a proximal prodelta environment.

CONCLUSIONS

This study shows that benthic ostracods can provide accurate and high-resolution information about the Late Quaternary palaeoenvironmental evolution of modern coastal-deltaic areas, particularly in terms of past salinity and river discharge oscillations.

Core 1 ostracod distribution patterns reveal a transgressive-regressive depositional cycle developed beneath the modern Po delta plain in response to Late Pleistocene-Holocene eustatic and climatic oscillations.

The freshwater-oligohaline ostracod fauna (assemblage 4) from the organic-rich deposits overlying the glacial alluvial succession indicates the development of a paludal back-barrier environment during the early phase of Holocene transgression.

Around 6,000 cal. yr BP the shift from freshwater-oligohaline to marine environmental conditions is evidenced by the record of a shallow marine high diversified ostracod fauna (assemblage 2), that records the rapid approaching of marine transgression and the maximum landward migration of palaeoshoreline in the core area.

Later, a prodelta environment characterized by fluvial influenced marine ostracod faunas established. The alternate record of two ostracod assemblages (assemblage 1 and 3) reveals the development of a complex prodelta setting affected by frequent river discharge oscillations during the first stages of Po Delta formation.

After the Ficarolo avulsion, elevated amounts of river runoff products were discharged in the study area. Due to the incapability of benthic ostracods to tolerate so high sedimentation rates, an accurate palaeoenvironmental record of the most recent phases of Po Delta progradation (last ca. 600 cal. yr BP) cannot be reported.

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