



## Palaeoenvironmental reconstruction of late Quaternary foraminifera and molluscs from the ENEA borehole (Versilian plain, Tuscany, Italy)

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### ABSTRACT

Foraminifera and molluscs from the 90 m deep ENEA borehole (Versilian plain, central Italy) were studied for palaeoenvironmental purposes. Palaeontological analyses, integrated with U/Th and radiocarbon data, helped to recognize late Quaternary sea-level changes and supplied results on tectonic mobility of the area. The study highlighted four sedimentary phases. The first phase consists of a shore environment attributed to MIS 7.1. A hiatus corresponding to MIS 6 is hypothesized at the top of this interval. Recognition of the paleo-shoreline of MIS 7.1 at  $-72.8$  m signifies a vertical displacement due to the extensional tectonics of the Apennine orogenesis. The second phase consists of a transgressive succession with evidence of warm temperatures, which was interpreted as part of the transgression leading to the MIS 5.5 highstand. The third phase includes sub-aerial and lacustrine deposits. Radiocarbon dates and palaeoecological reconstruction led us to attribute this interval to MIS 4, MIS 3 and MIS 2. The fourth phase begins with a lagoon environment attributable to Holocene sea-level rise and ends with marsh episodes, signifying the progradation of the alluvial plain. This reconstruction confirms the hypothesis of tectonic stability for the Versilian area during the Holocene.

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### Introduction

Marginal marine environments, such as coastal marshes, lagoons, and estuaries, are the most suitable environments to record the effects of climatic and sea-level changes. In particular, benthic fauna shows a detectable response even to small changes of environmental parameters, making them good palaeoenvironmental markers for the late Quaternary succession. In core sequences, lagoonal environments that indicate sea level to within an uncertainty of 2 m (Lambeck et al., 2004) are easily recognised by their faunal content. A detailed palaeoenvironmental reconstruction may be performed by means of palaeontological analysis and can be finalised by recognizing sea-level markers and sea-level changes. This reconstruction is useful for pointing out transgressive and regressive trends.

Benthic foraminifera have long been recognised as useful tools for palaeoenvironmental reconstruction, due in part to recent studies on dead and living assemblages in marine marginal environments. The potential of benthic foraminifera as environmental tools is well documented in studies on boreholes drilled on alluvial plains along

the Adriatic and Tyrrhenian coasts of Italy (Mazzini et al., 1999; Fiorini and Vaiani, 2001; Carboni et al., 2002; Amorosi et al., 2004a, b; Bergamin et al., 2006). Benthic marine and non-marine molluscs prove to be a powerful tool in palaeoenvironmental reconstruction as they indicate well defined biota and climatic changes (Pérès and Picard, 1964; Ložek, 1964; Basso and Corselli, 2007). Consequently, the integrated use of molluscs and foraminifera as environmental tools is particularly suitable for the study of the ENEA borehole because it covers the entire range from terrestrial to marine infralittoral environments.

The ENEA borehole was drilled in the Versilian plain close to Massaciucoli Lake. The Versilian plain is the innermost part of the Viareggio basin along the Tyrrhenian coast of Tuscany, which originated by an extensional neotectonic phase involving the Tuscany–Umbria sector during the Late Pliocene–Pleistocene (Mauffret et al., 1999). The Versilian Pleistocene–Holocene subsurface succession was reconstructed by Federici (1993) by studying 101 boreholes, the most important of which was 187 m deep. The complete stratigraphic column includes nine units characterised mainly by sandy marine deposits alternating with continental clayey sediments.

In previous studies of the ENEA borehole (Antonioli et al., 1999; Nisi et al., 2003; Lambeck et al., 2004), a total of 21 dates (19  $^{14}\text{C}$  and two  $^{230}\text{Th}/^{234}\text{U}$ ) crossing MIS 1, 2, 3, and 5 were utilised for the

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chronological frame. The paleo sea-level reconstruction was based on the lithological interpretation and the scattered presence of *Cerastoderma glaucum* and *Cladocora caespitosa*, which are considered good indicators of paleo sea level.

The aim of this study is to improve the accuracy of previous studies, pointing out the depositional sea-level indicators by means of benthic assemblages used as palaeontological proxies. The study of foraminifera and molluscs revealed the depositional environments and their succession highlighted the sea-levels changes. These sea-level changes can be referenced to the geochronological framework, with a final result of reconstructing the late Quaternary palaeoenvironmental evolution of the plain.

## Materials and methods

A 90 m deep borehole named “ENEA” was drilled in 1998 at 0 m asl, directly south of the Massaciucoli Lake (32TPP 606 501) (Figs. 1 and 2). A total of 116 samples were gently washed over 125  $\mu\text{m}$  sieves and oven-dried at 60°C. The lithological core succession is characterised, from the bottom (–90.00 m) to –67.00 m by fine sands alternating with clay and silty sand containing molluscs and coral fragments,

changing into medium fine sands. From –67.00 to –55.00 m, laminated clays and silty clays occur. The following layer consists of 7 m of coarse gravel and pebbles in sandy matrix (from –55.0 to –48.0 m). Next, (from –48 to about –35 m), clay and silty clay sediments with vegetal remains are present, covered by an alternation of sandy silt and sandy clay with locally oxidized organic deposits in pockets (to –29 m). Medium to fine sand and coarse sand-bearing scarce fossiliferous content follow until –12 m. The upper part of the core contains coarse and medium sand with molluscs fragments followed by peaty clay bearing *Cerastoderma glaucum*, alternating with sandy silt and silty sand.

## Foraminifera

The >125  $\mu\text{m}$  size fraction was selected for the qualitative analysis performed on all 116 available samples. Among these, 80 samples were barren or contained poorly preserved, allochthonous specimens, eight showed very rare foraminiferal content, and 28 had sufficient foraminiferal density for quantitative analysis. The dry residue was split into aliquots containing approximately 300 well-preserved specimens, which were picked and classified according to the generic

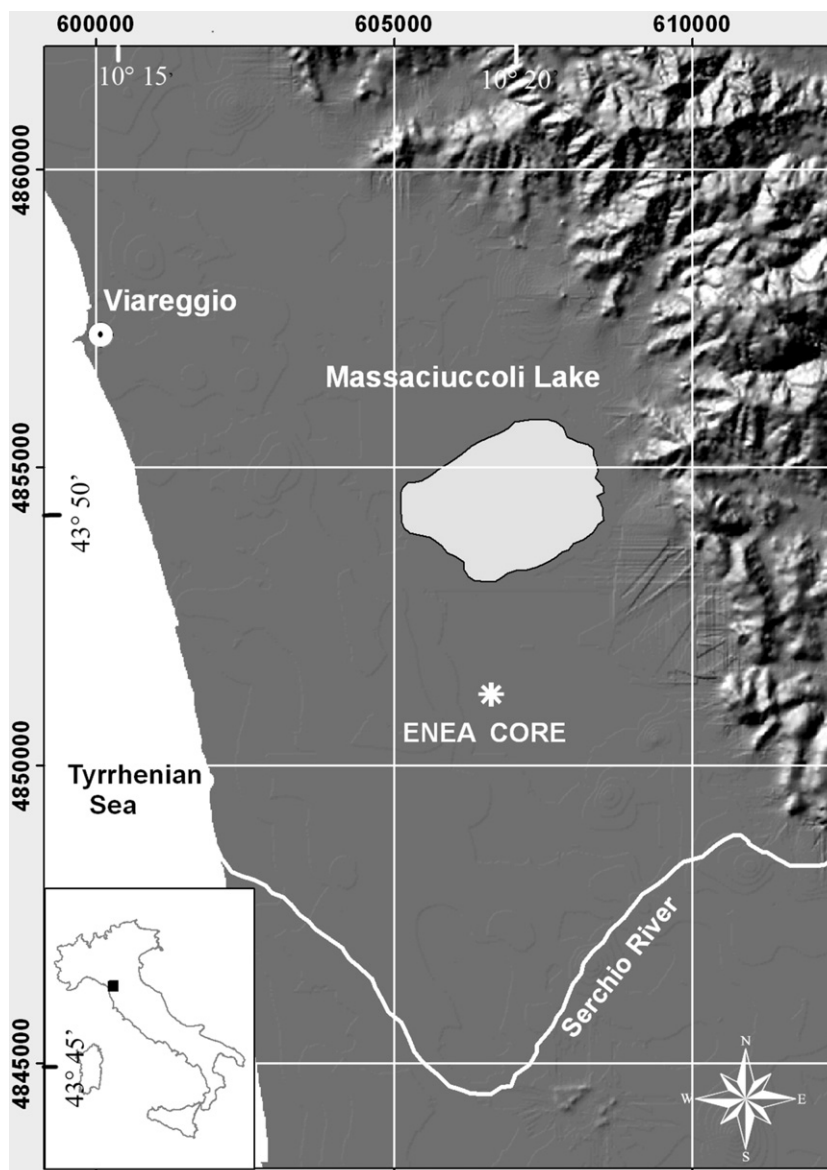


Figure 1. Location of the ENEA borehole.

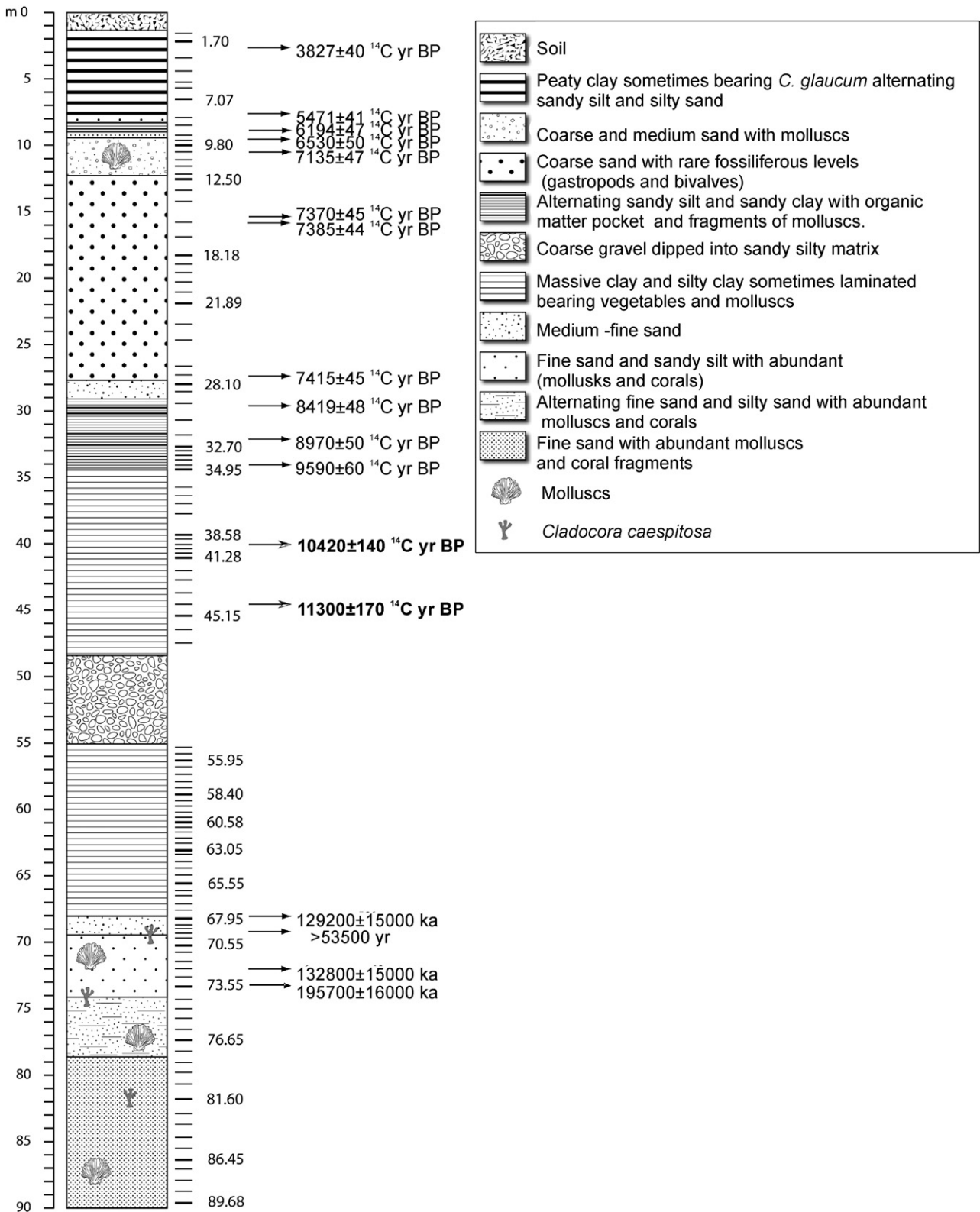


Figure 2. Lithological log of the ENEA borehole.

classification of Loeblich and Tappan (1987). In cases of low foraminiferal abundance, the specimens contained in the whole residue were counted. Specimens showing mechanical damages, indicating possible transport, were not considered. Species diversity was quantified by the  $\alpha$ -index and the Shannon index (H) (Fisher et al., 1943; Murray, 1991) and calculated by means of the PAST data

analysis package (Hammer and Harper, 2007). Results of quantitative analysis and diversity indices are reported in Appendix 1. The quantitative distribution of the most common species is shown in Figure 3.

The relative abundance of species was processed by SPSS (version 12) statistical software to carry out hierarchical clustering (Q-mode

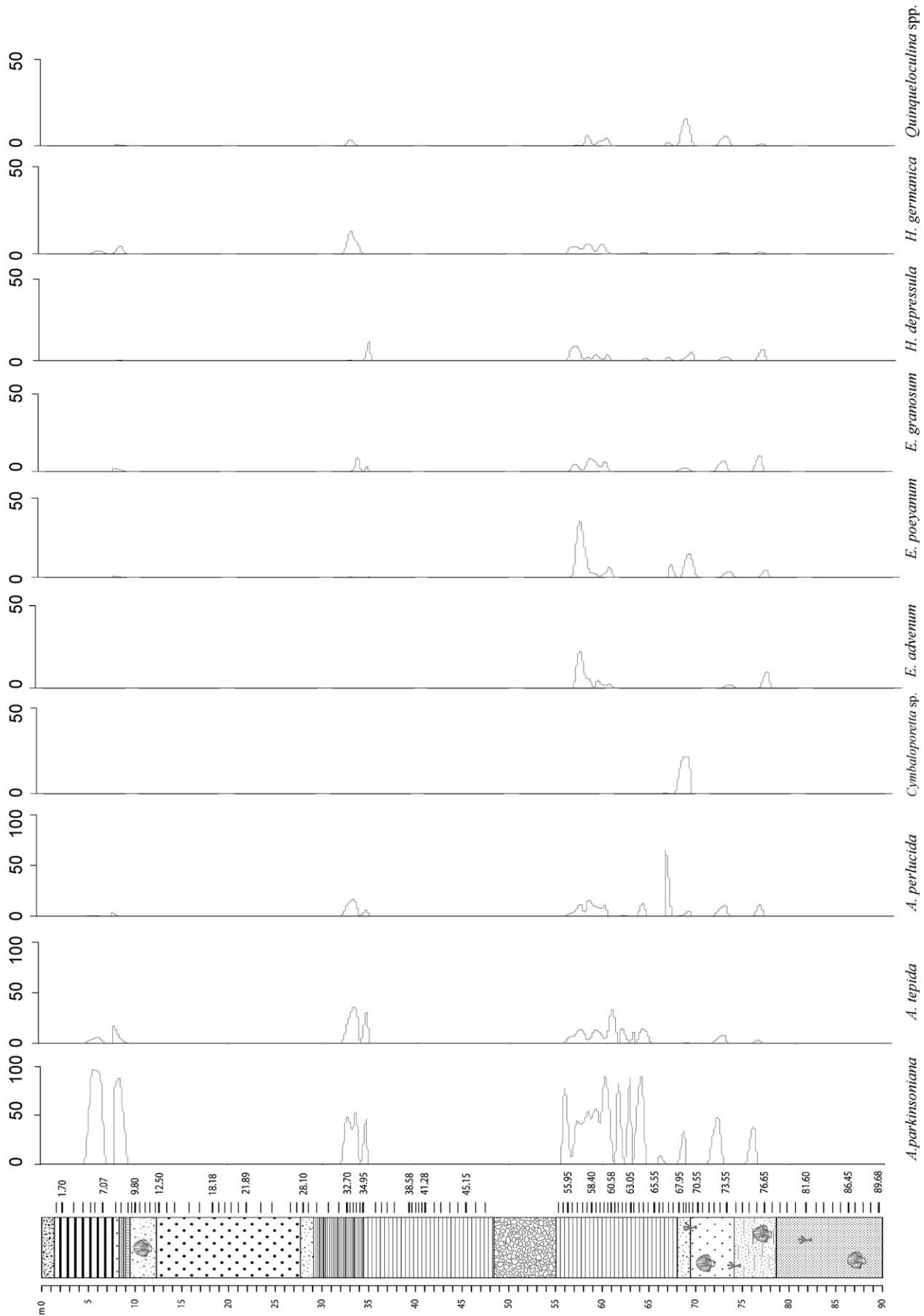


Figure 3. Relative abundance of the 10 most common species along the core depth.



Cluster Analysis (CA)). Only the 22 species more abundant than 3% in at least one sample were considered significant for the statistical analysis (Kovach, 1987). Q-mode CA using Squared Euclidean Distance was performed to group samples characterised by homogeneous foraminiferal assemblages, corresponding to uniform ecological conditions. The assemblages were recognised by the mean foraminiferal parameters and the abundance range of single species in the samples of each cluster.

### Molluscs

A total of 61 samples yielded molluscan assemblages of gastropods and bivalves characterised by non-marine, brackish and marine taxa on which qualitative and quantitative analyses were carried out. Results are reported in Appendix 2. The distinctive ecological character of non-marine (freshwater and terrestrial) taxa was taken from Ložek's (1964) palaeoecological method applied to non-marine European Quaternary molluscan assemblages for palaeoenvironmental reconstructions. The ecological attribution of marine and brackish species was defined after Pérès and Picard (1964), Barnes (1994) and Cesari (1994). The assemblages were grouped into biocoenoses as defined by Pérès and Picard (1964). Calm water muddy sand (SVMC), eurythermal, euryhaline (LEE), unstable muddy (MI) and photophilous algae (HP) were recognised. On the basis of the ecological requirements of the molluscan species and their percentage abundance in each sample, different types of assemblages were singled out. Among accompanying taxa, only species with abundance higher than 3% were considered.

### Dating

Nineteen radiocarbon and two  $^{230}\text{Th}/^{234}\text{U}$  dates from Antonioli et al. (1999) and Lambeck et al. (2004) were considered in this study (Fig. 2, Table 1). To improve the chronological resolution of the core, new radiocarbon dates were carried out on the terrestrial molluscs *Cochlicopa lubrica* and *Oxychilus* sp., collected at  $-39.63$  and  $-44.18$  m, respectively. They were analysed at the Poznan Radiocarbon Laboratory, PL (POZ), with the 1.5 SDH-Pelletron Model "Compact Carbon AMS," serial number 003. All dates were calibrated using program CALIB 5.01 (Stuiver et al., 2005). Two additional Th/U dates were carried out using a multi-collector inductively coupled mass spectrometer (MC-ICP-MS)

on two *Cladocora* layers from the core, from  $-72.8$  and  $-68.5$  m, respectively.

Although the MC-ICP-MS method usually has a high degree of precision, the younger sample had a measured initial delta- $^{234}\text{U}$  value that appears much too low for seawater ( $\sim 108$  per mil), indicating an unreliable age. We consider the older sample age more reliable.

### Results

Distinct assemblages were identified for both foraminifera and molluscs (Table 2).

#### Foraminifera

The Q-mode analysis (Fig. 4) dendrogram highlights three clusters: A, B and C. Clusters A and B include samples characterised by homogeneous assemblages (F1 and F2, respectively), while cluster C (F3), due to the clustering method, groups two less similar samples. The first cluster includes samples characterised by very low specific diversity and strong dominance of *Ammonia parkinsoniana*. In the second cluster, samples contain assemblages dominated by *A. parkinsoniana* and *Aubignyna perlucida*. The two samples of cluster C are characterised by abundant *Cymbaloporeta* sp. 1 *sensu* (Cimerman and Langer, 1991).

#### Foraminiferal assemblage F1 (inner lagoon)

Dominant taxon: *Ammonia parkinsoniana* (35.0–96.3%).

The high dominance of *A. parkinsoniana* and the very low specific diversity (mean  $\alpha$ -index 1.5; mean Shannon index 0.9; Appendix 1) attribute an oligo-specific character to this assemblage. Other less abundant species in this assemblage are *A. perlucida*, *Elphidium poeyanum*, *Haynesina depressula*, *Haynesina germanica* (up to 16.4%, 15.3%, 12.1%, and 8.8%, respectively). Very similar assemblages found in late Quaternary subsurface sediments of the Tuscan coast (Ombrone River mouth, Versilia plain) and Po plain were attributed to brackish, lagoon-marsh environments (Fiorini and Vaiani, 2001; Carboni et al., 2002; Bergamin et al., 2006) and to the central part of a brackish-water lagoon (Amorosi et al., 2004a). Moreover similar assemblages with dominant *A. parkinsoniana* and very low species diversity were found in recent sediments from the Fogliano and the Orbetello lagoons, Tyrrhenian coast (Carboni et al., 2009; unpublished data), from the Edku

**Table 1**

Dates used for the paleoenvironmental reconstruction. The radiocarbon dates were calibrated by using CALIB 5.01 (Stuiver et al., 2005).

Ages ( $^{14}\text{C}$ yr BP)	Ages (cal yr BP)	Altitude (m asl)	Aging method	Marker	References
2206 ± 52	2152–2211	–1.0	conventional	Organic matter	Lambeck et al. (2004)
2716 ± 37	2777–2846	–2.1	conventional	Organic matter	Lambeck et al. (2004)
4122 ± 53	4088–4258	–2.5	conventional	<i>Cerastoderma</i>	Lambeck et al. (2004)
3827 ± 40	4150–4293	–2.6	AMS	Wood	Lambeck et al. (2004)
4467 ± 40	4576–4720	–2.7	conventional	<i>Cerastoderma</i>	Lambeck et al. (2004)
4480 ± 40	5163–5281	–3.0	conventional	Wood	Lambeck et al. (2004)
5405 ± 58	6179–6288	–4.0	AMS	Wood	Lambeck et al. (2004)
5471 ± 41	5790–5903	–7.5	AMS	Marine shell	Lambeck et al. (2004)
6194 ± 47	7011–7129	–8.9	AMS	<i>Hinia</i> sp.	Lambeck et al. (2004)
6530 ± 50	7418–7502	–9.5	AMS	<i>Cerastoderma</i>	Lambeck et al. (2004)
7135 ± 47	7565–7650	–10.5	AMS	<i>Cerastoderma</i>	Lambeck et al. (2004)
7370 ± 50	7786–7905	–15.3	AMS	<i>Venus</i> sp.	Lambeck et al. (2004)
7385 ± 44	7810–7913	–15.8	AMS	Marine shell	Lambeck et al. (2004)
7415 ± 45	7834–7929	–27.3	AMS	Marine shell	Lambeck et al. (2004)
8419 ± 48	9411–9499	–29.5	AMS	Wood	Lambeck et al. (2004)
8866 ± 68	9454–9592	–29.9	conventional	Organic matter	Lambeck et al. (2004)
8970 ± 50	9539–9688	–32.1	AMS	<i>Cerastoderma</i>	Lambeck et al. (2004)
9590 ± 60	10391–10531	–34.0	AMS	<i>Cerastoderma</i>	Lambeck et al. (2004)
10420 ± 140	12444–12529	–39.63	AMS	<i>C. lubrica</i>	In this paper
11300 ± 170	13023–13225	–44.18	AMS	<i>Oxychilus</i> sp.	In this paper
	129,200 ± 15,000	–68.0	$^{230}\text{Th}/^{234}\text{U}$	<i>C. caespitosa</i>	Antonioli et al. (1999)
>53500	>53500	–69.2	AMS	<i>Cerithium</i>	Lambeck et al. (2004)
	132,800 ± 15,000	–72.0	$^{230}\text{Th}/^{234}\text{U}$	<i>C. caespitosa</i>	Antonioli et al. (1999)
	195,700 ± 1,600	–72.8	$^{230}\text{Th}/^{234}\text{U}$	<i>C. caespitosa</i>	In this paper

**Table 2**  
Foraminiferal and molluscan assemblages.

	F1 (inner lagoon)	F2 (outer lagoon)	F3 (marine infralittoral environment)	M1 (freshwater environment)	M2 (terrestrial environment)	M3 (inner lagoon)	M4 (outer lagoon)	M5 (marine infralittoral environment)
Dominant taxa	<i>Ammonia parkinsoniana</i> (35.0–96.3%)	<i>Ammonia parkinsoniana</i> (7.5–57.0%), <i>Aubignyna perlucida</i> (3.3–65.1%)	<i>Cymbaloporetta</i> sp. 1 (21.1–21.4%)	<i>Bithynia leachi</i> (37.0–90.0%)	<i>Cochlicopa lubrica</i> (20–66.6%)	<i>Hydrobia acuta</i> (50–81.7%)	<i>Hydrobia acuta</i> (3.4–38.5%) and <i>Bittium reticulatum</i> (4.5–17.6%)	<i>Bittium</i> spp. (7.6–100%) and <i>Pusillina</i> spp. (5.1–47.7%)
Accompanying taxa > 3%	<i>Ammonia tepida</i> , <i>Elphidium granosum</i> , <i>Haynesina germanica</i> , <i>Haynesina depressula</i> , <i>Elphidium poeyanum</i> , <i>Elphidium advenum</i> , <i>Elphidium pulvereum</i> , <i>Rosalina bradyi</i>	<i>Ammonia parkinsoniana</i> , <i>Elphidium poeyanum</i> , <i>Planorbina mediterraneensis</i> , <i>Cornuspira involvens</i> , <i>Rosalina bradyi</i> , <i>Quinqueloculina seminulum</i> , <i>Quinqueloculina stelligera</i> , <i>Haynesina depressula</i> , <i>Aubignyna perlucida</i> , <i>Elphidium granosum</i> , <i>Quinqueloculina bosciiana</i> , <i>Ammonia beccarii</i> , <i>Quinqueloculina lata</i> , <i>Ammonia tepida</i> , <i>Nonionella turgida</i>	<i>Ammonia parkinsoniana</i> , <i>Elphidium poeyanum</i> , <i>Planorbina mediterraneensis</i> , <i>Cornuspira involvens</i> , <i>Rosalina bradyi</i> , <i>Quinqueloculina seminulum</i> , <i>Quinqueloculina stelligera</i> , <i>Haynesina depressula</i> , <i>Aubignyna perlucida</i> , <i>Elphidium granosum</i> , <i>Quinqueloculina bosciiana</i> , <i>Ammonia beccarii</i> , <i>Quinqueloculina lata</i> , <i>Ammonia tepida</i> , <i>Nonionella turgida</i>	<i>Bithynia tentaculata</i> , <i>Valvata piscinalis</i> , <i>Galba truncatula</i> , <i>Planorbis planorbis</i> , <i>Gyraulus laevis</i>	<i>Hydrobia acuta</i> , <i>Carychium minimum</i> , <i>C. tridentatum</i> , <i>Oxyloma elegans</i> , <i>Vallonia pulchella</i> , <i>Discus rotundatus</i> , <i>Oxychilus draparnaudi</i> , fragments of Helicidae	<i>Bittium reticulatum</i> , <i>Rissoo</i> sp., <i>Pusillina</i> spp., <i>Retusa truncatula</i> , <i>Bithynia tentaculata</i> (with opercula), <i>Valvata piscinalis</i> , <i>Cerastoderma glaucum</i> , <i>Lentidium mediterraneum</i>	<i>Rissoo labiosa</i> , <i>Pusillina</i> spp., <i>Hydrobia ventrosa</i> , <i>Nassarius pygmaeus</i> , <i>Chrysalida</i> gr. <i>obtusa</i> , <i>Ebala pointeli</i> , <i>Retusa truncatula</i> , <i>Parvicardium exiguum</i> , <i>Abra alba</i> , <i>Corbula gibba</i> , <i>Vermetidae</i>	<i>Cerithium vulgatum</i> , <i>Rissoo labiosa</i> , <i>R. ventricosa</i> , <i>Alvania cimex</i> , <i>A. geryonia</i> , <i>Crisilla semistriata</i> , <i>Nassarius nitidus</i> , <i>Chrysalida</i> gr. <i>obtusa</i> , <i>Folinella excavata</i> , <i>Turbonilla lactea</i> , <i>Arca noae</i> , <i>Mytilaster minimus</i> , <i>Ostrea</i> sp., <i>Loripes lacteus</i> , <i>Chama gryphoides</i> , <i>Tellina</i> sp., <i>Corbula gibba</i> , <i>Lentidium mediterraneum</i> , <i>Antalis</i> sp.

lagoon, Egypt (Samir, 2000), and from the Nueces bay, along the Gulf of Mexico coast (Buzas-Stephens et al., 2003).

#### Foraminiferal assemblage F2 (outer lagoon)

Dominant taxa: *A. parkinsoniana* (7.5–57.0%) and *A. perlucida* (3.3–65.1%). This assemblage has greater specific diversity compared to the F1 assemblage, with mean values of 6.5 and 2.0 for  $\alpha$ -index and H respectively (Appendix 1). Other species, such as *H. germanica* (0–12.7%), *H. depressula* (0.3–8.7%), *Elphidium granosum* (0–10.3%) and *E. poeyanum* (0.3–35.5%), generally common in lagoonal settings (Albani et al., 1998), are also found. The significant presence of *Quinqueloculina* species is recorded. A similar assemblage was described by Bergamin et al. (2006) and attributed to an open lagoon or shallow marine environment with freshwater inflow. In addition, the presence of *A. perlucida*, a typical species of estuarine/shallow marine environments (Murray et al., 2000), may suggest an environment characterised by ample food availability, without oxygen depletion (Jorissen, 1988).

#### Foraminiferal assemblage F3 (marine infralittoral environment)

Dominant taxon: *Cymbaloporetta* sp. 1 (21.1–21.4%). This assemblage is well localized in the core, associated with abundant *Cladocora caespitosa* corallites. Relatively high species diversity, typical of marine environmental settings (Murray, 1991), was recorded. The mean values of  $\alpha$ -index and H are 9.1 and 2.5 respectively. The most abundant species, *Cymbaloporetta* sp. 1, was found by Cimerman and Langer (1991) in coarse infralittoral sands from the Vulcano Island (southern Italy). This genus has not been reported elsewhere along the Italian coasts, while it commonly occurs in tropical coastal areas, mainly in back-reef environments (Hottinger et al., 1993; Bicchi et al., 2002). The significant percentages of *A. parkinsoniana* in sample 68.55 and *E. poeyanum* in sample 67.95 suggest an influence of freshwater contributions (Jorissen, 1988; Fiorini and Vaiani, 2001). The infralittoral environment with detritic bottoms suggested by *Cymbaloporetta* sp. 1 is also confirmed by *Planorbina mediterraneensis* (6.7–7.1%) and *Rosalina bradyi* (3.9–4.9%), which may have an attached lifestyle on vegetate covers (Langer, 1993) or on detritic sands (Sgarrella and Moncharmont-Zei, 1993).

#### Molluscs

##### Molluscan assemblage M1 (freshwater environment)

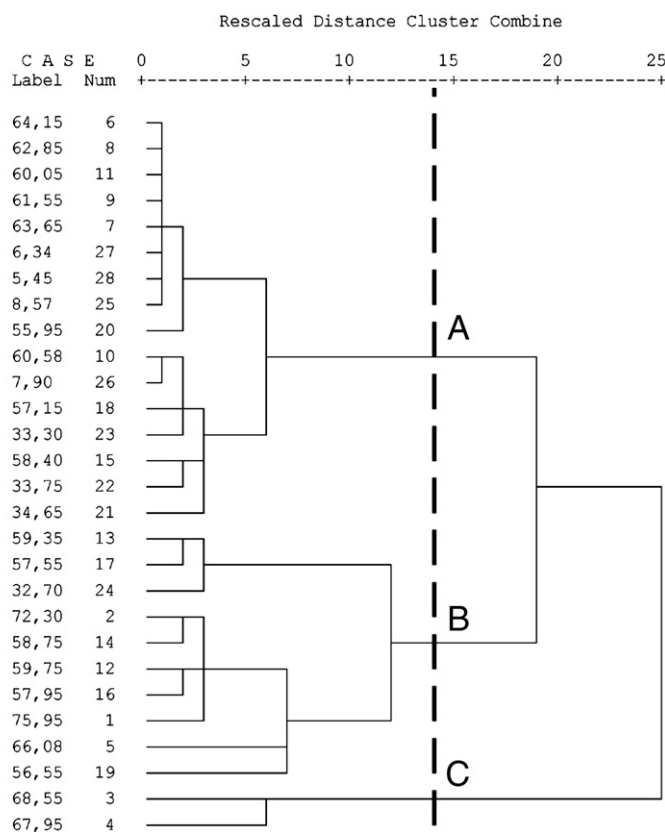
Dominant taxon: *Bithynia leachi* (37.0–90.0%). This assemblage, recorded in 12 levels, is characterised by monospecific to low species diversity dominated by freshwater prosobranchs and accompanied by freshwater pulmonates. The dominant species *B. leachi* and the planorbids *Gyraulus laevis* and *Planorbis planorbis*, together with *Galba truncatula*, are indicative of still-water shallow ponds or marshes rich in vegetation. (Ložek, 1964). Species preferring clean and very slowly flowing water, such as *Bithynia tentaculata* and *Valvata piscinalis*, are also recorded. The richest assemblage (at –64.65 m) is composed of two freshwater species, *B. tentaculata* and *V. piscinalis*, displaying 157 specimens in total and several opercula of *Bithynia*. These are accompanied by a very low percentage (0.9%) of *Hydrobia stagnorum*, typical of brackish water with low salinity (Giusti et al., 1995), suggesting a freshwater environment near the coast. The M1 assemblage is indicative of a shallow freshwater environment with slowly flowing current. The high frequency of opercula of *Bithynia* indicates selected transport of the material by small watercourses.

##### Molluscan assemblage M2 (terrestrial environment)

Dominant taxon: *Cochlicopa lubrica* (20–66.6%). This assemblage, occurring in 8 levels, is generally characterized by poor species diversity of land pulmonate gastropods, mainly found in moist sheltered places, open humid grassland, moist meadow, and

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Dendrogram using Ward Method



**Figure 4.** Dendrogram resulting from the Q-mode Cluster Analysis performed on the foraminifera results.

marshland. *C. lubrica* and *Vallonia pulchella*, typical of moderately open damp places, and highly hygrophilous taxa, such as *Oxyloma elegans* preferring marsh conditions, are frequent. *Discus rotundatus*, characteristic of moist sheltered places in broad-leaf woods, is indicative of Quaternary temperate climatic phases in Europe (Ložek, 1964; Kerney and Cameron, 1979). The best diversified assemblage (at –44.22 m) is characterised by the prevalence of land hygrophilous taxa, with *Oxychilus draparnaudi* dominant (up to 40%), indicating a damp plain. A brackish-water species, *Hydrobia acuta*, native to regions with widely fluctuating salinities (Giusti et al., 1995), occurs locally. This indicates close proximity to a brackish environment.

#### Molluscan assemblage M3 (inner lagoon)

Dominant taxon: *Hydrobia acuta* (50–81.7%).

This assemblage is represented in 6 levels by very high percentages of brackish taxa and by the common presence of freshwater species. A few marine littoral taxa are found as accessories.

The dominant taxa are *H. acuta* and *Cerastoderma glaucum*, which tolerate widely fluctuating salinities. These are accompanied by freshwater lacustrine or palustrine species, such as *B. tentaculata*, *V. piscinalis*, *Valvata cristata* and *Oxyloma elegans*, pointing to low salinity conditions such as those found in an inner lagoon. The brackish/marine ancillary species, such as *Bittium* spp. and *Pusillina* spp., are found in very low percentages and are generally common in eurythermal and euryhaline biocoenoses on hard and/or algal substrata of lagoonal environments (Fretter and Graham, 1978b; Barnes, 1994; Cesari, 1994).

#### Molluscan assemblage M4 (outer lagoon)

Dominant taxa: *Hydrobia acuta* (3.4–38.5%) and *Bittium reticulatum* (4.5–17.6%).

This assemblage, recognised in 4 levels, is characterised by the dominance of brackish taxa and by the common occurrence of species requiring higher salinity conditions, such as *Cerithium vulgatum*, *Bulla striata*, *Corbula gibba* and Vermetidae, pointing to an outer lagoon environment. Locally, *H. ventrosa* and *H. acuta* can reach very high percentages (up to 46%), showing variable brackish conditions. Representatives of *Nassarius*, frequent in the sampled levels, are ubiquitous occurring in different littoral biocoenosis that comprise the lagoonal assemblages (Pérès and Picard, 1964). *C. gibba* belongs to the MI biocoenosis. It is frequently found around river mouths with salinities exceeding 15‰ (Barnes, 1994), in environments with a high rate of fine sediment deposition, pointing to instability of the environment.

#### Molluscan assemblage M5 (marine infralittoral environment)

Dominant taxa: *Bittium* spp. (7.6–100%) and *Pusillina* spp. (5.1–47.7%).

This assemblage is characterised by very abundant and diversified molluscs in 23 samples, which yielded up to 447 specimens and 32 species. SVMC biocoenosis, typical of infralittoral shallow water with algal populations, or meadows of *Posidonia oceanica* (HP) are well represented in almost all the samples. The high frequency of *Pusillina* spp. and *Bittium* spp., both phyticolous, and the frequent occurrence of *Loripes lacteus* and *C. vulgatum* characterise most of the recorded assemblages. The strong presence of *Alvania* spp. together with the dominant taxa, between –72.75 and –67.95 m, point to a wide spreading algal or phanerogame environment. Marine infralittoral species typical of muddy and hard substrate are common. Such heterogeneous assemblages are probably due to diversified habitats, especially with regard to the substrate, likely constituted by sand, mud, and bioclastic and organogenic rocks. Among the hard substratum

dwelling, *Chama gryphoides* (9.9%), which prefers an interstitial environment, is the most common taxon between –68.85 and –67.95 m. Ubiquitous species with wide ecological requirements, such as *Nassarius* spp., or species withstanding salinity variation, such as *Hydrobia* spp., are present locally in low percentages. *C. gibba*, of the unstable muddy biocoenosis, is almost constant between –68.5 and –72.75 m, even if in low percentages.

Generally, the shallow-water depositional environment detected in the strata under consideration was favorable to a persistent SVMC biocoenosis. It was probably protected by *Posidonia oceanica* meadows and/or by a sandy barrier. This environment is probable, even if in some intervals, such as between –68.5 and –72.30 m, and at –81.60 and –84.45 m, a higher hydrodynamic condition and the instability of bottom are indicated by *C. gibba* and suspensivorous feeding burrower species. Moreover, three levels (–55.95, –57.15, –63.65 m) are characterised by a very scarce species, but with abundant *C. gibba*, reaching percentages from 38.3 to 54.5%. These occurrences testify to highly unstable bottom conditions.

## Discussion

### Palaeoenvironmental reconstruction

Integrating the lithological data with the palaeontological results, and with the support of radiocarbon dates, a palaeoenvironmental reconstruction is proposed (Fig. 5).

#### Interval 90.00–69.00 m depth

The interval between –90.00 and –69.00 m consists mainly of fine sands containing frequent *Cladocora caespitosa* fragments with the marine molluscan assemblage M5. Abundant foraminifera were recovered only in two levels, at –75.95 and –72.30 m, suggesting a marine infralittoral environment with freshwater influence due to the dominance of eurhaline species (F2). These marine sands are alternated with barren sandy levels (89.68, 76.45, 73.55) which may be related to a backshore environment. The whole interval may be interpreted as an alternation of backshore and very shallow marine environments, probably due to changes of coastal morphology more than eustatism. It may be referable to the sandy interval S3 described by Federici (1993), the top of which begins between –76 m and –90 m. The extremely low foraminiferal density may be due to very low mud content and nutrient concentration, which normally characterise these environments (Armynot du Châtelet et al., 2009; Alve and Murray, 1999).

A coral sample collected at –72.8 m, dated using the alpha counting Th/U dating technique, yielded an age of about 133 ka with large error bars (Antonioli et al., 1999) and corresponding to the beginning of MIS 5.5. Nevertheless, the new MC-ICP-MS Th/U dating on a *Cladocora* specimen collected at the same level provides an age of  $195.7 \pm 1.6$  ka, indicating a growth during the marine transgression of MIS 7.1. At –69.75 m, a barren sandy level is interpreted as an emersion event due to the sea-level decrease following the MIS 7.1 highstand.

#### Interval 69.00–67.50 m depth

The beginning of this interval (–69.05 m) is characterised by silty sands with very rare *A. parkinsoniana*. Successively silty sands and sandy silts with rare foraminifera, such as *A. parkinsoniana*, *E. poeyanum* and Miliolidae, associated with the molluscan assemblage M5 and abundant *Cladocora* corallites, suggest a shallow marine infralittoral environment with freshwater influence. Successively, at –68.55 and –67.95, the highest content in *Cladocora* is recorded and the foraminiferal assemblage (F3) is enriched in abundance and diversity, suggesting a freshwater influence decrease. Particularly at

–67.95 m, the assemblage dominated by *Cymbaloporetta* sp. 1 suggests an environment with sandy detrital bottoms, most likely very close to the *Cladocora* reef. In addition, assemblage F3 is related to the highest salinity recorded in the borehole and may have a warm-temperature significance. The assemblage M5 shows the increase of hard substratum species such as *C. gryphoides*, consistent with the considerable detrital content of the samples. The increase of *C. gibba* (–68.55 m) and suspensivorous feeder burrower species also indicate a higher hydrodynamic condition and instability of the bottom, which may be due to the rapid increase of sea level. The Th/U age of  $129.2 \pm 1.5$  ka recorded at –68.0 m does not accurately place this interval into a geochronological framework due to the large error bar (Antonioli et al., 1999). Nevertheless, the palaeoenvironmental reconstruction highlights a trend that could be interpreted as part of the transgression leading to the MIS 5.5 highstand. This depositional sequence is abruptly interrupted at the top by an erosional surface.

#### Interval 67.50–64.60 m depth

In the next overlying interval (–67.20 m), freshwater mollusc remains of the assemblage M1 were collected in clays and silty clays. A monotypic assemblage consisting of *B. leachi* with many opercula occurs in this interval. This species prefers stagnant or slow freshwater currents, pointing to a moderately damp plain with puddles or small watercourses.

In the overlying levels, at –66.75 m and –66.08 m, a probable slight sea-level increase is recorded by the establishment of a lagoon. In the lower level, foraminifera are not present and few brackish molluscs, referable to the M3 assemblage, have been recovered. In the upper one, both foraminifera and molluscs suggest an outer lagoon environment (F2 and M4).

In the upper interval, up to –64.60 m, sediments (mainly clayey deposits) are barren, except at –65.00 m, where the assemblage M1, referable to freshwater environment with very slow-moving to stagnant water, was recognised.

No absolute dates are available for the whole interval. However, after substage 5.5 the sea level was at about –67.50 m during the transition from substage 5.1 to stage 4, according to the sea-level curve proposed by Waelbroeck et al. (2002).

#### Interval 64.60–55.00 m depth

This interval, up to –60.5 m, is characterised by an ephemeral lagoon alternating with drying episodes, indicated by clay and silty clay levels containing foraminifera referable to assemblage F1, alternating with barren levels. Particularly at –64.15 m, the low-diversity F1 is accompanied by a mollusc assemblage dominated by freshwater elements (M1), together with some marine or brackish-water mollusc remains. The faunal evidence suggests the establishment of an inner lagoonal setting. At –63.65 m, the marine assemblage M5 associated with assemblage F1 occurs. The most abundant species, *C. gibba* (54.5%), points to the variability of the environment. In the overlying levels, from –63.05 to –60.05 m, fragmentary remains of marine or brackish molluscs are found.

Successively, from –60.05 m to –55.00 m, the environmental setting evolves into more marine conditions and, in the upper part of the interval, to a continental environment. The presence of F2 and M5 is recorded. At –57.15 and –55.95 m, the scarce presence of molluscs, associated with abundant foraminifera, suggests small restricted areas in the littoral zone with very shallow water and high environmental variability. The above continental environment is characterised by the presence of freshwater molluscs. The lack of absolute dating makes it difficult to attribute this transgressive–regressive sequence to an isotopic stage. However, an attempt was made by plotting the core depth on the sea-level curve of Waelbroeck et al. (2002), which intersect at a time corresponding to MIS 3.



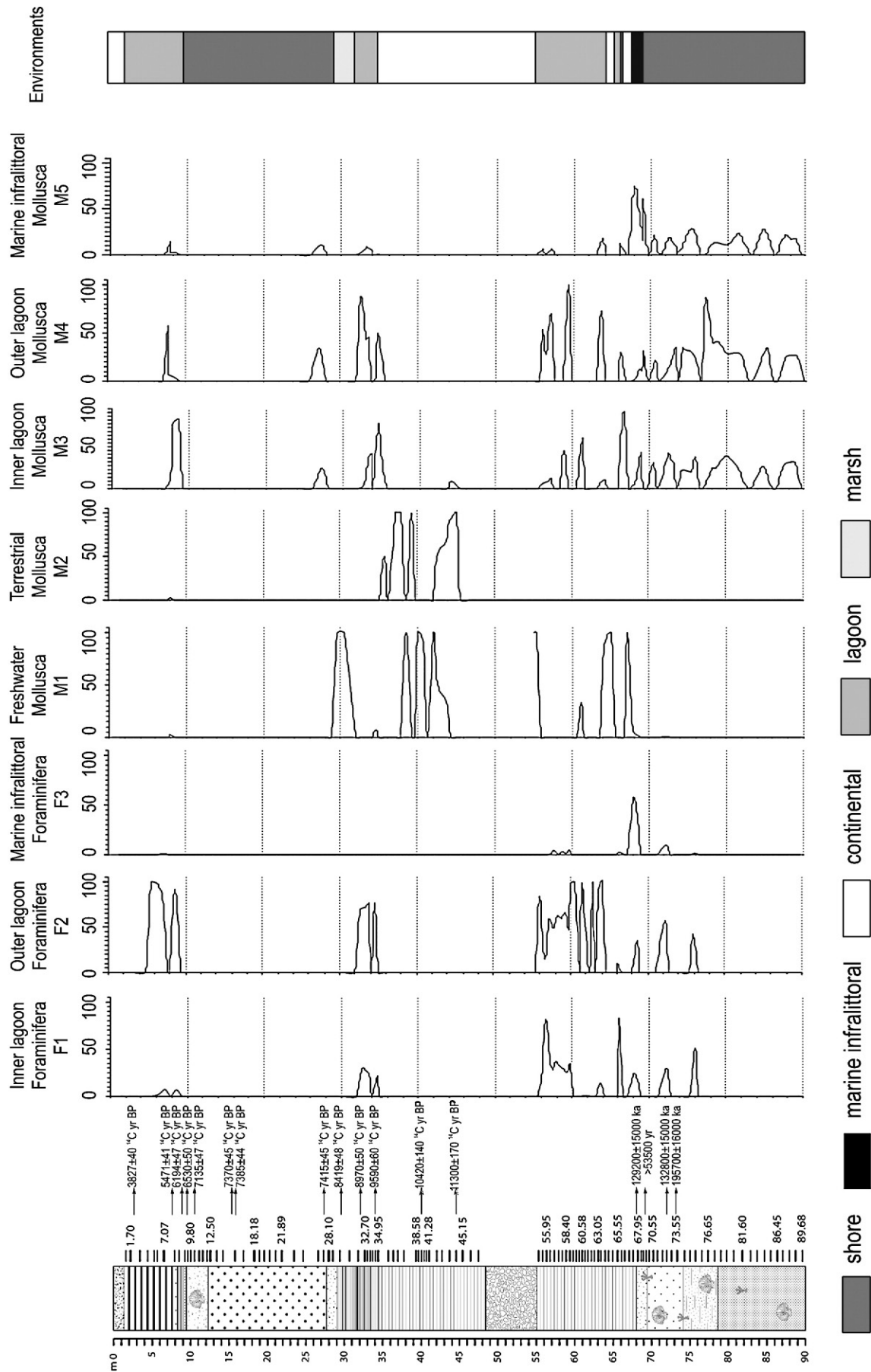


Figure 5. Paleoenvironmental reconstruction of the ENEA core based on the distribution of foraminiferal and molluscan assemblages, with geochronological references. As regards foraminifers, results from samples with very rare scattered specimens were not reported.

### Interval 55.00–48.00 m depth

A barren interval consisting of coarse gravel and pebbles in sandy matrix is present between –55.0 m and –48.0 m. It may be ascribed to an intense erosional phase related to a lowstand period that could be reasonably included in MIS 2. Accordingly, Carboni et al. (2002) found a similar interval between –44 m and –48 m in a core drilled near the Ombrone River mouth (southern Tuscany), at the base of the postglacial succession. It was interpreted as the Ombrone River delta body prograding into a lagoon, possibly during an intense erosional phase such as the LGM. Mazzini et al. (1999) studied a 51-m-deep borehole drilled in the alluvial plain of the Albegna River (southern Tuscany), finding a conglomerate body between the bottom and –45.20 m. They attributed this to a very high energy palaeoenvironment, ascribed to the influence of the Albegna River.

### Interval 48.00–35.00 m depth

Between –48.00 m and –35.00 m, non-marine clay and silty clay sediments have been recognised. In the lower part (from –47.10 to –45.15 m), fragments of terrestrial molluscs (Limacidae, Helicidae, M2) occur. They point to an emerged landscape of a probably cold/cool climatic phase. The overlying silty clayey levels (from –44.22 to –42.49 m) are characterised by the prevalence of terrestrial and hygrophilous species with the dominance of *O. draparnaudi*, which prefers moist sheltered places, and a constant presence of *O. elegans* living in permanently wet places. A reptile egg was also found. The scarce presence of truly aquatic species, and the occurrence of land snails, point to an open and mid-humid environment. From –42.10 to –40.00 m, scarce fragments of non-marine molluscs and opercula of *Bithynia* (M1 and M2) point to emerged areas with some scattered puddles. At –39.63 an oligotypic assemblage of land species (M2) occurs, pointing to moderately damp places.

The radiocarbon dates at –44.23 m and –39.63 m are  $11,300 \pm 170$  and  $10,420 \pm 140$   $^{14}\text{C}$  yr BP, respectively. They are referable to the final part of MIS 2 or to the very beginning of MIS 1 (Sbaffi et al., 2001; Carboni et al., 2005) and suggest a high sedimentary rate for this core interval. From –39.25 to –35.70 m, poor non-marine molluscan assemblages or barren levels occur. A few terrestrial species (M2) preferring damp sheltered places occur at –37.10 m and –35.73 m; in this latter level, the presence of *Discus rotundatus*, characteristic of temperate climate (Ložek, 1964), is indicative of an amelioration of the climate.

### Interval 35.00–29.50 m depth

At –34.95 m, the first record of the Holocene transgression with the development of an inner lagoon is recorded in silty clays by the presence of the assemblage M3 together with rare *A. parkinsoniana*. A brackish water lagoon lasts up to –32.70 m in sandy silt. The foraminiferal assemblages F1 and F2 are associated with rich molluscan assemblages M3 and M4, which indicate a brackish-water lagoon environment with rapid salinity oscillations. In the upper level, at about –32.70 m, the assemblage M4 together with assemblage F2 have been recognised. Nevertheless, the abundance of *H. ventrosa*, which prefers low salinities (6–25‰) and dislikes open coast (Fretter and Graham, 1978a), indicates freshwater influence.

From –32.70 to –29.00 m, the evidence establishes a brackish-water marsh, characterised by sandy silt and sandy clay changing over to medium-fine sands with rare foraminifera associated with freshwater mollusc remains including oxidized opercula of *Bithynia*. The radiocarbon date at –34.00 m ( $9590 \pm 60$   $^{14}\text{C}$  yr BP) allows us to attribute this lagoonal phase to the Versilian transgression. In good accordance, Bergamin et al. (2006) recognised the first record of the Versilian transgression, coinciding with the beginning of MIS 1 (Holocene), at  $9880 \pm 50$   $^{14}\text{C}$  yr BP.

### Interval 29.50–9.00 m depth

In this interval, sandy sediments of backshore environment have been recognised. They are generally barren except the sample at –27.30 m, which is characterised by very rare *A. parkinsoniana*, miliolids and molluscs, such as *Bittium* and *Pusillina*, typical of a littoral protected environment. The presence of the backshore environment over the lagoonal one is due to the progradation of the alluvial plain during the middle and last part of the Holocene (Orombelli and Ravazzi, 1996). The radiocarbon age of these sediments ranges between  $8419 \pm 48$   $^{14}\text{C}$  yr BP at –29.50 m to  $6530 \pm 50$   $^{14}\text{C}$  yr BP at –9.50 m, and they may be considered as corresponding to the siliceous sands S1 of Federici (1993).

### Interval 9.00–1.34 m depth

In the lower part (at –8.57 and –7.90 m), within silt and silty sands, rich brackish molluscan assemblages, with prevailing *H. acuta* (up to 81.70%), *B. reticulatum* and *Abra alba*, are recorded. A freshwater influx is indicated by non-marine taxa, such as *O. elegans* and the opercula of *Bithynia*. Assemblage M3 in conjunction with assemblage F1 points to a lagoonal environment.

From –7.75 m up to –1.34 m clay, sandy silt and silty sand alternate. At –7.75 m and –7.07 m, the number of species and specimens decreases. Fragmentary remains of some bivalves and gastropods belonging to Veneroida and Cerithiidae are present and foraminifera are absent, suggesting a backshore environment.

The overlying clays (–6.34 and –1.34 m) bear scattered marine molluscs with autochthonous foraminiferal oligotypical assemblages, pointing to an inner lagoonal environment, alternating with barren layers. The radiocarbon age for these intervals range from  $6194 \pm 47$   $^{14}\text{C}$  yr BP at –8.90 m to  $3827 \pm 40$   $^{14}\text{C}$  yr BP at –2.60 m.

### Comparison with other Tuscan boreholes

The palaeoenvironmental reconstruction of the ENEA borehole is comparable with the sequence of borehole Ombrone S1, located in the Grosseto plain, Ombrone river mouth (Carboni et al., 2002), and the S4 Albinia borehole (Mazzini et al., 1999). In the first one, a conglomerate level is present between –44 m and –40 m, while in the latter a similar lithology was recorded from the bottom (–51 m) to –45 m. This high-energy event may be related to intense erosion during the last lowstand. In both boreholes, lagoonal deposits overlay the conglomerate, indicating the beginning of a transgressive cycle related to the last deglaciation. One important difference is the 14-m-thick continental sediments, referable to MIS 2 followed by Holocene lagoonal deposits that cover the conglomerate in the ENEA core. In the upper part of the S1 and S4 boreholes, the transgressive trend leads to marine infralittoral conditions not seen in the ENEA core.

The ICRAM borehole (Bergamin et al., 2006), drilled a few km from the ENEA borehole (Versilian plain), presents a parallel palaeoenvironmental evolution characterized by three sedimentary episodes since MIS 5 (or MIS 3). The last sedimentary episode began at 10.6 ka and corresponds to the Versilian transgression. Marine upper circalittoral environment was recognised in Holocene sediments from this borehole.

The core M1 succession studied by Aguzzi et al. (2007) is comparable to the ENEA core, although the proximity of the Arno River determines the presence of delta sequences not found in the ENEA core, in which corresponding lagoonal environments were recognised. In addition, an 11-m-thick continental succession attributable to MIS 2 and a 50-m Holocene succession were recognised in M1, against the corresponding intervals of the ENEA core which are 20 m and 35 m for MIS 2 and for MIS 1, respectively. This is due to the location of core M1, close to the Arno River, which eroded pre-Holocene sediments during the last lowstand. Subsequently, the

valley was filled by a thick Holocene succession. This contrasts with the ENEA core, where a more limited erosion of pre-Holocene sediments occurred.

On the whole, the paleoecological evolution recognised from the study of the ENEA borehole is in good accordance with that deduced from other Tuscan boreholes. The highlighted differences may be mainly due to differing paleomorphology and distance of the drilling sites in respect to the ancient shoreline.

### Sea-level change and tectonic mobility

Lambeck et al. (2004) found excellent agreement between the model-predicted sea level and the observational evidence (lagoonal shells such as *Cerastoderma edule*—now classified as *Cerastoderma glaucum* for the Mediterranean area) in the Holocene portion (first 35 m of the ENEA core) indicating tectonic stability in this area during the Holocene. The present environmental reconstruction confirms the recognition of a lagoonal environment at the beginning of the Holocene succession. Hence, this core has become a regional reference for the marine Holocene transgression in the Mediterranean Sea (Versiliano).

The age of  $129.2 \pm 1.5$  ka at  $-68$  m, obtained from some corals found lower in the core (Antonoli et al., 1999; Nisi et al., 2003; Ferranti et al., 2006), is in good agreement with the paleoecological reconstruction of the present study. Due to the large error bar and to the rapid sea-level rise during the transgressive phase of MIS 5.5, a reliable paleobathymetric reconstruction by comparison with the paleo sea-level curve of Waelbroeck et al. (2002) is not possible. However, due to evidence for the MIS 5.5 paleo sea level at about  $+4$ – $5$  m, a few km from the ENEA core (Nisi et al., 2003), we could attribute the dated sediments here to the first part of this transgression.

The new date of  $195.7 \pm 1.6$  ka at  $-72.8$  m allows us to calculate a precise vertical displacement due to tectonic subsidence in this area. If we compare the 195.7 ka age with the Waelbroeck et al. (2002) eustatic sea-level curve, considering the Th/U error bar and the minimum highstand ( $-18$  m in Antonoli et al., 2004) during MIS 7.1, we infer a vertical displacement of about 54.8 meters. From this, we may suppose that the extensional phase of Apennine orogenesis was still active during MIS 7.1 (Mauffret et al., 1999). On the basis of the ages and the presence of MIS 5.5 outcroppings a few kilometers from the core in the Versilia plain, we hypothesise that the tectonic subsidence stopped after MIS 7.1 but before the MIS 5.5 transgression.

### Conclusions

Foraminiferal, marine and non-marine molluscan evidence, integrated with radiometric dating, permit us to reconstruct the palaeoenvironmental evolution of late Quaternary sea-level changes along the Tuscan coast. The main sedimentary phases corresponding to the most important eustatic changes related to the late Quaternary climatic events were recognised: the oldest one from the bottom to  $-69.00$  m, with subsequent ones from  $-69.00$  m to  $-67.50$  m, and from  $-67.50$  m to  $-35.00$  m, and the last one from  $-35.00$  m to the top.

The first interval corresponds to a shore environment referable to MIS 7.1, ended by an emersion event and a consequent probable hiatus. The recognition of the paleo-shoreline of MIS 7.1 at  $-72.8$  m indicates a vertical displacement. This is probably due to the extensional tectonics referable to the Apennine orogenesis.

The second phase corresponds to a transgressive trend from a foreshore environment, evolving into marine infralittoral conditions with paleontological evidences of warm temperature. It could be interpreted as part of the transgression leading to the MIS 5.5 highstand. This is in agreement with the presence of MIS 5.5 highstand evidences at  $+4$ – $5$  m a few kilometers from the ENEA core.

The third phase, from MIS 4 to MIS 2, starts with continental environment followed by a brackish lagoon characterised by environ-

mental variability. Subsequently, lacustrine and brackish conditions are established, developing into a marine infralittoral environment. This evolution corresponds to a slight sea-level rise, possibly included in MIS 3. The overlying coarse gravel and pebble deposits may be attributed to a sea-level lowstand, possibly included in MIS 2. The upper part of this third phase, between  $-48.00$  and  $-35.00$  m, corresponds to an emerged environment. Based on the radiocarbon dates, this interval may be attributed to the final part of MIS 2. However, the presence of the temperate land pulmonate *D. rotundatus*, in the uppermost levels, suggests the beginning of a climatic amelioration.

The last phase begins at about  $-35.00$  m with the development of an inner brackish lagoon, indicating the beginning of the Holocene sea-level rise along the Tuscan coast (Versilian transgression). After the sea-level stabilisation, the coastal progradation leads to a freshwater marsh episode followed by a backshore environment and, subsequently, a short brackish-marsh episode. At the top of the borehole, a continental subaerial environment with sporadic lagoonal episodes is recognised. The agreement of these results with the previous model-predicted sea level along the Italian coast confirms the tectonic stability of the Versilian area during the Holocene.

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### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.yqres.2010.07.006.

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