

Benthic foraminiferal assemblages of the imperial harbor of Claudius (Rome): Further paleoenvironmental and geoarcheological evidences

The Holocene
21(8) 1245–1259
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DOI: 10.1177/0959683611405239
hol.sagepub.com


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Abstract

This paper presents a paleoenvironmental reconstruction of historical development in the area of the ancient harbor of Claudius based on micropaleontological and sedimentological data. Benthic foraminifera are reliable tools for this kind of research because they are sensitive to short-time environmental changes induced by both natural and anthropogenic events. By studying eight sediment cores collected from different sections of the harbor, it was possible to reconstruct a comprehensive picture of the harbor complex. Qualitative and quantitative analysis of foraminiferal associations and sedimentological data, along with radiocarbon dating, were useful to identify three key intervals in the history of the coastal area where the harbor developed. The first interval, located at the bottom of all cores, is characterized by a brackish water environment, corresponding to the formation of the first deltaic cusp of the Tiber River. The second interval is characterized by the harbor activities that developed after a general increase in water depth due to a diversion of the Tiber River mouth. The third interval marks the final phase of harbor activities and the subsequent filling of Claudius' basin. However, a link with the inner Trajanus' basin was maintained via the central part of the basin, which remained submerged longer, until the early Middle Ages.

Keywords

ancient harbor, foraminifera, Italy, paleoenvironmental reconstruction, sedimentology, Tiber delta

Introduction

Geoarcheological studies of harbor sites have received increased attention in recent years. Late-Quaternary geological records have increased the archeological data concerning ancient settlements in coastal areas. Particularly during the historical period, changes in sea level resulted in significant changes in coastal paleoenvironments over time and thus strongly influenced human maritime activities. In recent years, many researchers have carried out geoarcheological studies at ancient harbor sites along the Italian coast and elsewhere in the Mediterranean area, providing good proxy data to improve the quality of archeological reconstructions and to establish constraints on relative sea levels (Arnaud-Fassetta et al., 2003; Bini et al., 2009; Lambeck et al., 2004; Marriner and Morhange, 2007; Marriner et al., 2008; Reinhardt et al., 1998, 2006; Véron et al., 2006).

In the last decade, many researchers investigated the area of Portus (Claudius' and Trajanus' harbors), attempting to define its ancient configuration through geomorphological and paleontological studies (Bellotti et al., 2009; Giraudi, 2004; Giraudi et al., 2006, 2009). Recently, new paleoenvironmental data for the Portus area were obtained by Goiran et al. (2010), who proposed a depth of 7–8 m for the main basins (Claudius' and Trajanus' basins) and highlighted the importance of the junction channel as a means of access to the Tiber River as well as to the sea after the clogging up of Claudius' harbor. Bellotti et al.

(2009) attempted to reconstruct the configuration of Claudius' harbor using lithostratigraphical, biostratigraphical and chronological tools. According to their reconstruction, the harbor area was set close to the Tiber River mouth and was encompassed by two curved piers that were separated by a wide entrance facing the sea. In contrast, other studies suggested that Claudius' harbor had its main entrance to the southwest and a second entrance in the northern part of the ancient harbor (Giraudi et al., 2006). The literature indicates a close relationship between the geomorphological evolution of the Tiber delta and the development of the harbor. The postglacial sea-level rise and the solid discharge of the Tiber were the two antithetical mechanisms responsible for the landscape evolution of the deltaic area where the harbor was built (Bellotti et al., 2007).

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Received 23 September 2010; revised manuscript accepted 24 January 2011

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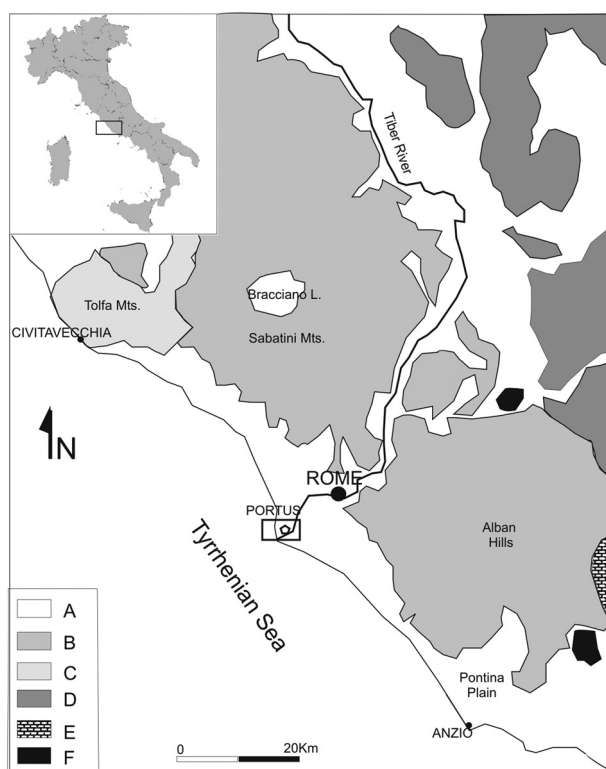


Figure 1. Map of the study area and sedimentary sequences of the Central Tyrrhenian margin (modified from Marra et al., 1995). A, neo-autochthonous cycles (Messinian–Pleistocene); B, volcanic sequences (Plio–Pleistocene); C, Tolfa Mts units (Upper Cretaceous–Eocene); D, Sabini Mts units (Upper Triassic–Upper Miocene); E, Lepini Mts units (Cretaceous); F, travertine deposits (Quaternary)

In 2004, ANAS (the Italian Agency for Roads) carried out a subsurface survey in the Tiber River delta plain by means of several drillings (Figure 1). This survey recovered Roman remains that provided new evidence of ancient structures referable to the well-known harbor of Emperor Claudius. In this study, micropaleontological (foraminiferal assemblages) and sedimentological analyses of eight cores are employed to obtain paleoenvironmental evidence for the configuration and historical development of the harbor. Benthic foraminifera are highly sensitive to environmental changes induced by both natural and anthropogenic processes in marine and transitional environments. They have been successfully utilized in previous geoarcheological studies of harbor sites (Bernasconi et al., 2006, 2007; Kraft et al., 2003; Marriner and Morhange, 2007; Reinhardt et al., 1994). Sea-level changes may be highlighted in the sedimentary record by sea-level markers such as lagoon deposits (Antonioli et al., 2009; Lambeck et al., 2004), which are easily recognized through their typical foraminiferal fauna. The benthic foraminiferal fauna of these environments, which show a distinct response to even small changes in environmental parameters, have proven to be informative sea-level markers in the late-Quaternary sedimentary record (Amorosi et al., 2004a, b; Bergamin et al., 2006; Carboni et al., 2002; Fiorini and Vaiani, 2001; Mazzini et al., 1999). These fossils are particularly suitable for paleoenvironmental studies of drill cores because they are highly abundant, enabling statistical analysis of small samples.

The aim of this study is to employ foraminiferal data to improve the stratigraphic record of the Tiber delta area during the Holocene, while also providing further chronological and paleoenvironmental constraints for the archeological reconstruction of Claudius' ancient harbor.

Geological setting

The northern coastal plain of the mouth of the Tiber River, where the studied area is located, is characterized by considerable environmental variability. In a context of substantial tectonic stability and a low subsidence rate, the landscape evolution of the area during the Holocene was controlled by the rates of postglacial sea-level rise and fluvial input. At the beginning of the Holocene, the coastal area was characterized by a marine bay in which the bay-head Tiber delta was prograding (Bellotti et al., 2007). During the Holocene, sediments discharged by the river partially filled the bay. About 6000 years ago, waves began to cause a severe reworking of the river-mouth sediments and the bay-head delta changed to a wave-dominated delta. About 5000 years ago, a continuous and sandy coastal barrier developed. Consequently, the previous bay became two natural coastal lakes. Since 5000 years ago the first deltaic cusp began to develop just in the area where the imperial harbor complex was later built (Giraudi, 2004). It was probably between 2800 and 2600 years ago that the mouth of the Tiber moved farther south to its current position, where it initiated several phases of delta progradation. Over the years, the two coastal lakes were well-connected to the sea at some times and completely isolated at other times, gradually turning into coastal ponds until they were finally reclaimed in the nineteenth century.

Historical background

As early as the fourth century BC, Rome controlled the mouth of the Tiber by founding the city of Ostia. The city had a harbor in the river channel, which probably extended, for some activities,

Table 1. Geographical coordinates of the cores

Core	Lat. north	Long. east	Depth	a.s.l.
3	41°47'03"3	12°15'38"7	60	150
4	41°46'54"2	12°15'25"6	25	170
5	41°46'44"4	12°15'00"4	60	100
6	41°46'38"7	12°14'47"7	25	120
8b	41°46'26"5	12°14'28"6	25	250
9b	41°46'20"0	12°14'38"2	30	160
11	41°47'19"5	12°15'18"5	25	70
12	41°47'10"6	12°15'00"4	25	50

into the nearby coastal lake. In the first century AD, the Ostia harbor could no longer deal with the increasing commercial traffic; so, in AD 42, the Emperor Claudius decided to build a new harbor that could manage this traffic throughout the year (Cassio Dione, *Hist. Rom.* 60, 11,1. ss). Claudius' basin was built about 3 km north of the mouth of the river by partly digging away the beach and partly enclosing the facing tract of sea between two piers. The basin was probably accessed from the west (Bellotti et al., 2009; Castagnoli, 1963; Giuliani, 1992), where the lighthouse, built on an artificial island, was located, according to ancient authors (Suet., *Claud.*, 20, 3; Plin., *NH.* 16, 40, 201). However, a secondary entrance from the north has been cited in several studies (Giraudi, 2004; Scrinari, 1960; Testaguzza, 1970). To contain storm damage, the Emperor Trajanus began to construct a new basin between AD 100 and 112. This basin was hexagonal in shape (today perfectly preserved) with sides measuring 357.77 m. Trajanus' harbor was located fully inland relative to Claudius harbor but was linked to it via a wide canal. An additional canal linked the hexagonal basin with the Tiber.

After a phase characterized by a stable shoreline, which lasted for most of the Imperial Period, a progradation phase set in as the Empire began to decline. During the early Middle Ages,

corresponding to the end of a cool-humid climatic phase, the mouth moved forward a few hundred meters. This natural event, which coincided with the fall of Rome, caused the degradation of the harbor complex. Harbor activities continued only in the hexagonal basin, where only one quay was maintained in activity during the early Middle Ages. The progradation phase came to a halt during the 'Medieval Warm Period', but the port was unusable by this time and mostly reduced to a swamp. Later, an intense progradation phase during the 'Little Ice Age' caused the shoreline to shift even further to the west, burying Claudius' basin and reducing Trajanus hexagonal basin to a lake.

Materials and methods

Grain size analysis of the collected sediments are based on mechanical sieving and laser diffractometry for > and < 62µm fractions, respectively.

Micropaleontological and lithostratigraphical analyses were conducted on eight boreholes drilled in the archaeological site of the imperial harbors of Claudius and Trajanus between 0.5 m and 2.50 m above sea level (Table 1). Five of the cores were collected along a transect perpendicular to the present coast shoreline (Figure 2).

Foraminifera

A total of 149 samples, from eight boreholes were analyzed for benthic foraminifera. To avoid problems related to the specific attributions of juvenile specimens, very abundant in paralic environments, the fraction of each sample larger than 125 µm was used for qualitative and quantitative analyses. The samples were gently washed over 125 µm sieves and oven dried at 40°C. The qualitative analysis was performed on all 149 samples, but the quantitative analysis was possible only on 71 samples, because the remaining 78 contained no faunal remains or contained only

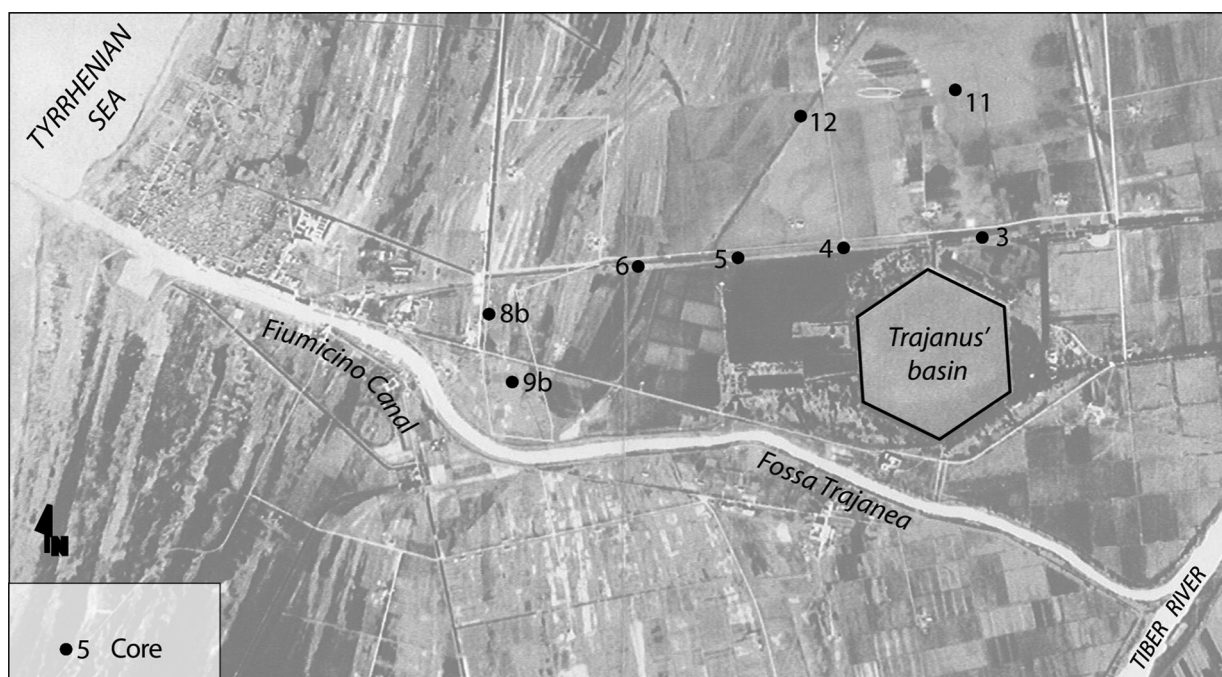
**Figure 2.** Core locations

Table 2. Dates used for the paleoenvironmental reconstruction

Lab identifier	Core	Sample depth (m below the surface)	Conventional ^{14}C age (yr BP \pm 1 σ)	$\delta^{13}\text{C}$ (‰)	Calibrated age (yr BP \pm 1 σ)	Material	References
LTL-461 a	9b	3.50	1140 \pm 40	-27.1	970–1165	Peaty-sand	Bellotti et al. (2007)
LTL4274a	9b	11.70	2874 \pm 35	-4.6	3080–2940	Forams	In this paper
LTL-463 a	12	4.50	1885 \pm 50	-24.5	1735–1.880	Sand with vegetal remains	Bellotti et al. (2007)
LTL-465 a	12	6.50	2840 \pm 35	+0.4	2875–2990	Marine mollusc fragments	Bellotti et al. (2007)
LTL-467 a	5	7.75	2165 \pm 50	-19.8	2065–2305	Vegetal remains	Bellotti et al. (2007)
LTL4273a	6	7.10	2666 \pm 40	-5.7	2845–2745	Forams	In this paper
LTL-470 a	6	16.50	3920 \pm 60	-27.1	4255–4420	Vegetal remains	Bellotti et al. (2007)
LTL-471 a	4	17.50	5565 \pm 110	-2.3	6205–6484	Marine mollusc fragments	Bellotti et al. (2007)

rare or displaced microfauna (57 samples) or insufficient microfauna to perform a quantitative analysis (21 samples). The dry residue from these samples was split into aliquots containing approximately 300 specimens, which were picked and classified.

The generic attributions followed Loeblich and Tappan (1987), and individual species were determined on the basis of previous studies of Mediterranean benthic species (Cimerman and Langer, 1991; Jorissen, 1988; Sgarrella and Moncharmont Zei, 1993). Species diversity was quantified by the α -index (Fisher et al., 1943). This diversity index reliably accounts for rare species. Index values increase only slightly with sample size but the use of this index assumes that the number of individuals of each species follows a logarithmic series (Murray, 1968, 1991, 2006). The diversity index was calculated using the PAST (Palaeontological Statistics) data-analysis package, version 1.38 (Hammer et al., 2001).

The relative abundances of each species, together with species diversity expressed by the α -index, were organized into a matrix and processed with statistical software (SPSS 12) to carry out a hierarchical clustering (Q-mode Cluster Analysis, CA) and a Principal Component Analysis (PCA). To simplify the matrix, only the 28 species that were more abundant than 4% in at least one sample were considered significant for the purposes of the statistical analysis (Fishbein and Patterson, 1993; Patterson and Fishbein, 1989). The CA, which is useful for finding natural groupings of samples, employed the Squared Euclidean Distance; among the possible clustering methods, the Ward method was chosen because it produces dendrograms with well-defined clusters (Parker and Arnold, 1999). The PCA is a descriptive method employed to examine the relationships among variables and it was carried out taking into account the first two principal components.

Dating

The six radiocarbon dates from Bellotti et al. (2007) were considered in this study (Table 2). To improve the chronological resolution of the core, two new radiocarbon datings were carried out on benthic foraminifera collected from core 6 at -5.90 m (7.10 m below the surface, Table 2) and from core 9b at -10.1 m (11.70 m below the surface, Table 2). The samples were analyzed at the Italian Center for radiocarbon dating by Accelerator Mass Spectrometry, CEDAD Laboratory of the Department of Engineering Innovation of the University of Salento, with a 3-MV Tandem accelerator manufactured by High Voltage Engineering Europa. All dates were calibrated using the program OxCal 4.1.

Results

Sedimentological characteristics

The lower section of all eight cores is generally composed of fine sediments. Poorly sorted mud and silt are located deeper than 15 m below the land surface. Thin levels of silty fine sand or several-millimeter thick intercalations of muddy sand and silty sand may be found locally, sometimes with vegetal remains or fine mollusk fragments.

In the interval ranging from approximately 10 to 15 m below the surface, sediments are generally rich in fine sand and are mostly gray in color, followed by ochre, with poor to medium sorting. Samples richer in sand (generally >60%) were mostly sourced from cores collected further landward (east of core 6). Only core 8b contains a sandy mud bed with vegetal remains (between -12.5 and -11 m). Very thin peaty levels or rare concentrations of fine gravel are locally present.

From -10 m to the surface, cores from the area further landward (cores 1 to 3) contain fine to coarse sands or occasionally silty sediments that are gray deeper down and mainly ochre in the portion above -5 m. Sediments are poorly or moderately sorted with a positive skewness. Bivalves can occasionally be found in the lower sections, while peaty levels, vegetal remains and brick fragments from the Roman Period are locally present in higher sections. The 2 m closest to the surface have been heavily remodeled by human activity and are characterized by brown soil. At the same depth interval, cores from the central area (cores 4 to 6) exhibit two different intervals. The lower interval varies in thickness from 4 to 7 m and is made up of poorly sorted gray silty sand and sandy silt, with bivalve remains and wood fragments; skewness is commonly positive. The upper interval is made up of fine to coarse sands that are ochre or brown near the top, occasionally containing small bivalves and local concentrations of polygenic and rounded fine gravel. In cores from the southern-western areas (cores 7–9), the uppermost 10 m are composed of fine to medium sand with poor to moderate sorting and positive skewness. The color changes from gray at the bottom to ochre at the top. Fragments of bivalves, amphora remains and brick fragments are present locally.

Foraminifera

The results of the quantitative analysis of benthic foraminiferal assemblages abundant than 4% in at least one sample are reported in Appendix 1 (available online). A total of 161 (7 with open nomenclature) benthic foraminiferal species belonging to 58 genera were identified. Twenty-eight species showed a relative

abundance higher than 4% in at least one sample, while *Ammonia parkinsoniana* (the only species present in all samples), *Ammonia tepida*, *Elphidium poeyanum* and *Quinqueloculina stelligera* show very high frequencies (>20%, in at least one sample). Moreover, *Ammonia beccarii*, *Elphidium granosum*, *Haynesina depressula*, *Quinqueloculina pygmaea* and *Triloculina schreiberiana* show percentages ranging from 10 to 20%. Conservation status of foraminiferal tests is generally good.

Q-mode Cluster Analysis

The Q-mode CA (Figure 3) grouped the studied samples into groups each one characterized by homogeneous foraminiferal assemblages, which correspond to uniform ecological conditions. Each cluster is used to interpret the different paleoecological settings of the studied cores. The resulting dendrogram contains three main clusters (A, B and C) highlighted by a phenon line placed at 18% distance. Cluster A includes two subclusters (A1 and A2), in which sample groups are mainly distinguished by their α -index values and different frequencies of euryhaline taxa. Clusters A (A1 and A2) and B group samples characterized by rather homogeneous assemblages, while cluster C, because of the employed clustering method, groups six less similar samples. The first two clusters include samples characterized by very low specific diversity and are dominated by *A. parkinsoniana*, *A. tepida* and *E. poeyanum*. Samples in cluster C are characterized by a greater degree of diversity and a typical marine infralittoral assemblage, including *Ammonia* spp., *Elphidium* spp. and miliolids.

Foraminiferal subassemblage A1 (*Ammonia parkinsoniana* subassemblage). In this assemblage, *A. parkinsoniana* (4.3–77.5%) is the most frequent species in all samples, except in the sample –23.2 in core 4, where *A. tepida* dominates. *E. poeyanum*, *E. granosum*, *A. beccarii* and *H. depressula* are other important taxa. Among miliolids, *Q. stelligera* and *Q. pygmaea* are present in significant percentages (Table 3). Samples in subcluster A1 are characterized by relatively high α -index values (median 8.46).

A. parkinsoniana and above all *A. tepida* are typical species of paralic environments such as estuarine areas or lagoons, as they are tolerant of a wide range of salinity, temperature and oxygen content (Almogi-Labin et al., 1992; Carboni and Di Bella, 1996; Debenay et al., 2000, 2005; Frezza and Carboni, 2009; Jorissen, 1988; Mendes et al., 2004; Reinhardt et al., 1998; Ruiz Muñoz et al., 1996). Moreover, *A. parkinsoniana* shows tolerance to increased nutrient supply (Jorissen, 1988) and is dominant in polluted brackish-water environments (Carboni et al., 2009; Samir, 2000). *E. poeyanum*, *E. granosum* and *H. depressula* are also found in shallow marine deposits near river deltas (Barmawidjaja et al., 1992; Bellotti et al., 1994; Jorissen, 1988). According to Jorissen (1988), *E. poeyanum* and *E. granosum* are typical on clayey substrata characterized by high nutrient levels but with good oxygenation. *H. depressula* is also a common species in Mediterranean lagoons (Murray, 1991). *A. beccarii* is a typical marine species that is abundant in infralittoral sandy bottoms and can tolerate a moderate concentration of organic matter (Bellotti et al., 1994; Frezza and Carboni, 2009; Jorissen, 1988; Mendes et al., 2004; Ruiz Muñoz et al., 1996; Sgarrella and Moncharmont Zei, 1993). *Q. stelligera* and *Q. pygmaea* are frequent in the infralittoral zone, mainly on sandy or vegetated bottoms (Cimerman and Langer, 1991; Langer, 1993; Sgarrella and Moncharmont Zei, 1993). The occurrence of taxa as *A. parkinsoniana*, *A. tepida*,

E. poeyanum and *E. granosum* may indicate a brackish environment, such as a lagoon, or a slightly confined infralittoral environment affected by freshwater influence.

Foraminiferal subassemblage A2 (*Ammonia parkinsoniana* and *Ammonia tepida* subassemblage). *A. parkinsoniana* (11.2–49.6%) and *A. tepida* (12.3–27.9%) are the characteristic species of this subcluster. Overall, the abundance of *A. parkinsoniana* decreased compared with that of subcluster A1, whereas the concentrations of *A. tepida* and *E. poeyanum* increased strongly. *E. poeyanum* (3.3–27.0%) is also significantly frequent. Like *A. parkinsoniana* and *A. tepida*, *H. depressula* tolerates stressful conditions, surviving in a wide range of oxygenation levels, salinities and temperatures (Vaniček et al., 2000). *T. schreiberiana* is another frequent taxon normally found in the infralittoral and circalittoral zones (Cimerman and Langer, 1991; Yanko et al., 1994) and has also been reported to be epiphytic (Langer, 1993). The increasing occurrence of *A. tepida* in the subcluster A2 together with lower α -index values of the assemblage (median 4.49), suggests a lagoonal setting with more restricted conditions compared with assemblage A1 and an unstable and stressed environment (Bernasconi et al., 2006; Murray, 1991). However, the consistent presence of marine species, such as *E. poeyanum* and *T. schreiberiana*, is still indicative of an interchange with the open sea.

Foraminiferal assemblage B (*Ammonia tepida* and *Elphidium poeyanum* assemblage). This assemblage is dominated by euryhaline species such as *A. tepida* (14.4–38.9%) and by shallow water species such as *E. poeyanum* (10.1–25.4%). Nevertheless, compared with subclusters A1 and A2, this assemblage is dominated by *A. tepida* rather than by *A. parkinsoniana* (Table 3). *A. tepida* is common in shallow marine environments, and is dominant in lagoons and deltas (Albani and Serandrei Barbero, 1990; Almogi-Labin et al., 1992; Favry et al., 1998). The presence of *A. tepida* can also indicate moderately restricted conditions, exhibiting a strong correlation with high percentages of organic matter (Debenay et al., 2005; Jorissen, 1988). The significant presence of *Bulimina* spp. (median 3.5%), *Cassidulina carinata* (median 1.7%) and *Brizalina spathulata* (median 1.2%) confirms an environment with limited water circulation and high organic matter content (Barmawidjaja et al., 1992; Bellotti et al., 1994; Donnici and Serandrei Barbero, 2002; Jorissen, 1988). *Aubignyna perlucida* (median 2.6%), *H. depressula* (median 2.0%) and *Haynesina germanica* (median 0.6%) are subordinate components of this assemblage and further indicate an increase in organic matter content (Jorissen, 1988; Rossi and Vaiani, 2008). So the composition of the foraminiferal assemblage in cluster B indicates a confined environment with high organic content.

Foraminiferal assemblage C (*Quinqueloculina stelligera* and *Ammonia parkinsoniana* assemblage). Assemblage C is very diversified at species level and includes six samples. *Q. stelligera* (12.9–29.9%) dominates in five of the six samples. *A. tepida* (2.4–26.4%) and *A. parkinsoniana* (5.8–13.0%) are other important taxa, and *H. depressula* and *E. poeyanum* are also present in significant percentages (Table 3). This assemblage is characterized by typical marine infralittoral taxa (*Q. stelligera*, *Ammonia* spp., *Elphidium* spp.) and is referable to a well-oxygenated infralittoral marine environment, located in the area near the inlet and the outer part of the harbor (cores 9b, 8b). Moreover, the α -index reaches higher values (10.1–14.0), confirming less confined marine conditions and

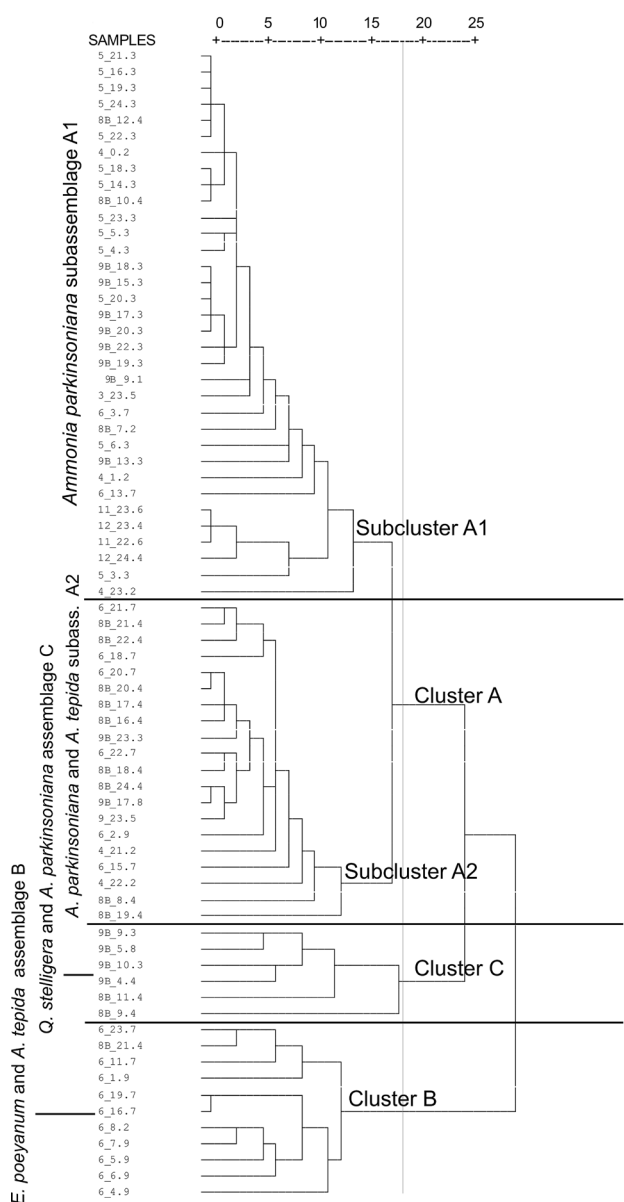


Figure 3. Dendrogram resulting from the Q-mode Cluster Analysis of the foraminiferal data. Three main clusters (A, B and C) are highlighted by a phenon line placed at 18% distance

indicating more stable paleoenvironmental conditions in respect to the previous ones.

Principal Component Analysis

The PCA was performed to identify the primary factors determining the distributions of species. In the plot of the first two components (Figure 4), which account for 31.9% of the total variance (component 1: 19.2%; component 2: 12.7%). In spite of the rather low total variance accounted in total by components 1 and 2, two groups of species corresponding to the main clusters of HCA are highlighted. *A. beccarii*, *A. parkinsoniana*, *A. tepida*, *E. poeyanum*, *H. germanica*, and *Quinqueloculina seminulina*, which reach their highest abundances in assemblages A (A1 and A2) and B, are characterized by negative values for component 1. The largest group, including variables with positive values for component 1, includes the normal marine species that characterize assemblage C. Thus, euryhaline species are inversely

correlated with component 1, whereas normal marine species are positively correlated with this component. Taking into account the ecological interpretations of the foraminiferal assemblages described above, we infer that increasing values of component 1 correspond to a transition from low and/or variable salinity to normal marine conditions.

It is more difficult to assign an unequivocal environmental significance to component 2 because of the concurrence of more environmental parameters and its relatively low variance.

The values of Factor 1 from the PCA and the α -index values are plotted against the borehole depth, together with the clusters found in the Q-mode CA. A good agreement between the diversity α -index and Factor 1 of PCA is recognised along the borehole's depth. A higher degree of confinement and/or lower salinity corresponds to low α -index and Factor 1 values, while normal marine conditions correspond to high values (Murray, 1991, 2006).

Vertical assemblage distribution

Core 3. This borehole is located in the inner part of Claudius' harbor area. At the bottom (−23.5 m), subassemblage A1 with vegetal remains and mollusk fragments is found, indicating a lagoon environment or a slightly confined shallow-marine environment with freshwater influence. The highest value of *E. granosum* indicates an environment with high organic matter content but with good oxygenation. From −18.6 m to the top, barren fine sands with rare silty and peaty levels referable to a littoral (probably beaches) environment are present (Figure 5).

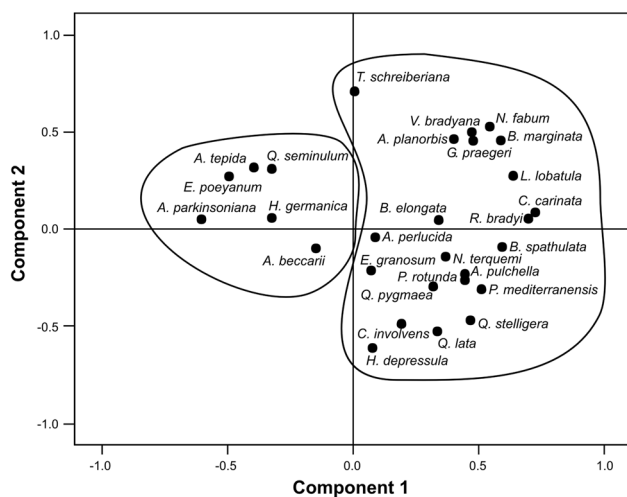
Cores 11 and 12. These boreholes were drilled in the northern part of the study area and are characterized from the bottom to −20.6 m (core 11) and to −18 m (core 12) by subassemblage A1, indicating a lagoon setting alternating with barren sandy deposits.

In these samples, the high percentages of euryhaline taxa, such as *A. parkinsoniana*, *A. tepida*, *E. poeyanum* and *E. granosum*, coupled with the absence of typical shallow marine taxa, highlight considerable fluvial influence with relatively high organic content and moderate variations in salinity, as confirmed by presence of rare valves of *Cyprideis torosa*, an euryhaline ostracod. Medium fine sands, mainly without faunal content, follow until the top of these cores (Figure 6). These deposits may be related to a deltaic bar and/or backshore environment. Locally rare levels characterized by reworked foraminiferal specimens are also found, probably due to storm events (core 11: −18.5 m, −10.5 m; core 12: −16.5 m).

Cores 4 and 5. These boreholes are located in the central-eastern portion of the harbor area. Fine sediments in the basal portion of each core (core 4: from −23.2 m to −14.8 m; core 5: from −23.3 m to −14.3 m) mainly contain the lagoonal subassemblage A1 (Figures 7 and 8). Both cores exhibit low foraminiferal abundance; consequently, quantitative analysis was possible for only 14 of 47 samples. In core 4, subassemblage A2 is found from −22.2 m to −21.2 m. The significant increase in euryhaline taxa from subassemblage A1 to A2 may be related to increased freshwater input. From −13.8 m in core 4 and from −12.3 m in core 5 upward, an alternation of silty sands bearing mainly subassemblage A1 with fine barren sands indicates different conditions ranging from outer lagoon to sandy beach-barrier conditions typical of a deltaic environment. This environmental pattern persists to the top of core 4, while the outer lagoonal (A1 subassemblage) setting is found from −12.3 m to −3.3 m in core

Table 3. Foraminiferal assemblages

	A1 Lagoon	A2 Lagoon with freshwater influence	B Lagoon with high organic matter	C Shallow marine water
α -index (median)	8.46	4.49	6.24	12.98
Dominant taxa	<i>A. parkinsoniana</i> (4.3–77.5%)	<i>A. parkinsoniana</i> (11.2–49.6%) <i>A. tepida</i> (12.3–27.9%)	<i>A. tepida</i> (14.4–38.9%) <i>E. poeyanum</i> (10.1–25.4%)	<i>Q. stelligera</i> (12.9–29.9%) <i>A. parkinsoniana</i> (5.8–13.0%)
Accompanying taxa	<i>A. tepida</i> (0.0–25.0%) <i>E. poeyanum</i> (0.0–21.4%) <i>E. granosum</i> (0.0–14.5%) <i>A. beccarii</i> (0.0–14.4%) <i>Q. stelligera</i> (0.0–14.3%) <i>H. depressula</i> (0.0–13.5%) <i>Q. pygmaea</i> (0.0–10.8%)	<i>E. poeyanum</i> (3.3–27.0%) <i>H. depressula</i> (0.0–15.4%) <i>T. schreiberiana</i> (0.0–11.7%)	<i>A. parkinsoniana</i> (2.0–19.3%) <i>A. perlucida</i> (0.0–5.2%) <i>H. depressula</i> (0.0–3.2%) <i>Bulimina</i> spp. (0.0–8.0%) <i>B. spathulata</i> (0.0–3.4%)	<i>A. tepida</i> (2.4–26.4%) <i>H. depressula</i> (3.9–8.3%) <i>E. poeyanum</i> (1.0–9.7%) <i>E. granosum</i> (0.7–2.3%) <i>R. bradyi</i> (1.0–3.9%)
Sample cores	core 3 sample: –23.5 m; core 4 samples: 0.2 m, –1.2 m, –23.2 m; core 5 samples: –3.3 m, –4.3 m, –5.3 m, –6.3 m, –14.3 m, –16.9, –17.3 m, –18.3 m, –19.3 m, –20.3 m, –21.3 m, –22.3 m, –23.3; core 6 samples: –3.7 m, –13.7 m; core 8b samples: –7.2 m, –10.4 m, –12.4 m; core 9b samples: –9.1 m, –12.3 m, –15.3 m, –17.3 m, –18.3 m, –18.3 m, –19.3 m, –20.3 m, –22.3 m; core 11 samples: –22.6 m, –23.6 m; core 12 samples: –23.4 m, –24.4 m	core 4 samples: –21.2 m, –22.3 m; core 6 samples: –2.9 m, –15.7 m, –18.7 m, –20.7 m, –21.7 m, –22.7 m; core 8b samples: –8.4 m, –14.4 m, –15.4 m, –16.4 m, –17.4 m, –18.4 m, –19.4 m, –20.4 m, –21.4 m, –22.4 m, –24.4 m; core 9b samples: –16.3 m, –21.3 m, –23.3 m	core 6 samples: –1.9 m, –4.9 m, –5.9 m, –6.9 m, –7.9 m, –8.2 m, –11.7 m, –16.7 m, –19.7 m, –23.7 m; core 8b sample: –21.4 m	core 8b: –9.4 m, –11.4 m; core 9b: –4.4 m, –5.8 m, –9.3 m, –10.3 m
Samples with insufficient microfauna	core 4: –1.2 m, –10.2 m, from –20.2 m to –16.8 m; core 5: –12.3 m, –11.3 m, –8.3 m, –7.3 m; core 6: –9.7 m, –12.7 m; core 8b: from –6.2 m to –3.7 m; core 9b: –11.3 m, –8.1 m; core 11: –21.6 m, –20.6 m; core 12: –21.5 m, –18.5 m	core 6: –17.7 m		core 9b: –7.1 m

**Figure 4.** Output of the Principal Component Analysis of the foraminiferal data. Two main groups are highlighted containing species corresponding the first to assemblage A and B, and the second to assemblage C

5. The increasing degree of diversity (at –6.3 m, maximum α -index = 17.8), and the significant presence of typical shallow marine taxa (miliolids, *Neoconorbina terquemi*, *Nonion fabum* and *Lobatula lobatula*) indicate a less confined environment,

probably due to a slight deepening of the basin. More marine conditions are also confirmed by species indicating a slight increase in salinity (Factor 1, Figure 8). Fine sands with silty-sandy levels shifting to yellow sands and gravel toward the top, lacking marine foraminiferal taxa, indicate a regressive trend toward backshore conditions.

Core 6. This borehole is located in the central portion of the ancient harbor and shows the most continuous marine influence. The entire core is constituted mainly by of silty clay and fine silty sands characterized by marine and lagoonal assemblages (A and B assemblages). In the basal portion (from –23.7 m to –14.7 m), alternation of assemblages A2 and B indicates a confined lagoonal environment with significant freshwater input (A2) and local episodes of stagnation due to the overstocking of organic matter (B). A quantitative decrease in microfauna is evident at –17.7 m, –12.7 m and –9.7 m. From –13.7 m to the top, subassemblage A2 is replaced by subassemblage A1, indicating an increased marine influence. These environmental conditions are also indicated by the significant presence of epiphytic and typical marine taxa, such as *L. lobatula*, *Asterigerinata planorbis*, *Gavelinopsis praegeri*, *N. fabum* and *Valvulineria bradyana* and by increasing α -index and Factor 1 values, which are related to salinity (Figure 9).

At –14.7 m, clear decreases in foraminiferal content and in specimen size are recorded, probably due to locally unfavorable conditions at the sea bottom. At the –10.7 m level, foraminifera are rare and poorly preserved.

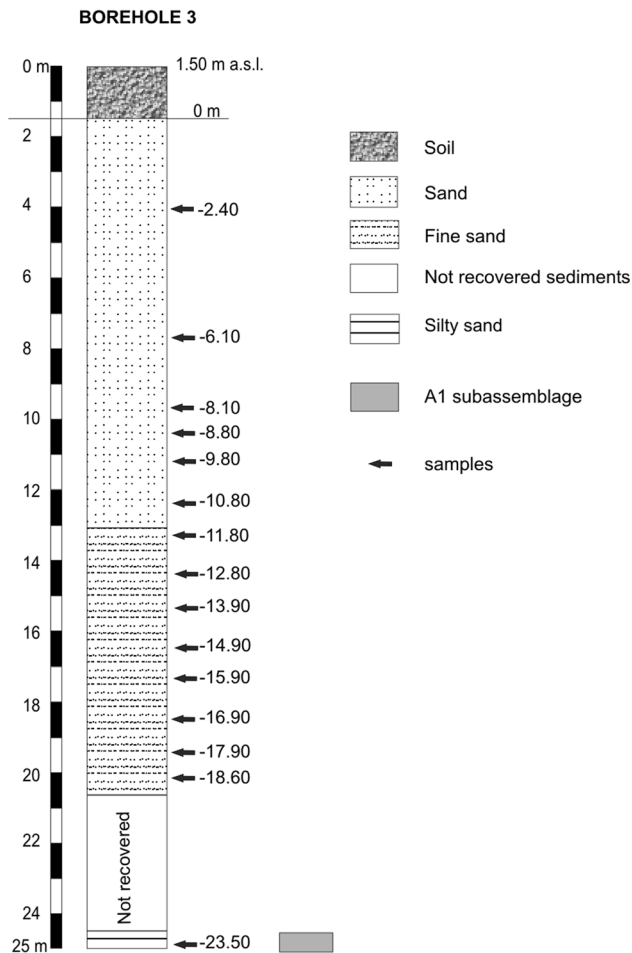


Figure 5. Lithological scheme and foraminiferal assemblages of core 3

Cores 8b and 9b. These boreholes are located in the outer western part of the harbor area. They are characterized by silty sands with local alternations of silty and clayey centimeters-thick deposits (core 8b: -20.4 m; core 9b: -20.3 m) and sandy silt levels (core 8b: -9.4 m; core 9b: -10.4 m). From the bottom to -14.4 m (core 8b) and to -14.3 m (core 9b), both cores exhibit evidence of a lagoonal environment (Figures 10 and 11). This inner-lagoon setting in core 8b is indicated by the presence of subassemblage A2 and confirmed by low Factor 1 and α -index values (Figure 10). An episode of high organic matter content is indicated by the presence of assemblage B at -21.4 m of depth in borehole 8b. In core 9b, subassemblages A1 and A2 alternate, suggesting periodic freshwater influence (Figure 11). In both cores, a barren episode overlays lagoonal deposits (core 9b: from -14.3 m to about -13.4 m; core 8b: -14.4 m to -12.9 m), corresponding to sandy lithotypes. Subsequently, a slight deepening indicated by the presence of typical marine infralittoral taxa (assemblage C) in alternation with the lagoonal assemblage (A) is carried out in both boreholes. This feature is also supported by the trends in diversity and salinity represented by the Factor 1 distribution (Figures 10 and 11). In core 8b, the significant euryhaline taxa frequencies at -10.4 m suggest continuing sporadic freshwater inputs (subassemblage A1). From -8.7 m up to -5.2 m, microfungal content declines sharply; the sandy deposits at -5.2 m are totally barren.

In both cores, barren medium sands are recorded from about -5 m to the top.

Paleoenvironmental reconstruction

An attempt to reconstruct the paleoenvironmental history of the area of Claudius' ancient harbor was made on the basis of the micropaleontological and sedimentological data.

Three different environmental scenarios can be identified: the first is characterized by a more or less confined lagoon environment (A1, A2 and B foraminiferal assemblages), the second is characterized by a shallow water marine environment with some freshwater influence (C foraminiferal assemblage) and the third is related to a supralittoral environment, barren of foraminifera. These three environmental scenarios form different combinations along the temporal evolution of each core, enabling us to create a paleoenvironmental reconstruction of the area in which the harbor system was built (Figures 12 and 13). Overall, the sedimentary succession evidenced from the studied cores can be subdivided into three intervals.

Interval 1. This interval was recognized with variable thickness in the bottom portion of each core. It is characterized mainly by a brackish-water environment, such as a lagoon or an infralittoral shallow water influenced by river inputs (subassemblages A1 and A2) (Figure 14A). The micropaleontological data highlight euryhaline foraminiferal assemblages (A1 subassemblage) dominated by typical estuarine species (*A. parkinsoniana*, *A. tepida*, *E. poeyanum* and *E. granosum*), consistent with fine-grain size sediments (mud, silty mud and silt poorly sorted).

At the bottom (about -25 m) of all cores, the foraminiferal and sedimentological data suggest an environment characterized by a more-or-less confined lagoon (A1 and A2). In particular, a more restricted environmental setting with more stressful environmental conditions (subassemblage A2) is evident in the basal portions of cores 4, 6, 8b and 9b, which are located in the central part of the area in which the harbor later developed. Both assemblages show lower diversity (A1: median α -index = 8.46; A2: median α -index = 4.49) and higher frequencies of species that tolerate stressful conditions (low oxygen content, organic matter, low salinity), such as *A. tepida* and *E. poeyanum*. The alternation of the two assemblages is probably due to local changes in coastal paleomorphology that periodically favored a more confined and organic-matter-enriched environment characterized by lower salinity. Moreover, the higher percentages of typical low-oxygen-tolerant species (assemblage B) in cores 8b and 6 indicates that organic-matter content fluctuated repeatedly at this site because of inputs from the river and subsequent stagnation events. In contrast, in cores 3, 12 and 11, which are located in the eastern and northern portion of the area, this phase is characterized by a lagoonal environment in the basal portion of the cores, followed by a subaerial environment. In fact, the absence of foraminifera, ostracods and mollusks (whole or/and fragments) indicates a sandy beach environment that persists up to the top. Supralittoral deposits with very few foraminifera and little vegetal debris and shell fragments are also found in boreholes 4 and 12.

On the whole, these deposits belong to a sedimentary unit that lies in an unconformity on the Emilian shelf deposits (Bellotti et al., 2007).

Locally, at -20.2 m and -16.8 m (core 4) and at -23.4 m (core 12), a slight faunal reduction is recorded and is probably due to environmental variability typical of the deltaic area.

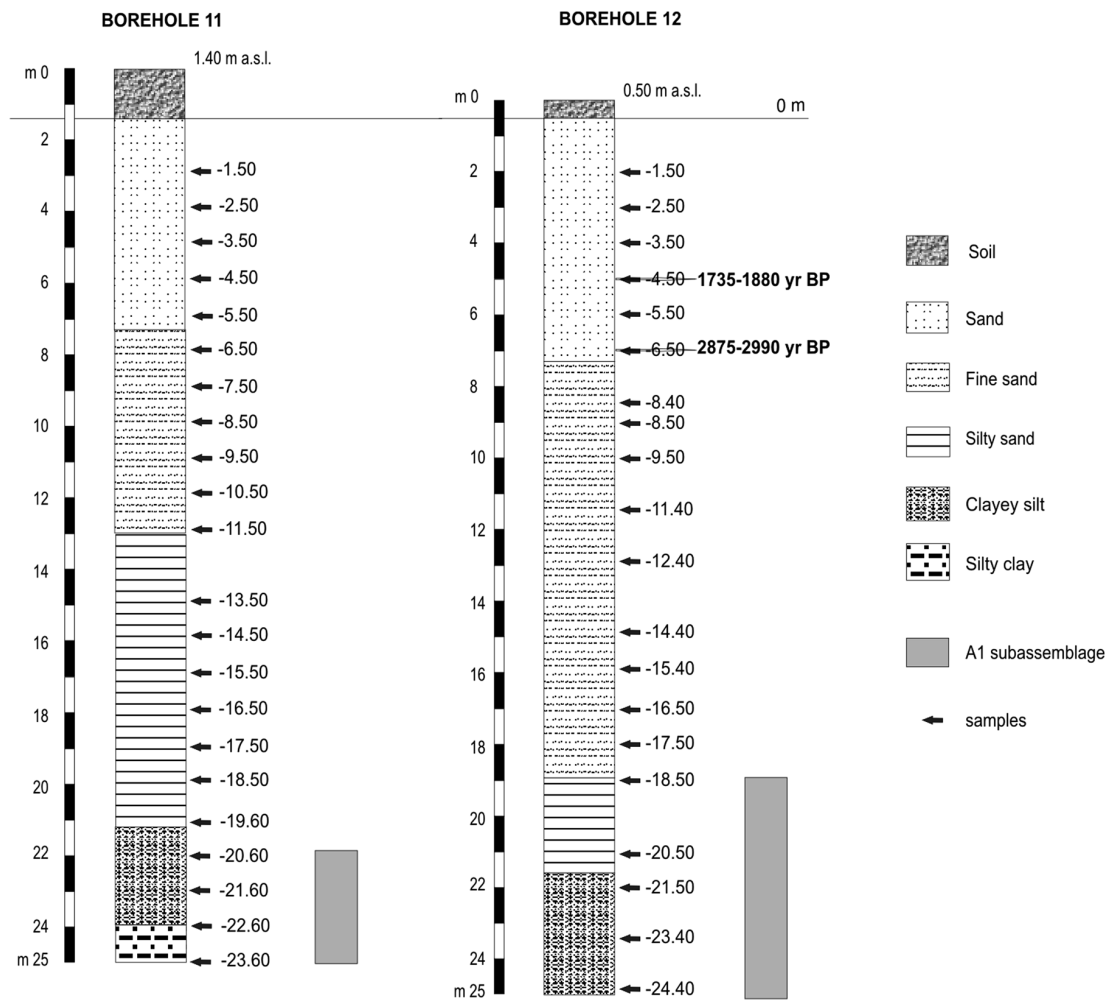


Figure 6. Lithological scheme and foraminiferal assemblages of cores 11 and 12

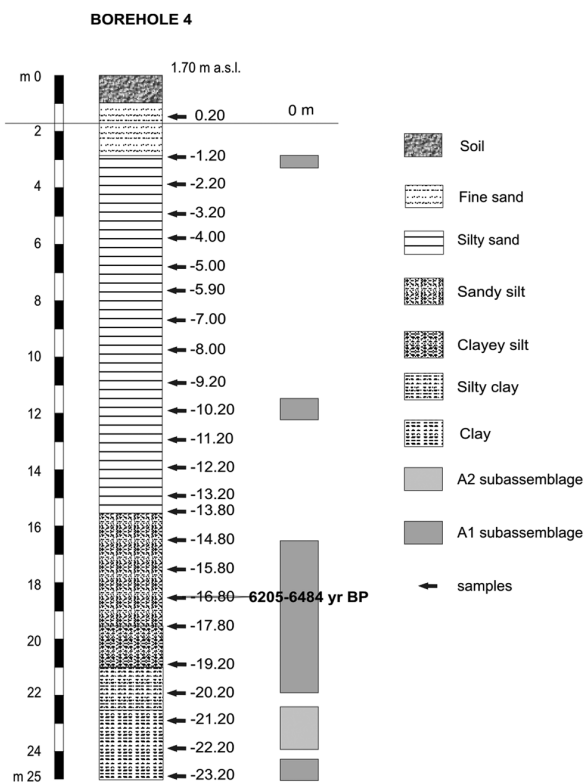


Figure 7. Lithological scheme and foraminiferal assemblages of core 4

This interval ends with barren sandy sediments that can be identified in cores 4, 5, 6, 8b and 9b at depths between -13.8 m and -14.7 m and is found slightly deeper in cores 11 and 12 (-19.6 m and -17.5 m, respectively). These sediments can be interpreted as a deltaic spit or a river-mouth bar. This interval contains sediments dated (Table 2) to 6205–6484 and 4255–4420 cal. yr BP (Bellotti et al., 2007). These dates are consistent with data from the literature (Bellotti et al., 2007; Giraudi, 2004; Giraudi et al., 2006), which report that the harbor complex was built in an area in which a deltaic cusp had previously developed.

Interval 2. Successively, in all boreholes, the alternation of sub-assemblages A1 and A2 with reduced microfaunal content or barren intervals, indicates the re-establishment of a lagoonal setting with the local formation of a deltaic sandy body.

In some boreholes (5, 6 and 11 at -10.3 m, -10.7 m and -10.5 m, respectively), silty sands without microfaunal content or characterized by circolittoral, poorly preserved, reworked specimens (*Uvigerina* spp., *Melonis* spp.) are found. Similar deposits have been found in the TRXIX borehole drilled in the channel leading to the hexagonal basin by Goiran et al. (2010) and dated to 980–775 cal. BC. These sediments can be interpreted as the product of an especially violent flood that brought circolittoral sediments to an outcropping a few kilometers inland to the river mouth. This event may have been related to the last deltaic phase before the southernmost displacement of the mouth of the Tiber. This latter event probably occurred between 790 and 360 cal. yr BC (3070±30

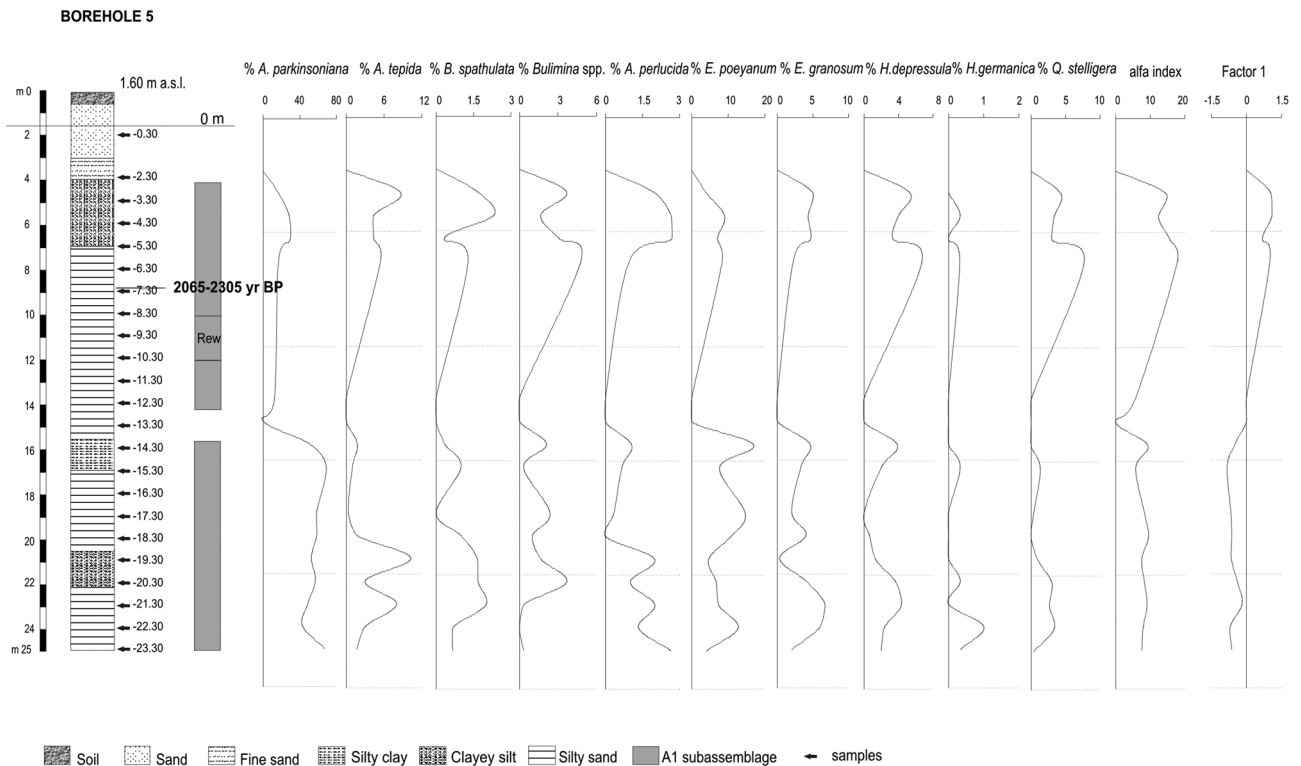


Figure 8. Lithological scheme, foraminiferal assemblages and distribution of the most significant species of core 5

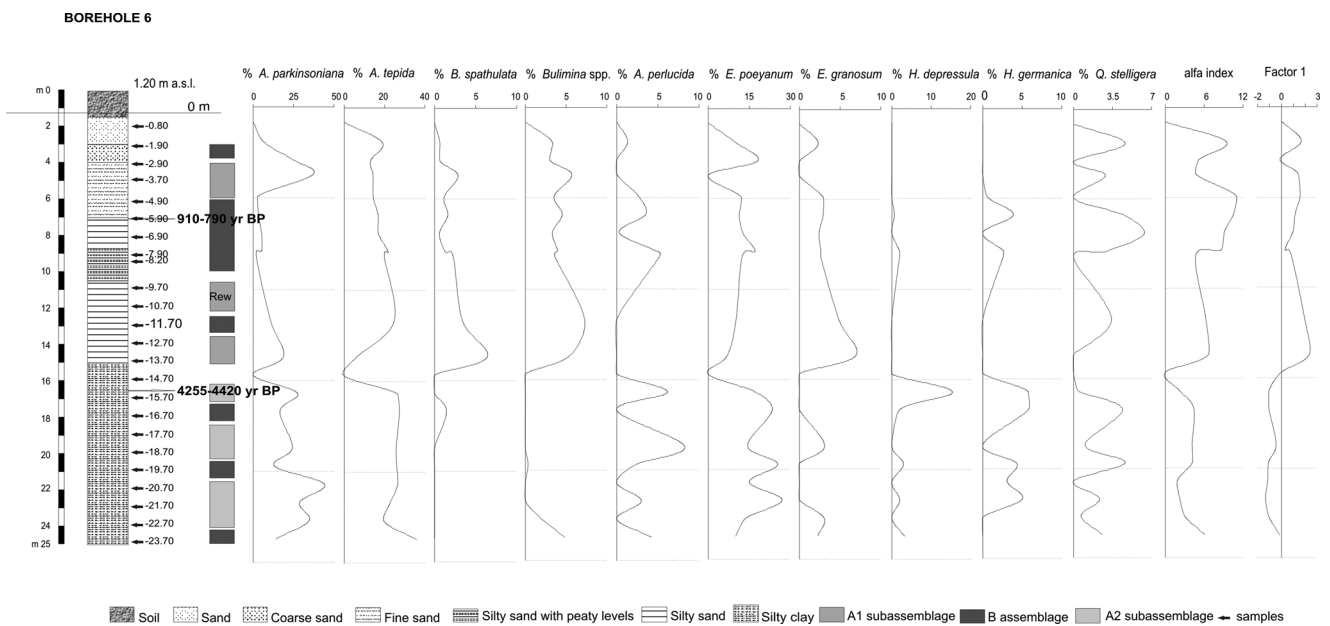


Figure 9. Lithological scheme, foraminiferal assemblages and distribution of the most significant species of core 6

and 2785 ± 30 BP (Goiran et al., 2010) or between 780 and 400 cal. yr BC (2450 ± 40 BP) (Giraudi et al., 2009). More recently the Tiber river displacement is dated between 810 and 540 yr BC (2555 ± 50 cal. BP) (Bellotti et al., 2011).

The phase of displacement of the mouth of the Tiber and the abandonment of the deltaic cusp is marked by a slight deepening of the basin recorded mainly in the boreholes 8b and 9b. The partial dismantling of the abandoned cusp is indicated by a reduction of river influence and a stronger marine infralittoral conditions (C assemblage) in cores 8b (-11.4 m and -9.4 m) and 9b (-10.3 m).

This deepening produced environmental changes in the various cores (Figure 14B): in the more western cores (8b and 9b), alternating lagoonal and marine assemblages are evident. In the central cores (5 and 6), a lagoonal environment with high nutrient input (assemblages A1 and B) is found. In the landward cores, lagoonal episodes (core 4 at -10.2 m) with intercalations of barren phases are recorded. It is not possible to define precisely when the harbor complex was built based on the fauna. However, because we know that the depth of the harbor was 7–8 m (Bellotti et al., 2009; Goiran et al., 2010), construction of the harbor definitely occurred after the general deepening of the area due to the

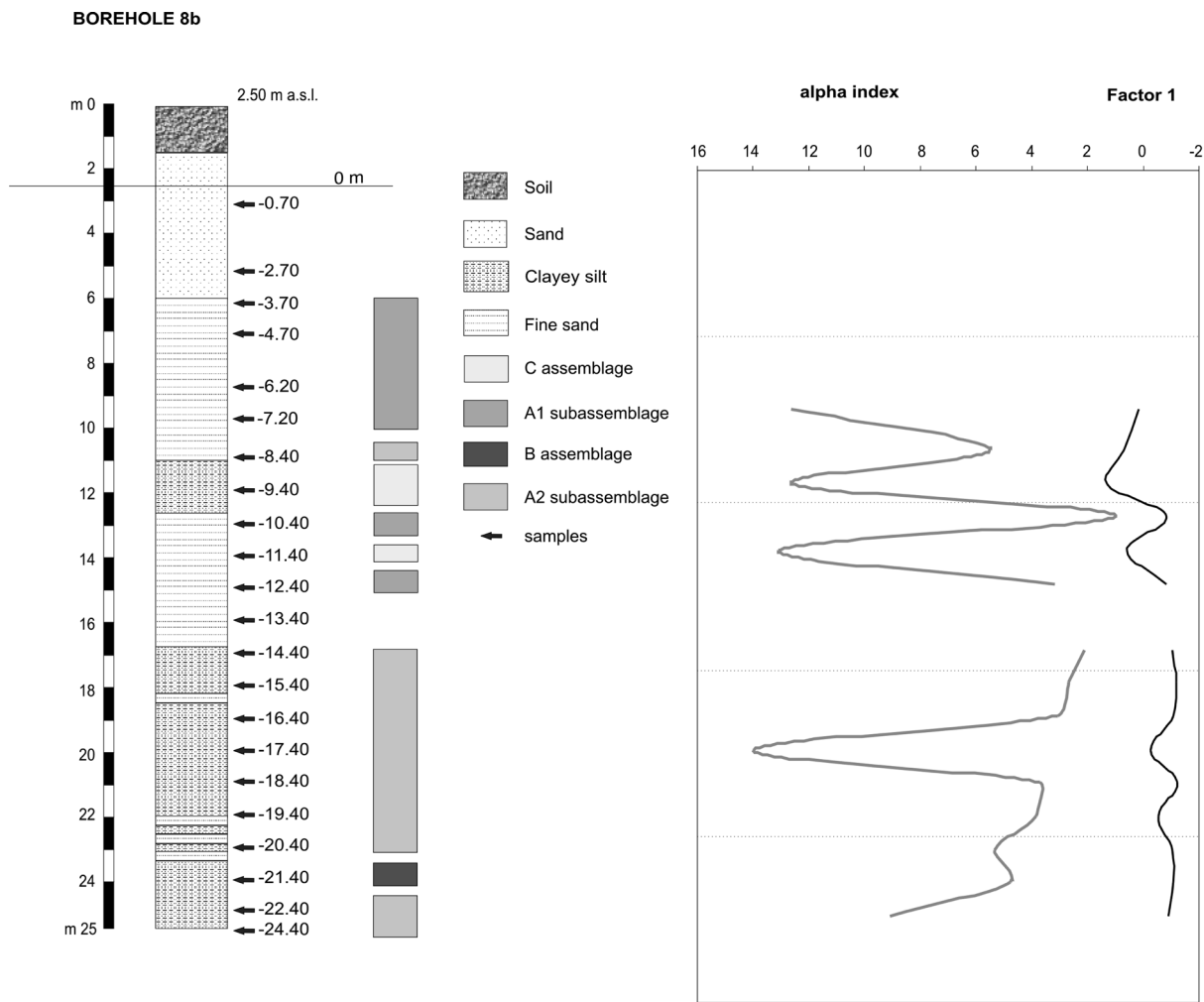


Figure 10. Lithological scheme, foraminiferal assemblages, alpha index and Factor 1 of core 8b

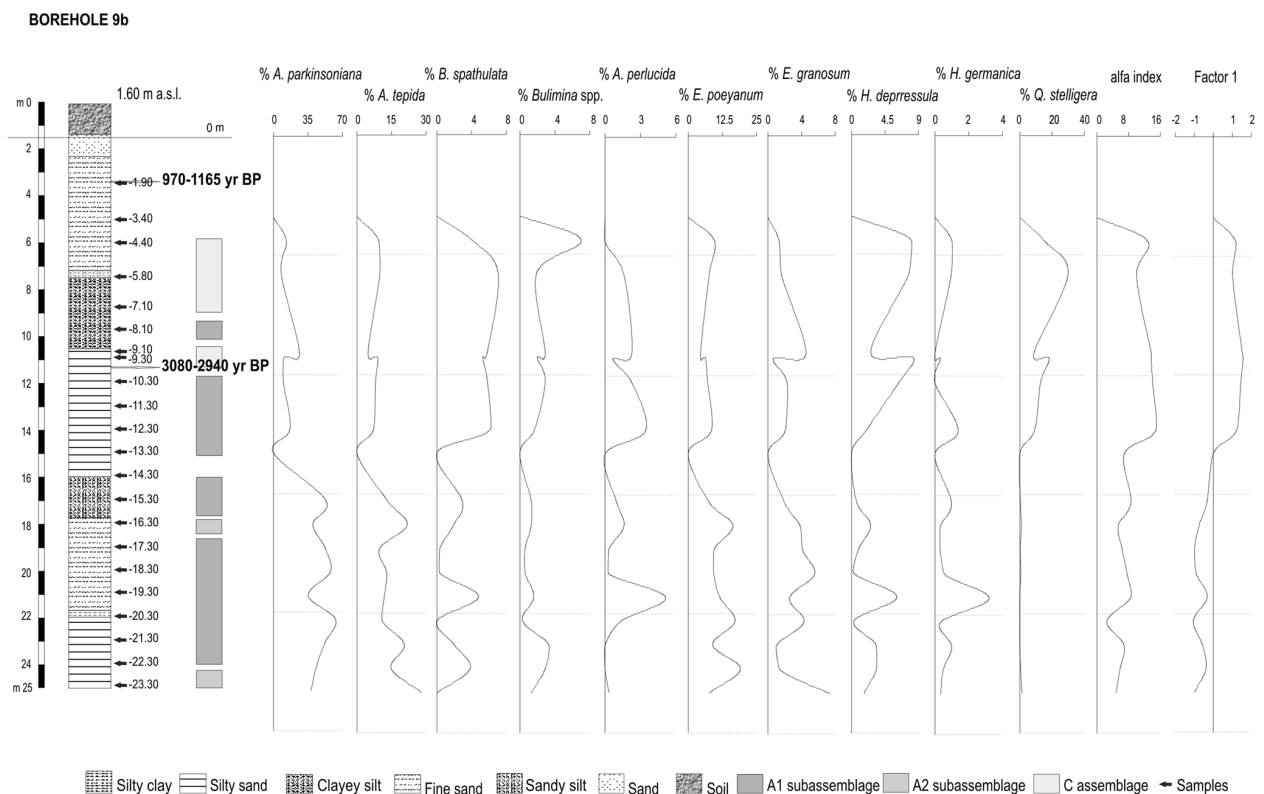


Figure 11. Lithological scheme, foraminiferal assemblages and distribution of the most significant species of core 9b

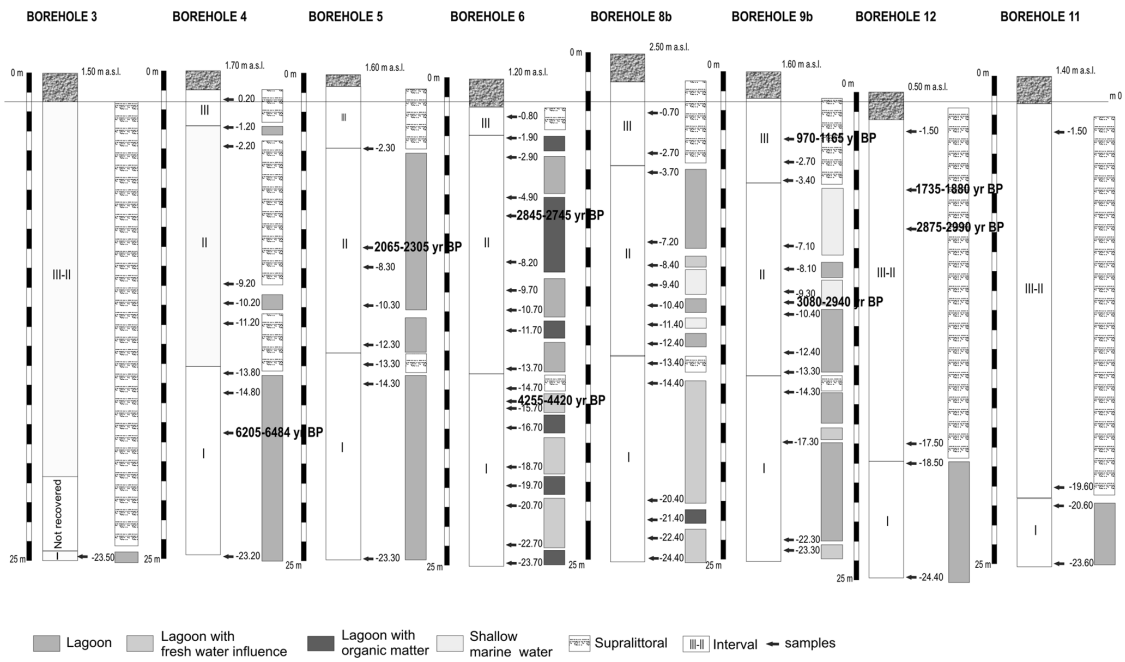


Figure 12. Paleoenvironmental reconstruction of the evolution of the ancient Claudius' harbor area in relation to the sampled cores

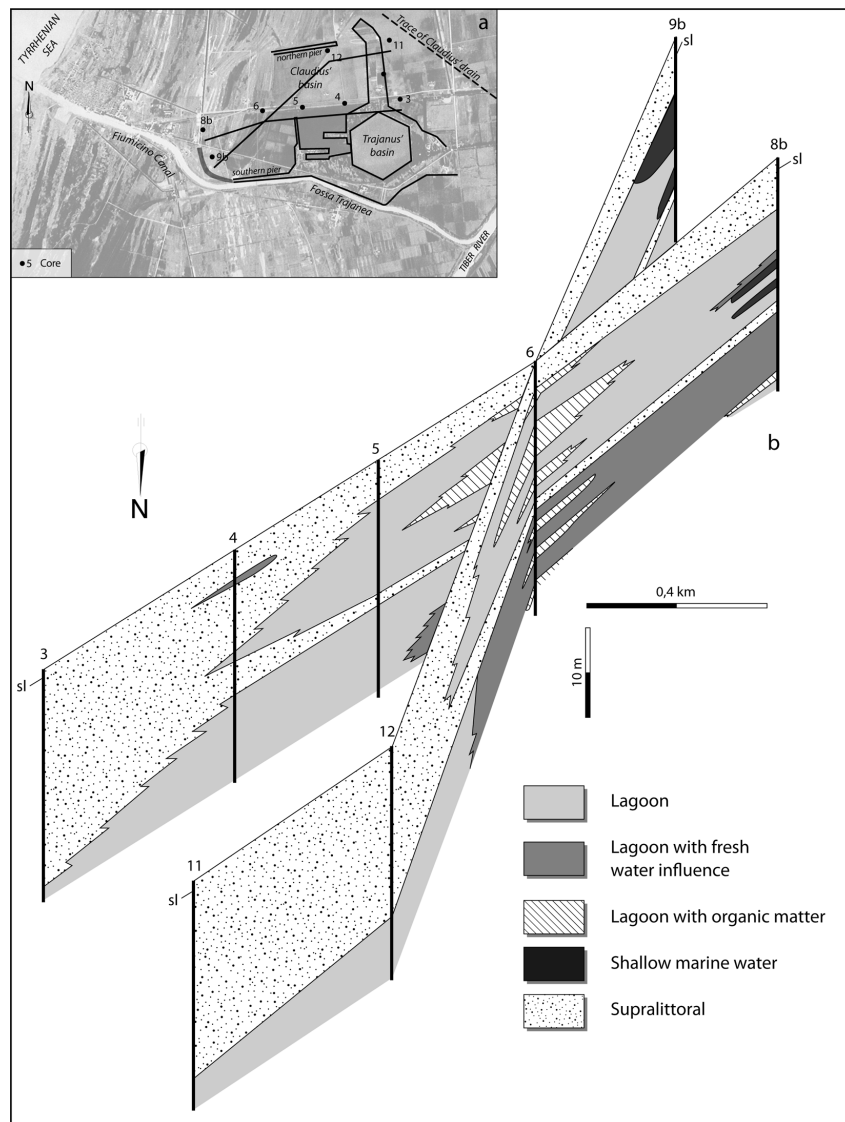


Figure 13. Fence diagram showing environmental correlations among the eight cores in the ancient Claudius' harbor area: (a) Map of the Claudius' and Trajanus' harbor area showing two traces of section; (b) Fence diagram; northern view was preferred for a better display of the lithological and paleoenvironmental units

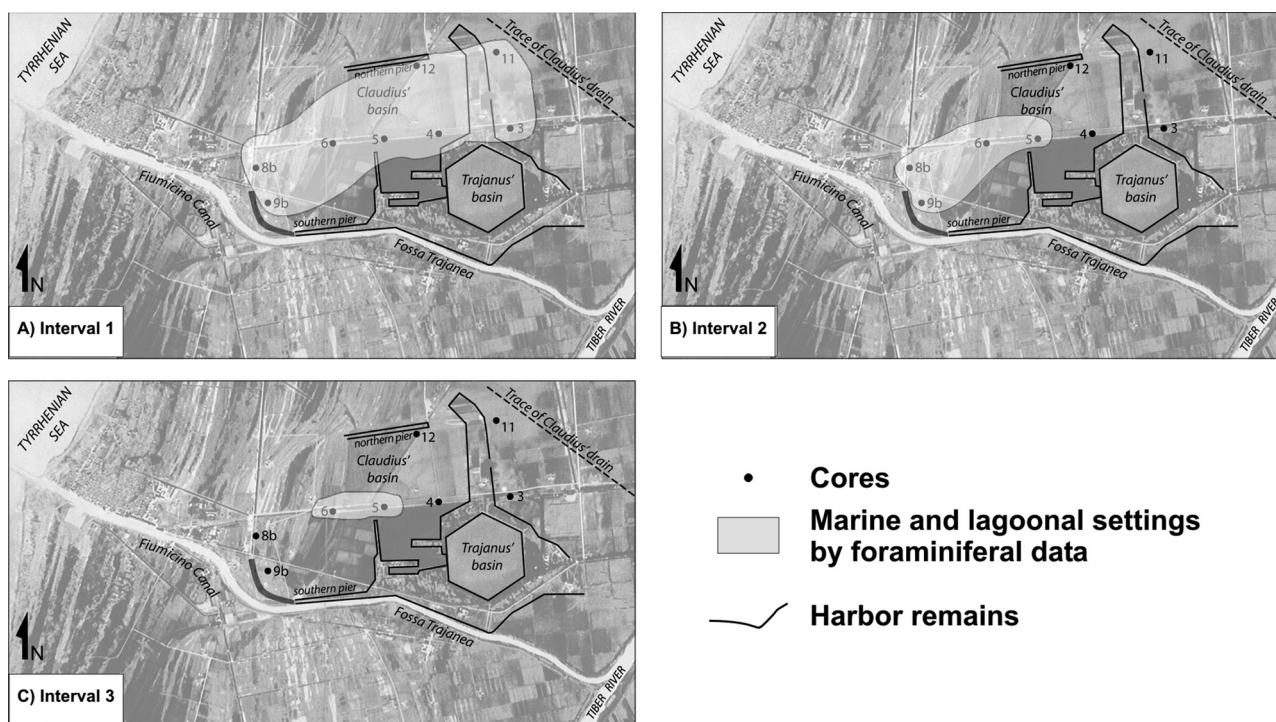


Figure 14. Representation of the ancient Claudius' harbor area during the three intervals: (A) Interval 1: lagoonal setting; (B) Interval 2: deepening of the basin and hypothetical construction of the Claudius' harbor; (C) Interval 3: filling phase of the harbor

shift of the river mouth. Confirmation of this hypothesis is provided by the age of the sediments found in core 5 at -7.75 m, which is equal to -4.95 m below the level of the Roman sea based on the core's drilling depth and the raising of the sea level since the Imperial Period (-1.2 m) (Lambeck et al., 2004).

Interval 3. In cores 8b and 9b, the uppermost 5 m are characterized by barren sands with rare peaty intercalations, one of which provides an age of 970–1165 cal. yr BP. Core 12 consists of sandy sediments with local vegetal remains that provide an age of 1735–1880 cal. yr BP at -4.0 m a.s.l. Cores 5 and 6 consist of a lagoonal environment up to about 2–3 m from the current surface, followed by barren sandy deposits. This interval records the final phase of harbor activities and the filling phase that followed. Filling seems to have occurred prematurely close to the northern pier (core 12), then close to the southern pier (cores 8b and 9b), while the central portion of the harbor (particularly cores 5 and 6) remained submerged the longest and provided a passage for boats that were still accessing Trajanus hexagonal basin from the sea during the early Middle Ages (Figure 14C).

Conclusions

Our integrated analyses of micropaleontological and sedimentological data provide significant further paleoenvironmental evidences regarding the morphological configuration of the ancient harbor of Claudius. At their bases, all cores show a lagoonal environment corresponding to the first deltaic cusp of the Tiber River. This cusp, which was deactivated because of avulsion that is thought to have taken place between 780 and 540 yr BC, was partly dismantled, causing the area to deepen slightly before Claudius' harbor was built. Claudius' harbor already showed premature filling near the northern pier during the Roman period. Based on the data available to us, we can confirm the presence of only one entrance to the west, delimited by two piers: one to the

north and one to the south, enclosing the entire harbor area (Figure 14B). It's not possible to confirm or to exclude a northern entrance. Around the year 1000 of the Common Era, the area close to the southern pier also appears to have been filled. At that time, only a narrow central strip remained suitable for shipping. These inferences are consistent with historical sources that record harbor activities in Trajanus' basin, which was connected to the sea via the original basin of Claudius.

The final filling of Claudius' basin and the complete isolation of Trajanus hexagonal basin (which forms a lake today) occurred during the development of the last phase of the wave-dominated Tiber delta progradation, which took place from the sixteenth century onward as a result of the 'Little Ice Age'.

Acknowledgements

We would like to thank the anonymous reviewers for their helpful suggestions and comments on the manuscript. This study was funded by the 'Progetto di Ricerca di Università 2008 – Le associazioni fossili nella ricostruzione paleoambientale e paleobiogeografica del meso-cenozoico appenninico e mediterraneo' (M.G. Carboni).

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