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Multiproxy reconstruction of Late Pleistocene-Holocene environmental changes in coastal successions: microfossil and geochemical evidences from the Po Plain (Northern Italy)

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ABSTRACT: Despite the overwhelming control exerted on worldwide coastal evolution by the Lateglacial-early Holocene sea-level rise, high-frequency rapid palaeoenvironmental changes are recorded within a thick postglacial succession buried beneath the southern Po Plain (Northern Italy). A multidisciplinary study involving sedimentology, micropalaeontology (benthic foraminifers and ostracods), geochemistry (major, minor and trace elements) and radiocarbon dating (^{14}C) on a 40m-long core (240-S5) retrieved inland of the Holocene beach ridges, allowed the reconstruction of articulate coastal scenarios and dynamics - including stages of drainage reorganization.

An alluvial plain nourished by the Apenninic Savio River developed in response to low sea-level conditions during the last glacial period. During the first stages of deglaciation (Lateglacial period) the study area was flooded and a coastal plain evolved near the coeval lagoon basin. Subtle change in microfossil content documents the occurrence of a short-term progradational episode that led to the temporary establishment of more terrestrial conditions (likely attributed to the Younger Dryas event - ca. 12,500 cal years BP). Complex and unstable Lateglacial palaeoenvironmental scenarios, and a mixed contribution from two Apenninic rivers (Savio River and Fiumi Uniti system), are suggested by the geochemical composition of coastal sediments.

A distinctive flooding event, possibly related to the MWP-1B, caused the abrupt replacement of the coastal plain by a barrier-lagoon system. This landward shift of facies was synchronous with a source area change from the Savio River to the Fiumi Uniti system, triggered by an important phase of drainage system reorganization. Short-term changes in microfossil content also highlight the occurrence of two early Holocene episodes of lagoon infilling not accompanied by significant changes in sediment composition.

The complete infilling of lagoon, which evolved in a swamp basin, took place only after ca. 7,600 cal years BP. The establishment of hypohaline environmental conditions is supported by subtle changes in geochemical composition.

Keywords: coastal evolution; geochemistry; microfossils; postglacial; Po Plain

INTRODUCTION

Understanding the sedimentary and environmental responses of coastal systems to climatic and relative sea-level changes is a fundamental issue for efficient land use and management of these areas, which commonly host highly populated cities and natural resources (water, gas and oil among the most important). A better comprehension of past coastal dynamics, even at a short-time scale, is essential to provide reliable evolutive scenarios and preserve marginal low-lying areas from flooding, especially under the treat of global warming and high rates of sea-level rise predicted by worldwide geological proxies and models for the next decades (Edwards et al. 2004; IPCC 2007; Leorri, Horton and Cearreta 2008; Horton et al. 2009; Kemp et al. 2009; Lambeck et al. 2011).

In this regard, paludal and lagoon deposits, commonly developed in coastal plain and back-barrier systems, are key-stratigraphic intervals of worldwide coastal zones, marking episodes of accelerated sea-level rise with marine transgressions (sea-level indicators in Lambeck et al. 2004).

More specifically, Lateglacial-early Holocene transgressive back-barrier successions, formed under the dominant effect of global forcing factors, can provide relevant information on the depositional response of coastal areas to high-frequency climate (Mayewski et al. 2004) and relative sea-level changes (Fairbanks 1989; Bard et al. 1996; Liu et al. 2004; Bard, Hamelin and Delanghe-Sabatier 2010; Bird et al. 2010), which commonly involve drainage reorganization at more proximal locations (Blum and Törnqvist 2000).

Short-term palaeoenvironmental variations were recorded within the postglacial sedimentary succession of North Atlantic lagoons (Freitas, Andrade and Cruces 2002; Cearreta et al. 2003, 2007; Cabral et al. 2006) and marshes (Leorri, Martin and McLaughlin 2006) by very sensitive microfossil proxy (benthic foraminifers and ostracods) and connected to natural (climate and relative sea-level oscillations) or anthropogenic forcing factors.

Similarly, the geochemistry of coastal wetland sediments is particularly useful in tracing palaeonvironmental changes, human impact and extreme events (e.g. Cundy and Croudace 1995; Daoust et al. 1996; Dellwig et al. 1999; Alvisi and Dinelli 2002; Tao, Chen and Xu 2006; Yang, Li and Cai 2006; Yang et al. 2008; Carrettero et al. 2011; Sabatier et al. 2012), becoming an even more powerful tool when combined with results from other disciplines such as micropaleontology and sedimentology.

This study focuses on the thick postglacial coastal plain-back-barrier succession of core 240-S5 drilled in the Po River coastal plain facing the North Adriatic Sea (Italy; text-fig. 1). The Po Plain area is known to be particularly vulnerable to future sea-level rise, as predicted by the most recent glacio-hydro-isostatic models for the Mediterranean Sea (Lambeck et al. 2011), and has been the location for several multi-proxy studies which evidenced a significant relationship between late Quaternary palaeoenvironments and sediment geochemistry (Amorosi et al. 2002, 2007, 2008; Curzi et al. 2006; Dinelli, Tateo and Summa 2007).

In this study, multidisciplinary approach, combining sedimentological, micropalaeontological (benthic foraminifers and ostracods), isotopic dating (^{14}C), and geochemical analyses, will be applied to reconstruct subtle palaeoenvironmental variations and the strict relationships between depositional setting and sediment chemistry in the Po Plain during the last transgression. This information will further contribute to the reconstruction of an evolutionary scenario for Mediterranean low-lying coastal areas subject to high rates of sea-level rise and variable climate conditions that may be applicable worldwide in the future.

GEOLOGICAL SETTING AND DEPOSITIONAL EVOLUTION OF PO PLAIN

The Po River coastal plain represents the eastern portion of the Po Plain, a peri-sutural basin bounded by two mountain chains (the Alps to the north and the Apennines to the south). This basin is filled by 700-800m of sediments accumulated during the Pliocene and Quaternary in a NE–verging thrusting of the Apennine front towards Adriatic foreland (Pieri and Groppi 1981; Castellarin and Vai 1986). Although evidences of compressional tectonic are shown by seismic data (e.g. Pieri and Groppi 1981; Ricci Lucchi et al. 1982), the late Quaternary succession of the Po River coastal plain has been deposited under relatively undisturbed conditions (Amorosi et al. 1999, 2004). The sedimentological and micropalaeontological analyses of tens cores drilled for the geological mapping project have provided a sound late Quaternary stratigraphic framework, showing an alternation of continental, paralic, and shallow marine deposits formed mainly as response to relative sea-level variations (e.g. Amorosi et al. 1999, 2003, 2008). The most recent transgressive-regressive sedimentary wedge, which lies onto glacial alluvial succession, records the Lateglacial-early Holocene marine transgression and the following depositional regression with delta and strandplain progradation (text-fig. 2; Amorosi et al. 2003, 2004). More specifically, during the last glacial period, around 20,000 cal years BP, a worldwide remarkable sea-level fall (ca. 100-120m; Fairbanks 1989; Bard et al. 1996) produced a vast alluvial plain all over the north Adriatic area including the Po Plain (e.g. De Marchi 1922; Van Straaten 1970; Amorosi et al. 2003, 2008). The subsequent shoreline transgression, resulting from the postglacial sea-level rise (Fairbanks 1989; Bard et al. 1996), produced north migrating barrier-lagoon systems (Correggiari, Roveri and Trincardi 1996). Two of these systems, originating during the Late glacial-early Holocene period, have been observed in the north Adriatic shelf (Cattaneo and Trincardi 1999; Storms et al. 2008). Age, position, and present-day water depth of these depositional bodies are consistent with coastal transgressive evolution, recording the main phases of sea-level rise after the Last Glacial Maximum-LGM (Storms et al. 2008).

The sedimentary record of retrograding barrier-lagoon systems is also well documented in the subsurface of the Po River coastal plain, where a back-barrier succession, mainly composed of lagoon clays resting on backswamp sediments, passes upward to transgressive barrier sands, thus recording the landward migration of the palaeoshoreline (e.g. Amorosi et al. 1999, 2003). At the time of maximum marine transgression (ca. 7,000 cal years BP), documented by marine fine-grained sediments at distal locations (text-fig. 2), the shoreline was located landward of its present-day position (up to 20-30 km in some areas); after that, deceleration in sea-level rise and increasing sediment fluxes induced the progradation of the deltaic-alluvial system (e.g. Amorosi et al. 1999, 2003).

In the Po Plain subsurface a well developed succession of back-barrier deposits, locally exceeding 10m of thickness, are commonly observed in close proximity to the maximum landward position of the palaeoshoreline (Amorosi et al. 1999, 2003; text-fig. 2). These successions show an overall transgressive-regressive trend in which brackish lagoon sediments, sandwiched between hypohaline paludal deposits, mark the peak of the transgression at landward locations (Amorosi et al. 1999).

In addition, facies changes are paralleled by distinctive variations in chemical composition of sediments, locally showing remarkable relationships between palaeoenvironmental and sediment provenance changes (e.g. Curzi et al. 2006; Amorosi et al. 2002, 2007).

MATERIALS AND METHODS

The core 240-S5 was analyzed as a part of the geological mapping project of the Quaternary deposits of the Po Plain at 1:50.000 scale (Cibin, Severi and Roveri 2005), supported by Regione Emilia-Romagna and Geological Survey of Italy. It is 40m long and was drilled 8.7 km inland from the shoreline at 2m above sea level by wire line perforation system, which guaranteed a continuous and undisturbed subsurface record with a recovery percentage higher than 90%. According to the subsurface geological sections and core stratigraphy reported with the geological map (Cibin, Severi and Roveri 2005), core 240-S5 was drilled in an area not affected by marine flooding during the Holocene (text-fig. 2). Indeed, the last evidence of subsurface shallow-marine deposits is observed 2.5 km seaward, in core S6; whereas lagoon and swamp deposits are remarkably thin landward (see core 514 in text-fig. 2). The core includes ca. 16m-thick lagoon and paludal sediments.

A sedimentological report of the core, including mean grain size, sedimentological structures, color (following Munsell charts) and accessory components, as organic matter, peat horizons and mollusk shells, is included with the geological map (Cibin, Severi and Roveri 2005). For this study 106 samples were collected for micropalaeontological analysis (benthic foraminifers and ostrocods) to aid facies characterization between 32 and 4m depth. The lowermost 8m and the uppermost 4m of the core, including mainly fluvial channel sands and indurated fine-grained alluvial deposits, respectively (Cibin, Severi and Roveri 2005), were not analyzed.

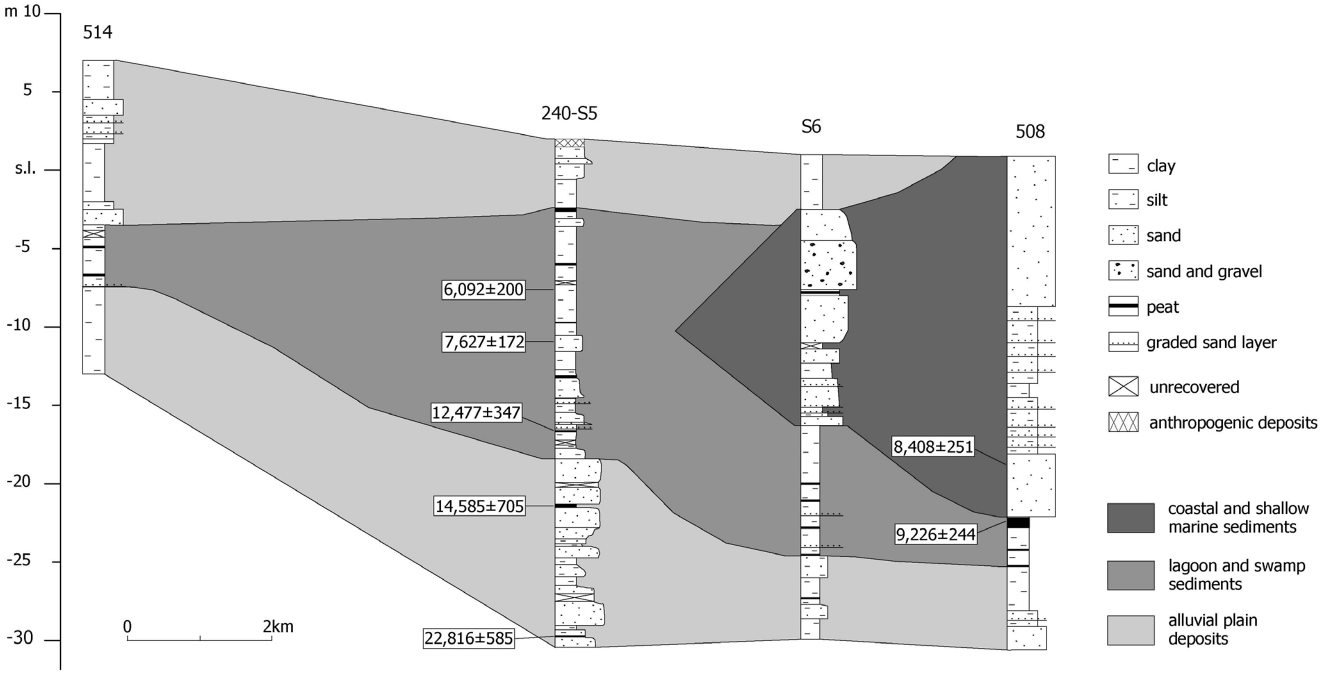
TEXT-FIGURE 1
General location of the Po Plain area with position of boreholes mentioned in this paper and section trace of text-fig. 2. The study area is included in the box.

All samples (of approximately 160 g each) were dried at 60°C for 8 hours and soaked in water or water plus hydrogen peroxide (35% vol.). The samples were then washed through sieves of 63 µm (~240 mesh) and dried again for 24 hours. The 63 micron sieve eliminated all the silt and clay particles, leaving the fine sand and larger fraction (i.e. the fraction including size range of most adult ostracods and foraminifers). After drying the samples, the residues were examined under stereozoom microscope (WILD M8) to qualitatively-semiquantitatively analyze the meiofauna (foraminifers and ostracods).

Foraminiferal taxa (Appendix 1) were identified on the basis of original microfossil descriptions *(fide* Ellis and Messina 1940) and published works of Jorissen (1988), Albani and Serandrei Barbero (1990), Sgarrella and Montcharmont Zei (1993), Fiorini and Vaiani (2001) and Rasmussen (2005). The identification of ostracod species (Appendix 1) relied on reference works by Bonaduce, Ciampo and Masoli (1975), Breman (1975), Athersuch, Horne and Whittaker (1989), Henderson (1990) and Meisch (2000).

Autoecological information on species and palaeoenvironmental significance of mixed benthic foraminiferal-ostracod assemblages were mainly inferred by comparison with modern assemblages (Breman 1975; Jorissen 1988; Athersuch et al. 1989; Henderson 1990; Montenegro and Pugliese 1996; Coccioni 2000; Debenay et al. 2000; Meisch 2000; Smith and Horne 2002; Murray 2006). Further information was obtained by comparing microfossil data with the associations found within coeval successions buried beneath other portions of Po Plain (Fiorini and Vaiani 2001; Amorosi et al. 2004; Fiorini 2004), Po River delta (Bondesan et al. 2006; Rossi and Vaiani 2008), Versilia plain (Carboni et al. 2010), Arno coastal plain (Aguzzi et al. 2007; Amorosi et al. 2009) and Orbetello and Ombrone coastal plain (Mazzini et al. 1999; Carboni et al. 2002).

For geochemical analyses, 30 samples evenly distributed along the core were collected. All samples were oven dried at 40°C to complete dryness and homogenized in an agate mortar. Chemical determinations were obtained by X-ray fluorescence spectrometry (Philips PW 1480) on pressed powder pellets following the matrix correction methods of Franzini, Leoni and Saitta (1972, 1975), Leoni and Saitta (1976) and Leoni, Menichini and Saitta (1986). The estimated precision and accuracy for trace-element determinations are better than 5%, except for those elements at 10 ppm and lower (10–15%). Bromine has



TEXT-FIGURE 2
Stratigraphic cross-section beneath the southern Po Plain, in the area of core 240-S5 (see text-fig. 1 for location of boreholes; modified after Cibin, Severi and Roveri 2005).

been determined using a net/background approach and artificial standards (mixing NaBr to a normal soil sample) used for calibration. Under the instrumental conditions a determination limit is 5 ppm. Loss on Ignition (LOI) was evaluated after overnight heating at 950°C and represents a measure of volatile substances such as water, inorganic carbon and organic matter. This parameter alone does not allow differentiation between these substances, however, sound partitioning can be made in combination with major element data. The results were constrained within a regional framework based on literature data from several boreholes (Amorosi et al. 2002, 2007, 2008; Curzi et al. 2006; Dinelli, Tateo and Summa 2007) and present day river sediments (Dinelli and Lucchini 1999).

Chronological framework of the cored succession is well-constrained by five radiocarbon dates (Cibin, Severi and Roveri 2005) performed on samples rich in organic matter. Conventional ages were calibrated in this work using CALIB version 6.0 (referenced as Stuiver and Reimer 1993) available at the website http://calib.qub.ac.uk/calib/. The calibration curve for terrestrial samples IntCal09 was applied (Reimer et al. 2009). All the ages younger than 20,000 years BP are reported here as calibrated (cal.) years BP (Tab. 1).

STRATIGRAPHY OF CORE 240-S5

Apart from the uppermost 0.3m of anthropogenic origin, five major stratigraphic intervals/facies associations were recognized in core 240-S5 (see text-fig. 3). Following an ascending order, these intervals are described below in terms of sedimentological and micropalaeontological features.

40-20.10m: Late Pleistocene alluvial plain facies association

This facies association, ca. 20m thick, is composed of a metric alternation of greyish yellow fine sands and silts-silty clays. Sandy successions, barren in macrofossils, commonly show a fining-upward tendency, while fine-grained intervals are characterized by few scattered continental mollusks and thin accumulations of decomposed organic matter and peat. A rare and poorly preserved meiofauna is recorded throughout the facies association. Specifically, few planktonic foraminifers (*Globigerina bulloides* and *Globigerinoides* spp.) and shallow-to-deep marine benthic foraminifers (including *Bolivina* sp., *Bulimina* sp., *Cassidulina laevigata carinata*, *Cibicidoides* sp., *Siphonina reticluata*, *Planulina arimensis*, *Nonionella turgida,* and *Uvigerina* sp.) with evident traces of abrasion are accompanied by scattered fragments of ostracod valves (text-fig. 3). No palaeontological samples were collected from the lowermost 8 meters. Two thin peaty layers at ca. 31.50 and 23.50m core depth furnish Late Pleistocene ages: ca. 22,800 cal years BP and 14,600 cal years BP, respectively (text-fig 3; Tab. 1).

On the basis of sedimentological features and the poorly preserved microfossil assemblage, this interval is interpreted as an alluvial depositional setting developed during the last glacial period, as supported by radiocarbon dating. Sandy successions document the activity of ancient river courses crossing the Po Plain (fluvial-channel deposits), while fine-grained intervals record the occurrence of alluvial overbank areas characterized by ephemeral slackwater bodies, as ponds, forming in small-size depressed basins lateral to the active channel.

20.10-18.10m: coastal plain facies association

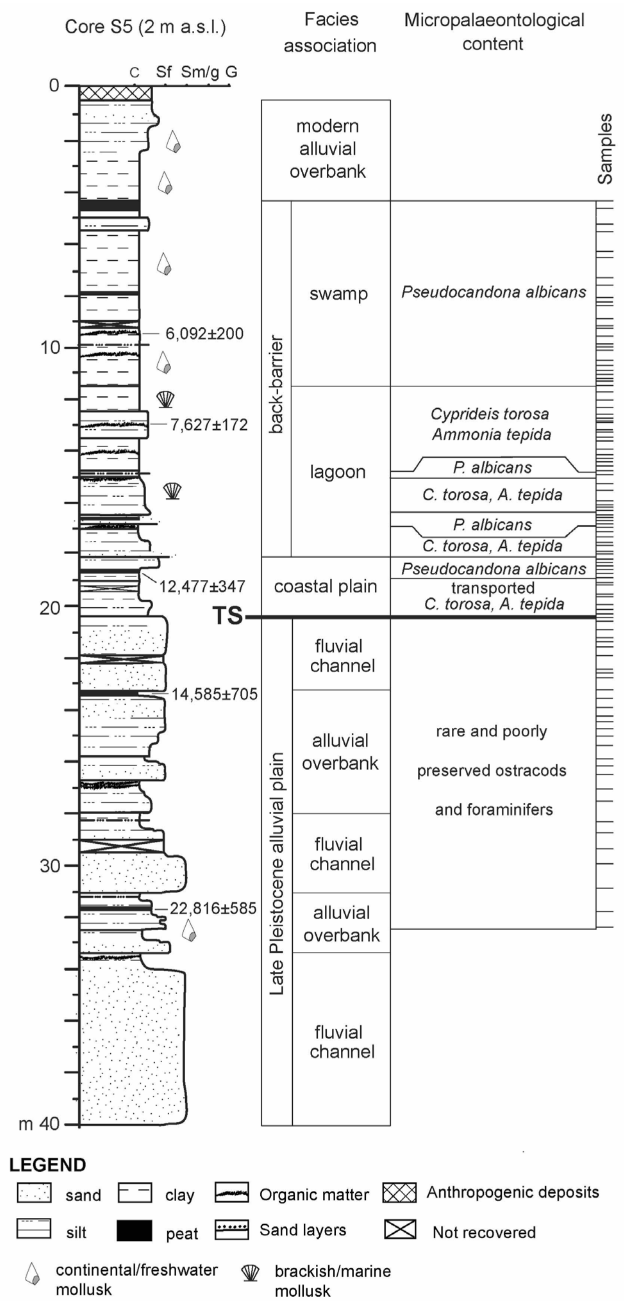
This interval consists predominantly of grey silty clays and silts with a well-developed peaty layer around 18.50m core depth (text-fig. 3). Few juvenile valves of *Cyprideis torosa,* accompanied by poorly preserved specimens of *Ammonia tepida*, are recorded up to ca. 19m core depth (text-fig. 3). In contrast, abundant valves of the mesohaline ostracod *Pseudocandona albicans* with the secondary occurrence of other mesohaline and freshwater species, as *Candona neglecta* and *Ilyocypris decipiens*, characterize the uppermost portion of this interval showing a peaty layer dated around 12,500 cal years BP (text-fig. 3; Tab. 1).

This facies association corresponds to a variety of depositional environments developed during the Lateglacial period in a low-gradient coastal plain, located not far from the coeval coastline and interpreted as the first transgressive depositional record of the study area (transgressive surface-TS is located at the lower boundary of this facies association; see text-fig. 3). More specifically, juvenile or poorly preserved specimens of typical brackish meiofauna (*Cyprideis torosa-Ammonia tepida*; Athersuch, Horne and Whittaker 1989; Debenay et al. 2000), found within the lowermost silty portion of this interval, are considered transported from a nearby lagoon area. The occurrence of autochthonous adult valves of *Pseudocandona albicans* within the uppermost meter of the clayey succession is indicative of the transition to a hypohaline slackwater organic-rich basin, possibly formed, according to the chronological framework, during the Younger Dryas stadial.

18.10-11.60m: lagoon facies association

This interval consists of grey sandy silts and silty clays generally organized in a fining-upward (FU) tendency. Thin sandy layers occur around 18m and 17m core-depth. A high organic matter content, locally forming thin peat intercalations, is recorded throughout this interval along with brackish/marine bivalves (text-fig. 3). The meiofauna is commonly characterized by numerous valves of *Cyprideis torosa*, a typical brackish ostracod (Athersuch et al. 1989; Meisch 2000), accompanied by a benthic foraminiferal assemblage dominated by the euryaline species *Ammonia tepida* in association with small amounts of a few other taxa (mainly *Ammonia parkinsoniana*, *Haynesina germanica* and *Cribroelphidium* spp.). Few valves of other brackish or shallow-marine ostracods tolerant to salinity oscillations and high organic matter concentrations, such as *Loxoconcha elliptica*, *Palmoconcha turbida* and *Cytherois fischeri* (Ruiz et al. 2000), are locally encountered. An abrupt change in microfossil content is recorded twice around 16.5m and 15m core-depth, in conjunction with centimetric-thick, organic-rich layers containing valves of *Pseudocandona albicans*. A sample at 12.9m core-depth furnishes an age of ca. 7,600 cal years BP (text-fig. 3; Tab. 1).

On the basis of sedimentological and micropalaeontological features, this interval is interpreted as a brackish back-barrier environment, developed in the Po Plain during the early Holocene in response to the landward migration of a barrier-lagoon system. Indeed, the autochthonous assemblage *Cyprideis torosa-Ammonia tepida* is recorded within recent sediments of brackish Mediterranean lagoons (Samir 2000) and within several Holocene lagoon successions buried beneath Mediterranean coastal areas (Mazzini et al. 1999; Amorosi et al. 2004; Fiorini 2004; Aguzzi et al. 2007; Carboni et al. 2002, 2010). In contrast, the organic-rich stratigraphic intervals with a



TEXT-FIGURE 3
Lithology, facies associations and microfossil content of core 240-S5. Only the main microfossil characteristics are reported along with the main taxa of benthic foraminifers and ostracods. TS: transgressive surface. Radiocarbon dates are reported as calibrated years BP (see also Table 1).

mesohaline ostracod species preferring stagnant waters are interpreted to reflect two abrupt, brief periods of paludal conditions occurred before 7,600 cal years BP.

11.60-4.30m: swamp facies association

This facies association is composed of a massive 7m-thick succession of yellowish grey silty clays, grading upward to grey

TABLE 1
Radiocarbon dating for core 240-S5. Conventional age from Cibin, Severi and Roveri (2005).

Core depth (m)	Dating material	Conventional age (year BP)	Calibrated age (cal year BP)
9.50	Organic clay	5,290±100	6,092±200
12.90	Organic clay	6,770±105	7,627±172
18.50	Organic clay	10,650±130	12,477±347
23.40	Organic clay	12,500±220	14,585±705
31.60	Organic clay	19,050±230	22,816±585

silty clays from 7m core-depth, with decimetric to centimetric-thick silty layers, and marked at the top by a well-developed 50cm-thick peat. A 15cm-thick peaty layer formed by decomposed organic matter is also recorded around 8 meters core-depth. Traces of bioturbation and scattered freshwater mollusks are found throughout the succession. The meiofauna is dominated by the mesohaline species *Pseudocandona albicans*, with the sporadic occurrence of other mesohaline and freshwater ostracods as *Candona neglecta* and *Ilyocypris decipiens*. Poorly preserved specimens of the true euryhaline ostracod *Cyprideis torosa* occur at ca. 10m core-depth within a silty layer (text-fig. 3) while few valves of the mesohaline species *Heterocypris salina* are found within the uppermost peat. A radiocarbon age from the lower part of the clayey succession dates this interval to the mid-late Holocene period (ca. 6,000 cal years BP; see Tab. 1 and text-fig. 3).

On the basis of sedimentological features combined with a low diversified hypohaline ostracod fauna, dominated by species preferring stagnant waters as *Pseudocandona albicans* (Henderson 1990; Meisch 2000), this interval is interpreted as a wet, low-energy depositional setting rich in vegetation, such as a swampland developed at the landward margin of a back-barrier area and occasionally affected by high energy events (silty layers containing transported brackish ostracods).

4.30-0.30m: modern alluvial overbank facies association

This facies association, 4m-thick, consists dominantly of bioturbated yellow silty clays and clayey silts organized in a coarsening-upward trend and containing scattered continental mollusks. A decimetric sandy layer with a sharp, no erosive lower boundary is recorded around 1m core-depth. No samples were collected within this interval (text-fig. 3).

On the basis of sedimentological features, this interval is interpreted as an overbank facies association formed on the modern alluvial Po Plain. The overall coarsening-upward trend suggests a progressive approach of the active channel, in particular the thin sandy layer at ca. 1m core-depth possibly reflects a levee deposition formed during small-scale river floods.

GEOCHEMISTRY OF CORE 240-S5

The geochemistry of sediments from core 240-S5 is characterized by the mixing between a carbonate and a silicate fraction, as emphasized by the opposite trends between CaO and Al_2O_3, SiO_2, Fe_2O_3, and K_2O (obviously related to the silicate fraction) (text-fig. 4).

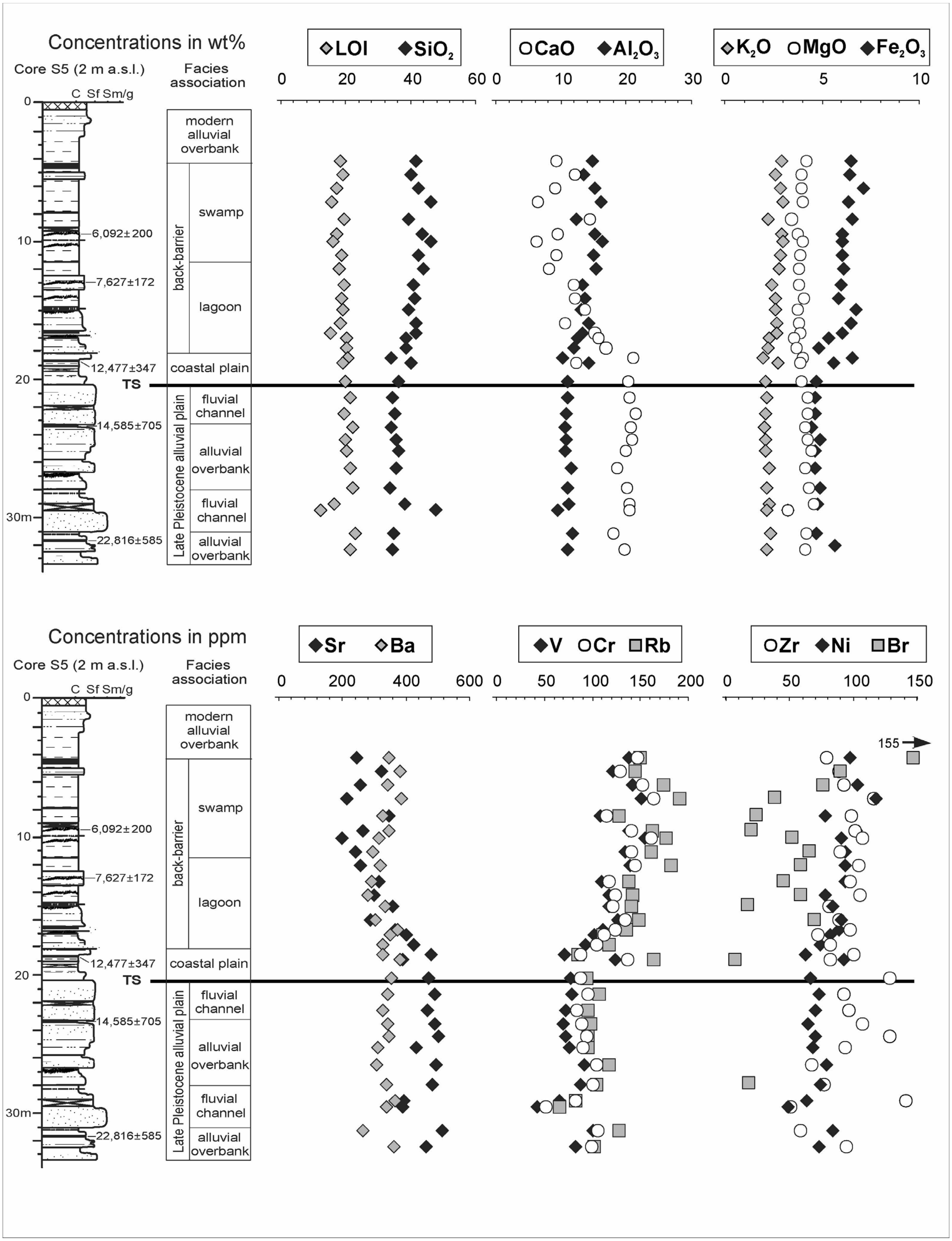
Although occasionally controlled by the presence of Ca-silicates (e.g. plagioclase, pyroxenes), concentration of CaO is mainly related to the abundance of calcite, dolomite and possibly aragonite. The highest carbonate fraction, constant around 21%, is within the Late Pleistocene alluvial section in the lowermost core portion (up to ca. 20m core depth; see text-fig. 4). An irregular trend of carbonate concentration characterizes the coastal plain deposits, which display values ranging between ca. 20-12%. Corresponding with the transition to the back-barrier lagoon succession, CaO concentrations progressively decrease. A similar trend is displayed also by Sr (text-fig. 4), an element which commonly substitutes for calcium in many minerals.

The silicate fraction shows an opposite trend to calcium (text-fig. 4) with constant, and generally low, abundances within the Late Pleistocene alluvial deposits with increasing values in the overlying coastal plain succession (which is characterized by highly variable concentrations) and back-barrier clays. This trend is well displayed by the profiles of Al_2O_3, SiO_2, Fe_2O_3, and K_2O (among the major elements) and V, Cr, Rb and Ni (among the trace elements) (text-fig. 4). Even if the major element data could be partially affected by a closure effect (Aitchison 1986), the profile displayed by trace elements, determined absolutely by reference to standards, more clearly supports the balance between carbonate and aluminosilicate and confirms the decrease in the carbonate fraction in the upper stratigraphic portion of the 240-S5 core. Also note the peak in SiO_2 at 29.25m, matched by minima in almost all the other elements associated to the silicate fraction, which is related to a quartz enrichment in correspondence of a specific sandy layer.

The LOI content and MgO concentration don't show significant variations along the core, except for low values at 29.25m. Barium has an almost regular profile characterized by median concentrations of 340 ppm, with the exception of slightly lower values (median 300 ppm) recorded within lagoonal clays (text-fig. 4). This variation can be explained by the relation existing between Ba concentration and feldspars in the lower sandy samples. Zirconium shows few peaks (>120 ppm) within the alluvial succession, mainly associated to sands, while in the overlying clayey deposits its concentrations are more constant (text-fig. 4). Zirconium concentration is basically controlled by occurrence of the heavy mineral zircon, commonly associated with coarse-grained fluvial sediments (Vital and Stattegger 2000; Dypvik and Harris 2001; Dinelli, Tateo and Summa 2007).

Apart a few scattered points below 15.95 m, the Bromine profile points out that this element is constantly recorded starting from the lower part of the back-barrier succession (text-fig. 4). Although the precise mechanism is not completely understood (Mayer et al. 2007), Bromine in sediments seems to be controlled by reactions with organic matter (Harvey 1980). The major reservoir of Bromine is represented by seawater, both as direct seawater interaction and sea-spray dispersion (Alvisi and Dinelli 2002; Lucchini, Dinelli and Calanchi 2003).

In summary, the bulk geochemistry of core 240-S5 shows a marked difference between the Late Pleistocene glacial alluvial deposits and the overlying transgressive succession (text-fig. 4). While coastal plain deposits display an intermediate composition, suggesting a gradual transition to higher concentrations of alumosilicate related elements, a significant change in geochemical features occurs few meters above the transgressive surface in proximity to the lower boundary of the back-barrier succession. This trend is basically controlled by a change in grain size, as seen in the variation in the Rb/Zr profile (in



TEXT-FIGURE 4
Downcore profiles of selected elements discussed in the text. Bold horizontal line marks the Transgressive Surface (TS).

text-fig. 5). Low values, indicative of a coarse silt fraction (Dinelli, Tateo and Summa 2007), are common in the glacial fluvial channel deposits. Higher values, common in finer-grained sediments, characterize the overlying lagoon and swamp deposits and occasionally the alluvial overbank sediments. Coastal plain deposits show both features.

SEDIMENT PROVENANCE

Several studies, that discussed in detail the provenance of sediments in the Po Plain either using data from boreholes (Amorosi et al. 2002, 2007, 2008; Curzi et al. 2006; Dinelli, Tateo and Summa 2007), marine cores (Picone et al. 2008) or surface soils (Amorosi and Sammartino 2007), identified clear signals of the major sediment sources in the area. In particular, the Po River sediments are characterized by high concentrations of Chromium and Nickel related to important contributions from ultramafic rocks that are not present in the Apenninic rivers sediments. Amorosi and Sammartino (2007) proposed a plot to separate the two sources (text-fig. 6a) based on Cr and V concentration and taking into account the grain size difference. The samples from 240-S5 core are all comparable to an Apenninic sediment source (text-fig. 6a) when the differences in absolute concentration related to grain-size among Late Pleistocene alluvial, coastal plain and back-barrier deposits are considered. Moreover the Cr/Al_2O_3 ratio (text-fig. 6b), originally proposed by Amorosi et al. (2002) as a provenance discriminator, does not reach values >11.5 that is the threshold separating Apenninic sources from Po River source (Amorosi and Sammartino 2007). This parameter shows a slight increase in the upper portion of the core but it does not reach values typical of Po River provenance. In contrast, these values are directly comparable to those of boreholes 240-S9 and 239-S2 (text-fig. 1) and more clearly related to an Apenninic provenance (Amorosi et al., 2002). The low value at 29.25m occurs in the already mentioned sandy sample (see previous chapter).

These data are also comparable to those of the major rivers in the area, such as the Fiumi Uniti (63 V, 106 Cr, 10.9 Cr/Al_2O_3) and Savio (94 V, 122 Cr, 10.3 Cr/Al_2O_3) (Dinelli and Lucchini 1999), which could have been the most important contributors of sediment to the core site (see text-fig. 1 for location). The higher values observed in 240-S5 samples are related to the finer grain size of lagoon and swamp deposits.

Thus, because it is in proximity of Apenninic chain and too far from the major historic Po River branch, our data indicate that the core site has never received significant sediment contribution from the Po River during the late Quaternary. Moreover, core 240-S5 did not record coastal or open marine depositional environments, that could have been influenced by sediments transported from other areas by longshore drift currents, such as shown in several cores located in proximity of the shoreline (Amorosi et al. 2002; Curzi et al. 2006).

The provenance of 240-S5 core sediments can be better constrained using other geochemical indexes that compare the Mg/Ca ratio to the Ba/Al ratio (text-fig. 7). The former is conditioned by the presence and type of carbonate material, while the latter reflects the occurrence of feldspars or clays. Magnesium can also be abundant in fine grained rocks since it is a major component of many clay minerals leading to major changes in the ratio, particularly if there is a change in calcium carbonate content, as in the present case. The plot of these two ratios, in addition to reference data from the Fiumi Uniti and the Savio River drainages (Dinelli 1995; Dinelli and Lucchini 1999, 2004), establishes a clear sedimentary provenance. Late Pleistocene alluvial sediments are similar to the Savio River ones, while the Holocene back-barrier sediments are more similar to the Fiumi Uniti. The composition of coastal plain deposits is indicative of a mixed sediment contribution to the core site from the Savio River and Fiumi Uniti system during the Lateglacial period (text-fig. 7).

LATE PLEISTOCENE-HOLOCENE PALAEOENVIRONMENTAL EVOLUTION IN THE FRAMEWORK OF REGIONAL SEA-LEVEL AND CLIMATIC CHANGES

The thick alluvial succession, recorded at the lowest stratigraphic portion of core 240-S5 and dated to the Late Pleistocene (between ca. 23,000 and 15,000 cal years BP; see text-fig. 3), reveals that a high-energy fluvial environment developed in the study area during the last glacial period. This is consistent with the regional stratigraphical framework (e.g. Amorosi et al. 1999, 2003), showing that a wide alluvial area occupied the Po Plain in response to the sea-level drop of the last glaciation (up to 100-120m at ca. 20,000 cal years BP; Fairbanks 1989; Bard et al. 1996). Sediment composition of alluvial deposits clearly indicates an Apenninic provenance, suggesting a strong influence by the Savio River (text-fig. 7).

The ensuing relative sea-level rise, occurred in the north Adriatic between ca. 13,000-7,000 cal years BP (Lambeck et al. 2004), led to the abrupt drowning of the continental areas and pervasive coastal sedimentation across the Po Plain (e.g. Amorosi et al. 2004; Cibin, Severi and Roveri 2005). Within the core succession, the first transgressive record is shown by the transgressive surface dated at 14,600-12,500 cal years BP, at the passage from glacial fluvial deposits and the overlying coastal plain sediments (TS in text-fig. 3). During the earliest stages of transgression, a low-gradient coastal plain developed at the core site and the occurrence of a transported brackish meiofauna suggests the presence of a nearby lagoon area. A semi-coeval barrier-lagoon system, dated around 14,300 cal years BP, is preserved on the northern Adriatic shelf at ca. 90m water depth (Storms et al. 2008). The formation of this isolated sediment body is connected by the authors to the high rates of sea-level rise (up to 60 mm/year) occurring during the melt-water pulse MWP-1A, dated at 14,300-14,000 cal years BP (Fairbanks 1989; Bard et al. 1990, 1996).

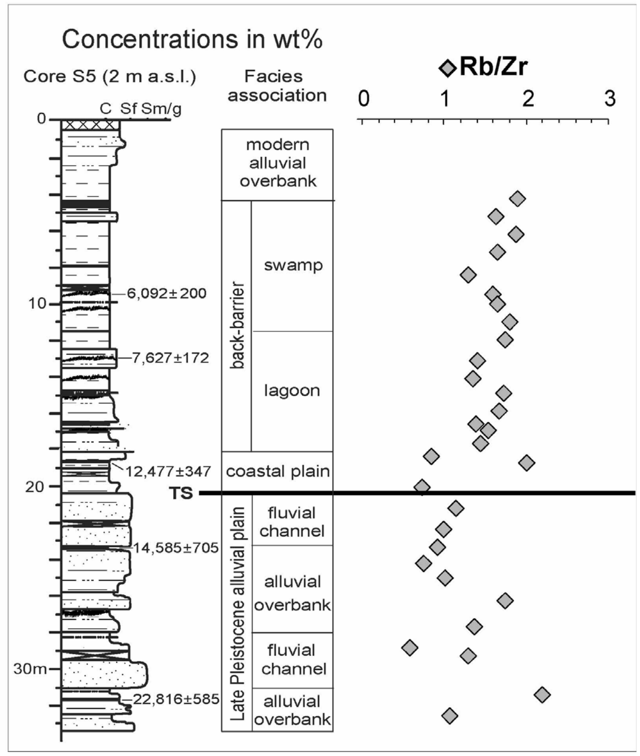
In the uppermost portion of the coastal plain succession, the occurrence of organic rich deposits containing a mesohaline ostracod fauna and a well-developed peaty horizon likely reflects a minor, short-term episode of coastal progradation with a seaward migration of the barrier-lagoon system. The radiocarbon age of ca. 12,500 cal years BP (see text-fig. 3) shows that this short-term depositional episode occurred during a time interval, the Younger Dryas, characterized by sea-level rise deceleration, and climatic deterioration (Mangerud et al. 1974; Bard et al. 1996; Bard, Hamelin and Delanghe-Sabatier 2010; Fiedel 2011). Complex palaeogeography and unstable palaeoenvironmental conditions affected the study area during the Lateglacial period. The geochemical composition of coastal plain sediments shows intermediate values respect to those recorded within the underlying glacial alluvial deposits and the overlying back-barrier succession. Therefore, a mixed sediment contribution from the Savio River and the Fiumi Uniti system can be envisaged and considered indicative of a first stage of drainage reorganization (text-fig. 7).

The coastal plain then rapidly evolved into a protected brackish lagoon, providing evidence for a remarkable palaeoenvironmental change, clearly recorded both by microfossil assemblages and chemical composition of sediments. The former highlight an abrupt passage to an abundant brackish meiofauna dominated by *Cyprideis torosa* and *Ammonia tepida*; the latter shows a distinctive reduction of carbonates, paralleled by an increase in the alumosilicate fraction and a general finer grain size. The development of a lagoon basin at the core site marks a rapid landward migration of the back-barrier system likely driven by the melt-water pulse MWP-1B. This fast transgressive pulse following the Younger Dryas (Fairbanks 1989; Blanchon and Shaw 1995) is characterized by relatively high rates of sea-level rise (ca. 10 mm/years) and high wave energy (Storms et al. 2008). Although no radiocarbon dating is available at the transition between coastal plain and lagoon deposits, the chronological framework of the core and widespread deposition of early Holocene lagoon muds across the Po Plain (e.g. Amorosi et al. 2005; Curzi et al. 2006) support this interpretation. The provenance of the back-barrier succession sediments also changed, indicating a composition more similar to the present day Fiumi Uniti River system (text-fig. 7), which probably flowed to a more eastern position during the pre-historical period. This minor change in sediment provenance within the transgressive succession of core 240-S5 implies a drainage system reorganization possibly induced by an increasing rate of sea-level rise.

Short-term environmental changes also occur within back-barrier system during the early-mid Holocene period, suggesting complex coastal dynamics and frequent oscillations in the balance between sediment supply and accommodation space under eustatic sea-level rising conditions. Abrupt variations in microfossil content, with the sudden substitution of *Cyprideis torosa*-*Ammonia tepida* assemblage by *Pseudocandona albicans*, highlight two episodes of more restricted, swampy conditions in the lagoon basin (text-fig. 3). In contrast, no significant changes in sediment composition are recorded throughout the back-barrier succession.

Although an autocyclic control on these episodes of early Holocene lagoon infilling cannot be excluded *a priori*, allocyclic factors, mainly the changing relative sea-level and climate conditions, were probably dominant during the postglacial transgressive period. Indeed, millennial to centennial-scale climate events are globally well-documented in the Northern Hemisphere for the Lateglacial-early Holocene period (Bond et al. 1997; Mayewski et al. 2004), and a step-like eustatic sea-level trend characterized by phases of slow sea-level rise alternating with rapid rising events (Melt Water Pulses-MWPs) is suggested by several markers (Fairbanks 1989; Liu et al. 2004; Bard, Hamelin and Delanghe-Sabatier 2010; Bird et al. 2010).

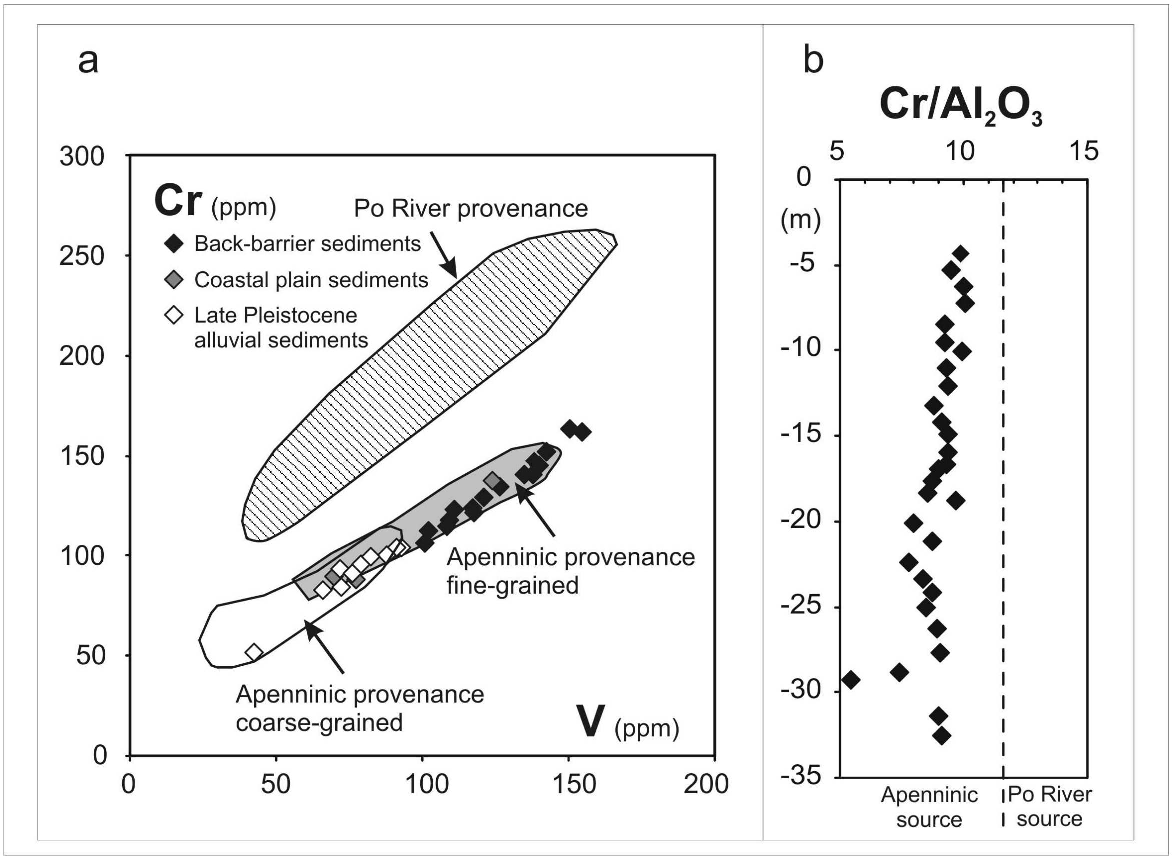
A similar cyclic depositional patterns are identified within coeval subsurface successions buried beneath several Mediterranean coastal plains, confirming a dominant allocyclic control. Up to three small-scale transgressive-regressive depositional cycles (parasequences) compose the transgressive succession (ca. 12,400-7,500 cal years BP) buried beneath the Po di Volano areas, at ca. 60 km northward from the core site (Amorosi et al. 2005; see text-fig. 1 for location). These parasequences were



TEXT-FIGURE 5
Downcore profile of the Rb/Zr ratio.

interpreted as the stratigraphic record of the step-like postglacial sea-level rising trend. In the subsurface of the Po Delta, 20 km northward, an episode of increasing fluvial activity dated around 9,500 cal years BP, possibly related to a sea-level stillstand, is recorded by the abrupt superposition of crevasse sands onto backswamp clays (Amorosi et al. 2008). Similarly, along the Tyrrhenian coast a climatic change signature is documented by pollen data from three small-scale, estuarine-swamp depositional cycles composing the Lateglacial-early Holocene (ca. 13,000-8,000 cal years BP) transgressive valley fill of the Arno plain (Amorosi et al. 2009). In particular, the oldest and the youngest "regressive" phases of estuarine infilling were tentatively related by the authors to the two most prominent and widespread cooling events of the postglacial period: the Younger Dryas (12,900-11,600 cal years BP) and the 8,200 years event, respectively.

During the subsequent phase of the sea-level highstand, starting about 7,500 cal years BP (Pirazzoli, 2005), the decreasing rate of sea-level rise and the increasing sediment supply/accommodation space ratio produced a seaward migration of shoreline and back-barrier system within a relative regressive trend across the Po Plain (e.g. Amorosi et al. 2003, 2004). In core 240-S5, the lagoon environment is replaced upward by a hypohaline swamp, dated to ca. 6,000 cal years BP, with a peculiar ostracod assemblage dominated by *Pseudocandona albicans*. Minor variations in geochemical composition of sediments have been observed by selected elements slightly below the boundary sep-



TEXT-FIGURE 6
a) Cr vs. V plot for the 240-S5 samples. The compositional fields identify different sediment source areas and different grain-size, not differentiated for the Po River provenance (from Amorosi and Sammartino 2007). Open symbols: Late Pleistocene alluvial sediments; filled grey symbols: coastal plain sediments; filled black symbols: back-barrier sediments. b) profile of Cr/Al203 for the 240-S5 core. The dotted line identifies the 11.5 value proposed by Amorosi and Sammartino (2007) as the limit between Apenninic and Po river provenance.

arating the lagoon from the swamp succession. Specifically, an increase in Al_2O_3, V, Cr, Rb paralleled by decrease in Sr and CaO is recorded from the uppermost 45 cm of lagoon sediments and possibly corresponds to a closure of the environment, supported by the increase in the clay fraction.

This low-lying swamp basin was then filled by a few meters of modern alluvial overbank deposits.

CONCLUSIONS

The detailed facies characterization of core 240-S5, combined with sediment geochemistry and radiocarbon dating, furnishes new insights on the late Quaternary history of the southern Po Plain, thus highlighting the stages of development of coastal plain and back-barrier systems along the northern Adriatic coast.

The palaeoenvironmental evolution observed in the core succession reflects an overall transgressive-regressive tendency controlled by changes in Late Pleistocene-Holocene relative sea-level, sediment supply, and accommodation space in the depositional basin. Despite the overwhelming control exerted by the Lateglacial-early Holocene rising sea-level trend on coastal evolution, this study documents palaeoenvironmental scenarios and dynamics in the southern Po Plain as recorded by microfossils and geochemical sediment features.

Although the core position produces a homogeneous Apenninic provenance of sediments, a subtle change in the source area, from the Savio River to the Fiumi Uniti system, is detected in connection with the superposition of an early Holocene lagoon onto a Lateglacial coastal plain. The rapid landward migration of the back-barrier system and the drainage reorganization of the southern Po Plain were driven by a fast transgressive pulse ascribable to the MWP-1B.

Subtle microfossil variations within the transgressive succession of core 240-S5 highlight the occurrence of short-term progradational episodes, not accompanied by significant change in geochemical features. More restricted conditions developed during the earliest stage of transgression (Younger Dryas stadial?), just before the flooding event which led to the establishment of an Holocene back-barrier system in the study area. Moreover, two abrupt lagoon infilling phases took place before ca. 7,600 cal years BP. Similar depositional patterns are recorded within coeval subsurface successions buried beneath the Po Plain and other Mediterranean coastal plains, suggesting a predominant allocyclic control on sedimentation.

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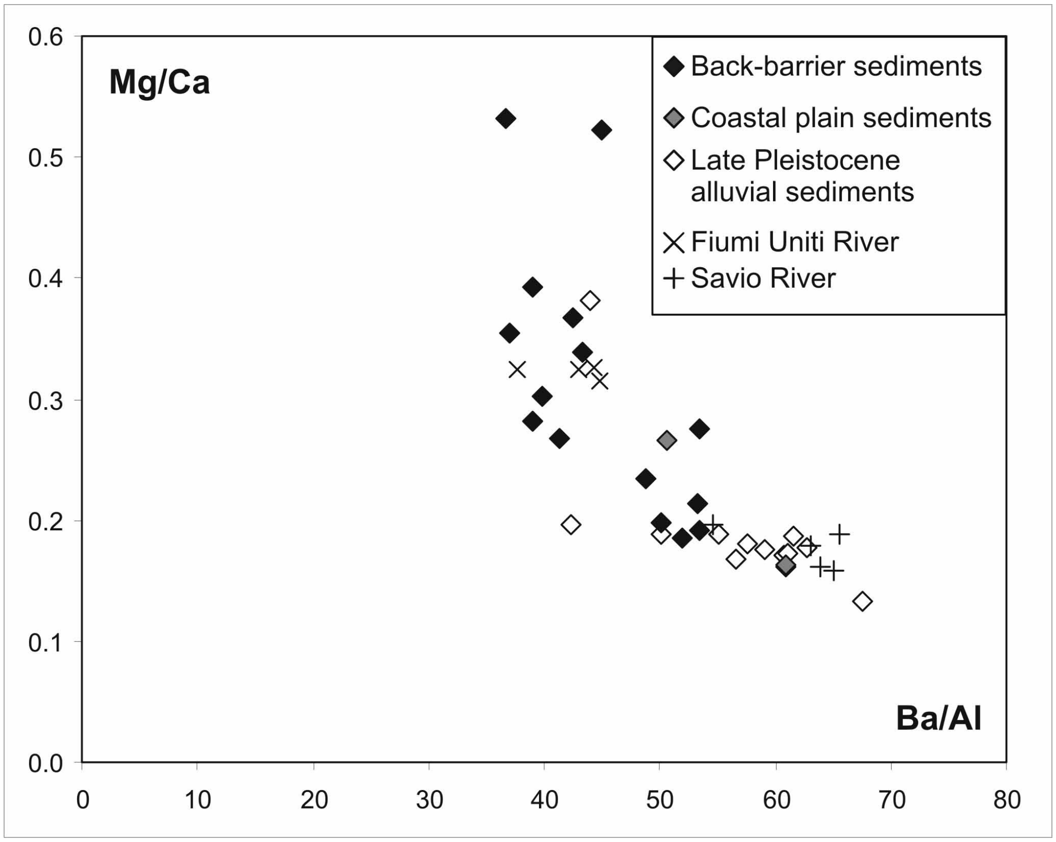

TEXT-FIGURE 7
Mg/Ca vs. Ba/Al diagram discriminating the source of sediments of core 240-S5. Open symbols: Late Pleistocene alluvial sediments; filled grey symbols: coastal plain sediments; filled black symbols: back-barrier sediments.

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APPENDIX 1

Taxonomic Reference List

This list includes genus and species of foraminifers and ostracods cited in the paper.

Foraminifera

Ammonia parkinsoniana - *Rosalina parkinsoniana* d'Orbigny, 1839; p. 99, pl. 4 figs. 25-27.

Ammonia tepida - *Rotalia beccarii* (Linné) var. *tepida* Cushman, 1926; p. 79, pl. 1.

Bolivina – *Bolivina* d'Orbigny, 1839; p. 60.

Bulimina - *Bulimina* d'Orbigny, 1826; p. 269.

Cassidulina laevigata carinata - *Cassidulina laevigata* d'Orbigny var. *carinata* Silvestri, 1896; p. 104, pl. 2, fig. 10a-c.

Cibicidoides - *Cibicidoides* de Montfort, 1808; p. 122.

Cribroelphidium – *Cribroelphidium* Cushman and Brönnimann, 1948; p. 18.

Globigerina bulloides - *Globigerina bulloides* d'Orbigny, 1826; p. 277, no. 1. Banner and Blow, 1960; p. 3, pl. 1, figs. 1-4.

Globigerinoides - *Globigerinoides* Cushman, 1927; p. 87.

Haynesina germanica - *Nonionina germanica* Ehrenberg, 1840; p. 23.

Nonionella turgida - *Rotalina turgida* Williamson, 1858; p. 50, pl. 4 figs. 95-97.

Planulina arimensis - *Planulina arimensis* d'Orbigny, 1826; p. 280, pl. 14, figs. 1-3, 3bis.

Siphonina reticluata – *Rotalina reticluata* Czjzek, 1848; p. 145, pl. 13, figs. 7-9.

Uvigerina – *Uvigerina* d'Orbigny, 1826; p. 268.

Ostracoda

Candona neglecta – *Candona neglecta* Sars, 1887; p. 107, pl.15 figs. 5-7

Cyprideis torosa – *Candona torosa* Jones, 1850; p. 27, pl. 3 figs. 6a-e.

Cytherois fischeri – *Cytherois fischeri* Sars, 1866; pl. 114 figs. a-o.

Heterocypris salina – *Cypris salina* Brady, 1868; pl. 26 figs. 8-13.

Ilyocypris decipiens – *Ilyocypris decipiens* Masi, 1905.

Loxoconcha elliptica – *Loxoconcha elliptica* Brady, 1868; p. 435, pl. 27 figs. 38, 39, 45-48; pl. 40 fig. 3.

Palmoconcha turbida – *Loxoconcha levis* G.W. Müller, 1894; p. 344, pl. 27 figs. 8, 19, 22, pl. 28 figs. 4, 8. *Loxoconcha turbida* G.W. Müller, 1912; p. 308 (new name).

Pseudocandona albicans (Brady, 1864) – *Candona albicans* Brady, 1864; p. 61, pl. 4 figs. 6-10.

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