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A geochemical and sedimentological perspective of the life cycle of *Neapolis* harbor (Naples, southern Italy)

H. Delile [a, b, c, *], J.-P. Goiran [a], J. Blichert-Toft [c], F. Arnaud-Godet [c], P. Romano [d], J.-P. Bravard [e]

[a] *Maison de l'Orient et de la Méditerranée, CNRS UMR 5133, 69365 Lyon Cedex 7, France*
[b] *Department of Archaeology, University of Southampton, Avenue Campus, SO17 1BF Southampton, United Kingdom*
[c] *Ecole Normale Supérieure de Lyon, Université Claude Bernard-Lyon I, CNRS UMR 5276, 69007 Lyon, France*
[d] *Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università di Napoli Federico II, Largo S. Marcellino 10, 80138 Naples, Italy*
[e] *University Lumiere-Lyon 2, France*

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ABSTRACT

Since the discovery of the ancient harbor of Naples in 2004 during construction work on an underground railway, geoarchaeological studies undertaken on the archaeological excavation have revealed the main stratigraphic and paleo-environmental levels of the harbor site near the Piazza Municipio. However, knowledge of the dynamics and paleo-environmental changes in the water column of the harbor, as well as the processes of transport and deposition of sediments that led to siltation and infilling of the harbor basin, has been lacking due to the absence of high-resolution data. To fill these gaps, we have undertaken a three-dimensional study (longitudinal, transverse and vertical) of the harbor deposits by carrying out geochemical and sedimentological analyses of four stratigraphic sections of the archaeological excavation. The results show that after a phase of relative calm during the first half of the 1st c. AD, siltation of the harbor progressed exponentially up to the 5th c. AD, when dredging operations were carried out to obtain a water level sufficient for the development of maritime and harbor activities. We attribute this acceleration of siltation to a combination of climatic, anthropic and volcanic factors. Volcanic activity was responsible for a high-energy, tsunami-type event during the eruption of Vesuvius in 79 AD. From the 5th c. AD onwards, the harbor basin of Neapolis does not appear to have been functional as evidenced by its transformation into a lagoon following coastal progradation. The last stage of infilling was the development of a flood-dominated fan delta under the combined influences of climatic cooling in the Early Medieval Cool Period and agro-pastoral activities in the catchment area of the harbor. Several generations of paleo-channels, containing flash flood deposits, as well as sheet wash from sheet floods, are indicative of high environmental instability in this period.

1. Introduction

At the beginning of the 1990s, following excavations of the ancient harbors of *Caesarea* (Israel) (Reinhardt et al., 1994, 1998; Reinhardt and Raban, 1999) and Marseille (France) (Hesnard, 1994; Morhange, 1994; Morhange et al., 2001, 2003), geoarchaeologists for the first time became interested in the sedimentary archives of ancient harbor basins. The *Caesarea* and Marseille research projects contributed to understanding the history of excavated harbors with interactions between humans and the environment at the center of interest (sea-level variations, coastline progradation, siltation rates, anthropization, etc.) (Marriner and Morhange, 2007). Ancient harbor basins are particularly worthwhile studying because they were at the heart of trade between port cities and the rest of the Mediterranean world and ensured urban development and prosperity. Thus, the conditions to which harbors were subjected during their history, especially siltation, were decisive for the survival of urban centers. At *Neapolis* (Greek for Naples), survival was even more critical as commercial links between the cities of the Bay of Naples (Fig. 1A) and Rome were essential (e.g. Balland, 1965; Domergue and Rico, 2014).

It is within this historiographic context that the

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* Corresponding author. 7 rue Raulin, 69365 Lyon cedex 7, France.
E-mail address: hugo.delile@mom.fr (H. Delile).

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geoarchaeological studies carried out since the 2000s at *Neapolis* have focused on changes in coastline position and sea level (Irollo, 2005; Ruello, 2008; Amato et al., 2009; Giampaola, 2009; Cinque et al., 2011), the location and extension of the harbor basin (Giampaola et al., 2006; Carsana et al., 2009), and past landscape reconstruction in the area surrounding the city (Russo Ermolli et al., 2014; Allevato et al., 2009, 2010). Although these investigations provide geomorphological and stratigraphical information useful to paleo-environmental reconstruction of the harbor zone located in the bay of Echia (Fig. 1B), identification of the dynamics and paleo-environmental changes in the water column, as well as the processes of transport and deposition of sediments that led to siltation of the harbor basin, has been out of reach due to the absence of high-resolution data (except for pollen and plant remains that have provided information on the cultural history of the urban zone of *Neapolis*; Russo Ermolli et al., 2014 and Allevato et al., 2015). In the present work, we focus on the interaction between fluvial and marine influences on the harbor water column, as well as on siltation and its human control in a sheltered bay environment, topics still poorly understood compared with deltaic environments.

While harbor geoarchaeology principally uses methods based on micropaleontology (molluscs, ostracods, foraminifera, diatoms, pollen) and sedimentology (texture, granulometry, exoscopy) (Goiran and Morhange, 2003; Marriner and Morhange, 2007; Cubizolle, 2009), geochemistry has been shown recently for Rome (Delile et al., 2014) and Ephesus (Delile et al., 2015a) to be an additional source of quantitative paleo-environmental data. Here, we apply geochemistry and statistics to the deposits of the ancient harbor basin of Naples that has been exposed since 2004 by excavation work on two new lines of the Naples underground railway. The archaeological excavation provides a unique opportunity to study the harbor deposits of Naples by means of several stratigraphic sections oriented towards the four cardinal points, and thus to examine the infilling of the harbor basin through a three-dimensional approach (longitudinal, transverse and vertical). In harbor geoarchaeology so far, only the ancient ports of Marseille (Morhange, 1994; Morhange et al., 2001, 2003) and Istanbul (Algan et al., 2009, 2011; Bony et al., 2012) have been studied by way of stratigraphic sections uncovered by archaeological excavation.

2. Study area

2.1. Geography and geology

The city of Naples is the capital of the region of Campania, which lies between Latium to the north and Calabria to the south. Its western border, in particular the coastal area, is limited by the volcanic zone of the Phlegraean Fields, while its eastern fringe reaches the slopes of Vesuvius (Fig. 1A). The region has a Mediterranean climate with mild rainy winters and hot, relatively dry summers (Allevato et al., 2012).

The Neapolitan area is part of the plain of Campania, which is situated in a graben of the same name in which both volcanism and tectonics are active. Since the Quaternary, the plain of Campania and its extension under the sea have been subject to subsidence, which is variable for different sectors and periods (Cinque et al., 2011). Brancaccio et al. (1991) have estimated a rate of subsidence during the Quaternary of 2 mm per year on average. The littoral of the plain of Campania presents a varied geomorphological framework in which steep marine cliffs alternate with narrow coastal plains (e.g., Volturno). The Bay of Naples itself is defined by the Sorrento Peninsula to the southeast and the Gulf of Puteoli to the northwest (Fig. 1A). The bay contains a succession of projecting capes (e.g., Posillipo) and coastal plains (Sebeto and Sarno) (Fig. 1A).

The principal geological structures and formations are the result of tectonic and volcanic activity in the area, which has given rise to numerous hills composed of deposits of volcanic origin. The latter derives primarily from the Phlegraean Fields and secondarily from Vesuvius (Romano et al., 2013; Russo Ermolli et al., 2014). In general, the volcanic geology of the region consists of lavas, lithified yellow tuff (>39 ka BP), Campanian ignimbrites (~39 ka BP), Neapolitan Yellow Tuff (~15 ka BP, the principal geological formation of the sector), pyroclastic deposits from the Phlegraean Fields (<15 ka BP) as well as Vesuvius, and interstratified marine and terrestrial deposits along with pyroclastic deposits (<5 ka BP) (Romano et al., 2013).

2.2. Archaeology and geoarchaeology

In the middle of the 7th c. BC, Greek colonists from Cumae founded on the hill of Monte Echia the first urban center of Naples, called *Parthenope* (“virgin” in Greek). Later, at the end of the 6th c./beginning of the 5th c. BC, the city was re-located lower down in the plain, at the foot of the terrace of Pendino, and was re-named *Neapolis* (“new city” in Greek) (Fig. 1B). Archaeological remains from the Greek period are rare on the Neapolitan coast, while those from the imperial period are more common. These latter mostly consist of Roman villas situated on the promontory of Pizzofalcone, the slopes of the hill of San Martino (Fig. 1B) and the hill of Posillipo (Fig. 1A) (Romano et al., 2013). The second category of Roman infrastructure identified in the area includes the coastal road and the aqueduct of *Aqua Augusta*. Both served the principal urban centers of the plain of Campania, from the time they were built in the Augustan period (Keenan-Jones, 2010). The course of the Roman road (*via per Cryptam*) can be identified by the presence of tombs built along it (Romano et al., 2013). It begins at *Neapolis* and runs westward along the plain of Chiaia to end at the city of Pozzuoli. Pozzuoli was considered the granary of Rome for 250 years, and hence was integrated into the Pozzuoli-Ostia-Rome harbor system at the beginning of the 2nd c. BC (Zevi, 2001a, b; Tchernia, 2011).

The archaeological excavations carried out when construction took place on the two underground railway lines in Naples led to the discovery of the ancient harbor of the city in 2004, which was situated in a bay separating the two historical centers of *Neapolis* and *Parthenope* (Fig. 1B) (Giampaola et al., 2006; Carsana et al., 2009). The discovery of this Graeco-Roman harbor between the Piazza Municipio and Piazza Bovio confirmed initial hypotheses proposed by Capasso (1895) predicting its position to be in this sector. Aside from the reconstruction of the active periods of the harbor since its foundation, determined from pottery shards, two other discoveries were of interest to archaeologists. The first was the identification of traces of dredging directly visible at the bottom of the harbor. Concave and relatively deep grooves were identified in the volcanic substratum between −7.5 and −5.6 m below local mean sea level (lmsl) near the Piazza Municipio (Giampaola et al., 2006; Carsana et al., 2009). These dredging operations occurred between the end of the 4th c. and the 2nd c. BC and were intended to increase draft in order to counter siltation of the harbor. The second significant archaeological discovery in the ancient harbor of Naples were three Roman shipwrecks perfectly preserved in the harbor silt. These ships, dated to between the 1st and the 3rd c. AD, were found between −4.1 and −3.6 below lmsl (Giampaola et al., 2006, Giampaola, 2009; Carsana et al., 2009; Allevato et al., 2009, 2010).

Since its discovery in 2004, the study of the ancient harbor of Naples has been accompanied by geoarchaeological investigations that have revealed a sedimentary infill 15 m thick (−13 below lmsl to +2 m above lmsl) above the volcanic substratum (Amato et al., 2009). The depressions formed in the

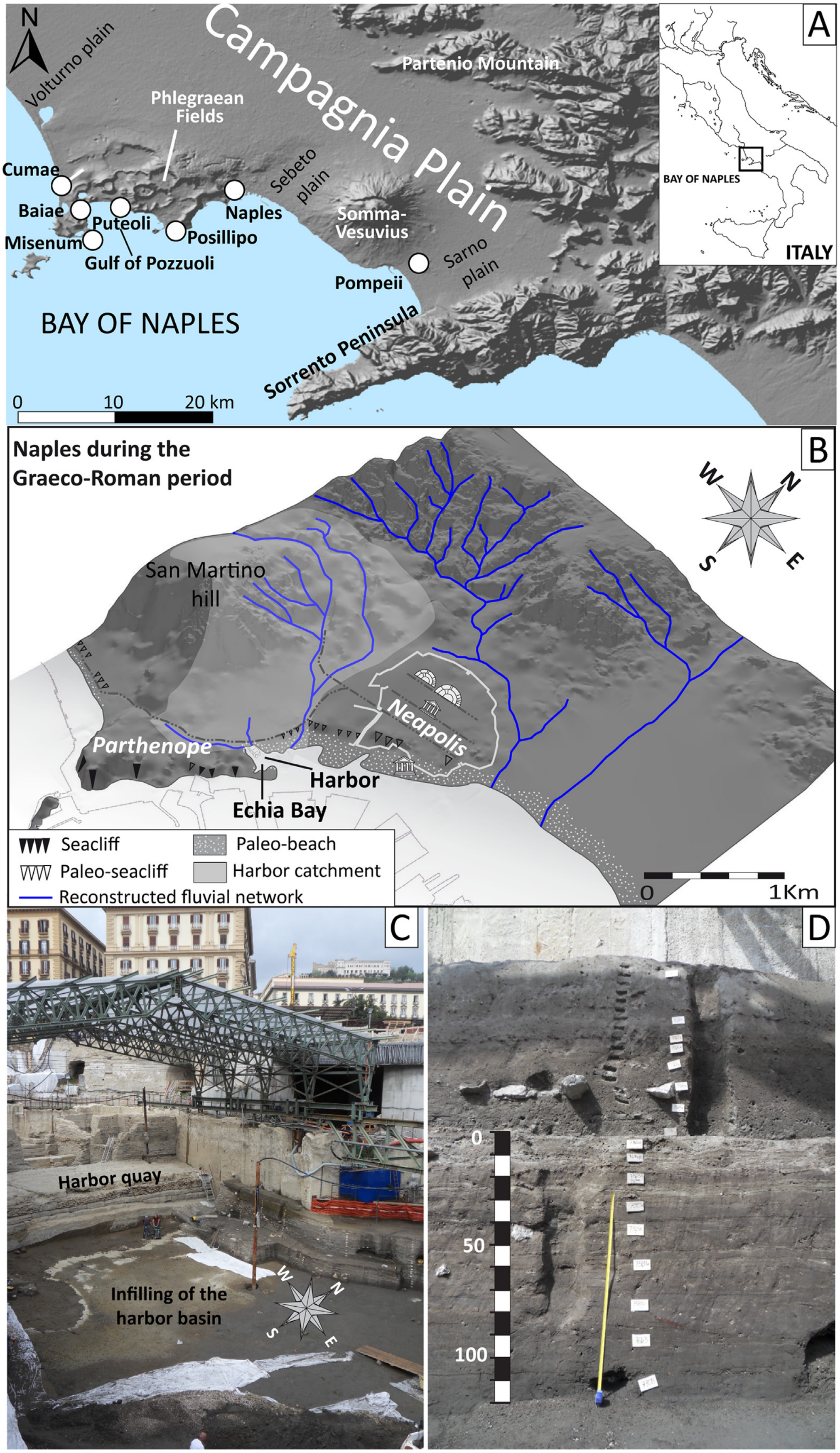

Fig. 1. Location of the study area. Naples is located halfway between two volcanic areas, Somma-Vesuvius and the Phlegraean Fields (**A**). Echia Bay and the harbor basin during the Graeco-Roman period (**B**) (modified from Russo Ermolli et al., 2014). The archaeological excavation of the ancient harbor of Naples is located a few meters below current sea level in front of Piazza Municipio (**C**). Panel **D** shows an example of the stratigraphic section of the harbor investigated in the excavation.

substratum by fluvial erosive activity during the first part of the Holocene are filled by an initial series of marine sediments deposited between −13 and −8 below lmsl during the marine transgression of the middle Holocene (Irollo, 2005). This transgressive phase caused the coastline to advance about 500 m into the interior relative to its present position. The marine sands of the shoreface continued to be deposited in a submerged environment up to the 3rd c. AD (Fig. 2). After the discovery of the three shipwrecks and a Roman wharf dated to the end of the 1st c. AD (Fig. 1C), a minimum marine sea level of −3 ± 0.5 m below lmsl was inferred for the end of the 1st c. AD, having been situated at −4.5 ± 0.5 m below lmsl in the 4th and 2nd c. BC (Amato et al., 2009; Russo Ermolli et al., 2014) (Fig. 2). Starting in late Antiquity, i.e., at the end of the 3rd c. AD, the environmental conditions of the harbor evolved gradually towards a more confined environment owing to the development of a sandy bar at the entrance of the bay of Echia (Amato et al., 2009; Russo Ermolli et al., 2014). This spit bar caused the formation of a lagoon at ~ −3.2 m below lmsl which persisted until the end of the 5th c. AD when sea level was still situated at ~ −2 ± 0.5 m below lmsl (Amato et al., 2009; Russo Ermolli et al., 2014). In this period, the lagoonal deposits were covered by gravelly-silty sands several meters thick (the top situated at up to +2.5 m above lmsl). This detrital discharge led to progradation of the littoral. Starting in the 6th c. AD, the ancient bay located today at the Piazza Municipio was covered by agricultural land, while the activities of the harbor took place further to the east (Russo Ermolli et al., 2014). In certain sectors of the harbor basin, these deposits were overlain by marshy and alluvial sediments, which can be found at up to +2.5 m above lmsl (Fig. 2).

3. Materials and methods

3.1. Sedimentological analyses

Beginning in 2011, we sampled the four stratigraphic sections (see an example in Fig. 1D) exposed by the archaeological excavation of the harbor to analyze in particular grain size distributions (see Delile et al., 2014; for details of sample pre-treatment) in order to understand the nature of the harbor basin infill and the hydro-sedimentary processes. A total of 131 samples were taken from the stratigraphic sections, all of which were dated by means of archaeo-stratigraphic units identified by archaeological remains recovered within the layers (pottery fragments and structures) (Giampaola, 2004; Giampaola et al., 2006; Russo Ermolli et al., 2014). An age-depth model has been constructed based on these archaeo-stratigraphic units (Fig. 2).

While the sediment fraction >1.6 mm was sieved using several sizes of sieves, the fraction <1.6 mm was measured by a Malvern Mastersizer 2000 laser granulometer. The interpretation of granulometric curves was based notably on the CM diagram (also known as the Passega image), opposing the median (D50) to the coarsest (D99) percentile, in order to determine depositional and transport processes (Salomon et al., 2012; Bravard et al., 2014; Delile et al., 2015a,b; 2016a) (Fig. 3).

Magnetic susceptibility (MS) measurements were performed on samples taken in the East section to detect variations in ferromagnetic mineral contents in the sediments, mostly Mn and Fe oxides, hydroxides, and oxyhydroxides (Dearing, 1999). Both in coastal and mountainous areas, MS reflects the terrigenous flux derived from fluvial hydrodynamics. Magnetic susceptibility was

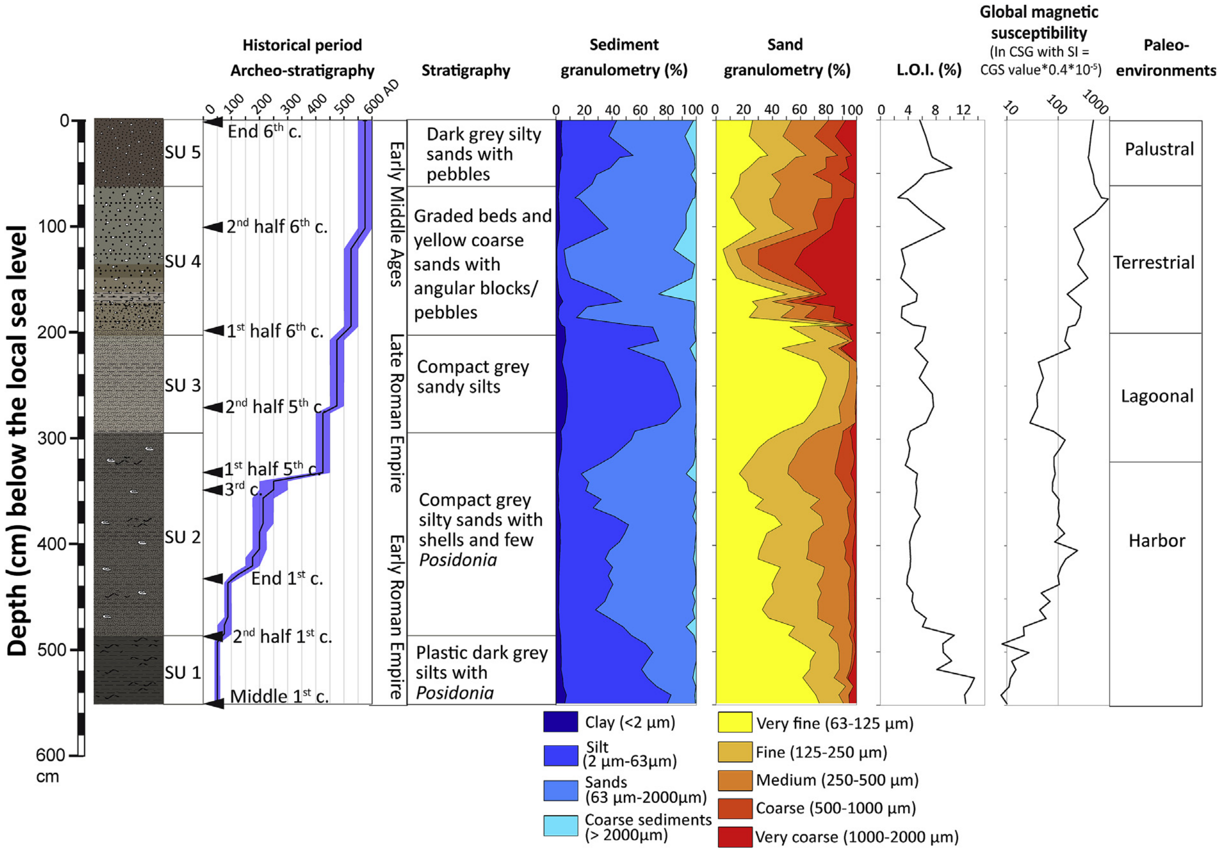

Fig. 2. Stratigraphic log of the East section showing the age-depth model constructed using archaeological dating (Giampaola, 2004; Giampaola et al., 2006; Carsana et al., 2009), grain-size distributions, L.O.I. contents, magnetic susceptibility values and the paleo-environmental succession (Carsana et al., 2009; Amato et al., 2009; Russo Ermolli et al., 2014).

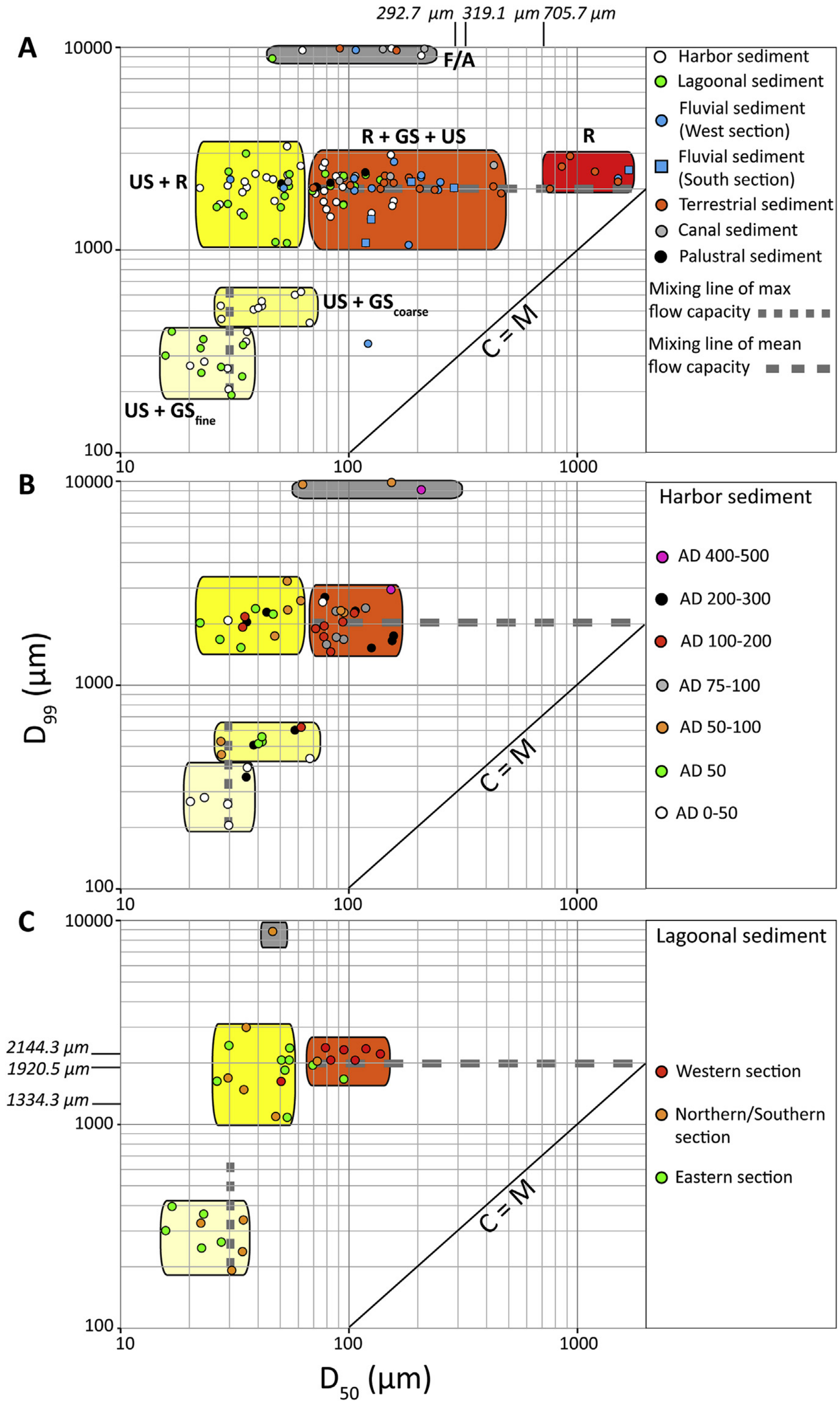

Fig. 3. Plot of the grain size 99 percentile (D 99) versus the median size (D 50) (C/M diagram) for all sediments (**A**), harbor sediments (**B**) and lagoonal sediments (**C**). Pure processes: R: rolling. Mixed processes: US+GS$_{fine}$: mixed uniform suspension and finely graded suspension; US+GS: mixed uniform suspension and graded suspension; US+R: mixed uniform suspension and rolling; R+GS+US: mixed rolling, graded suspension and uniform suspension; F/A: flash floods and/or anthropic inputs. Figures in italics show the decrease of sediment sizes in an eastward direction (see text).

measured three times using a Bartington MS2E1 (Dearing, 1999).

3.2. Major and trace element analyses

Geochemical analyses were carried out on the eastern stratigraphic section, chosen because it had the highest sampling resolution (61 samples, i.e., one sample every approximately 9 cm) (Figs. 2 and 4). Sample dissolution and other manipulations were carried out in a clean laboratory under laminar flow hoods. After sieving at 63 µm, aliquots of 100 mg sediment (fraction <63 µm) were dissolved in a 3:1:0.5 mixture of concentrated double-distilled HF, HNO_3, and $HClO_4$ in Savillex beakers left on a

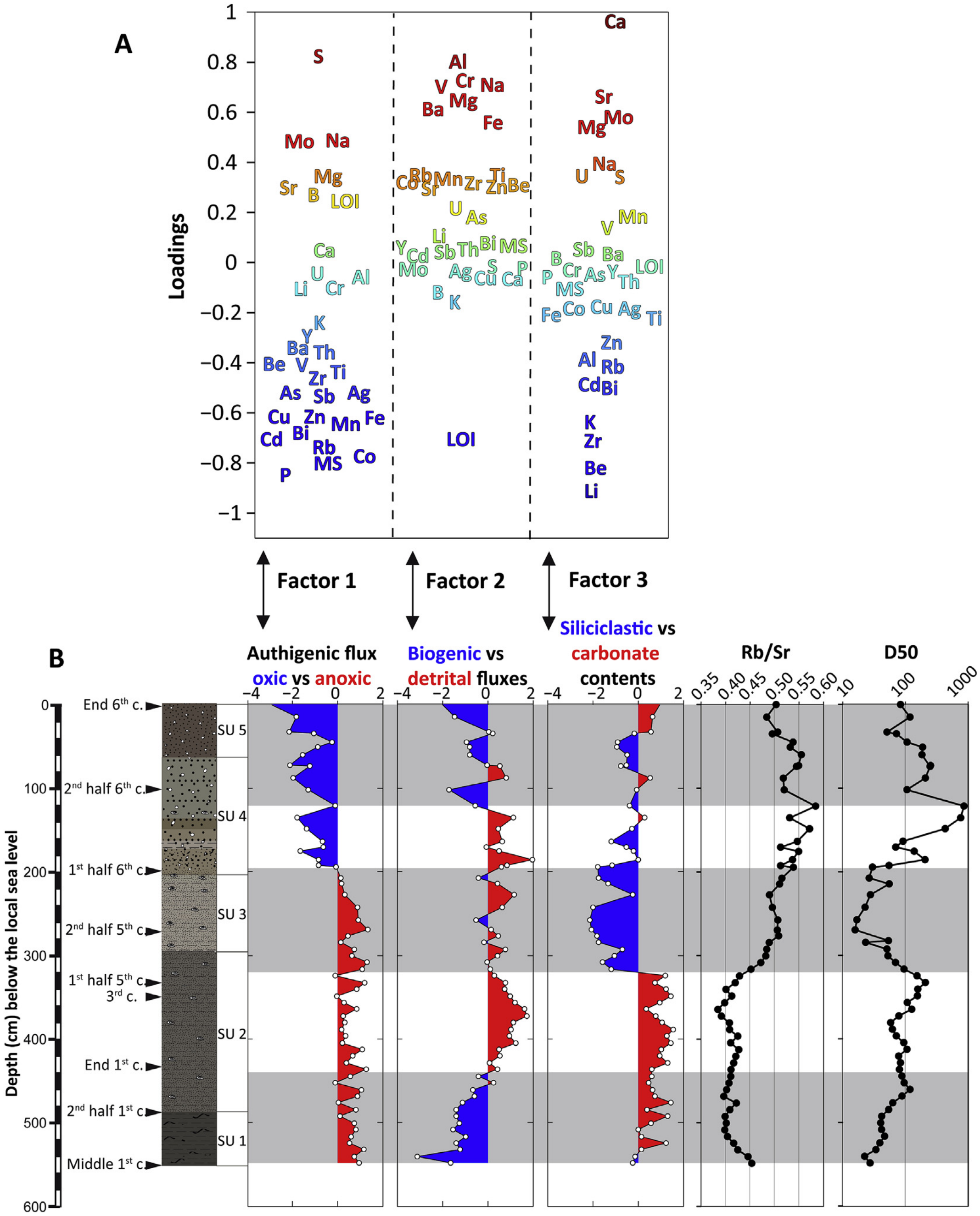

Fig. 4. Factor analysis of major and trace element concentrations. The number of factors is limited to three. (**A**) Component loadings. Factor 1 (36.5%) includes authigenic elements (redox sensitive) opposing oxic (Mn, MS, Co, Cd, Zn, Rb) (F1 < 0) to anoxic conditions (S, Mo) (F1 > 0). Factor 2 (15.8%) opposes elements indicative of detrital fluxes (Al, Fe, Mg, etc.) (F1 > 0) to those indicative of a biogenic component (L.O.I.) (F1 < 0). The third factor F3 is dominated by the carbonate (Ca, Sr) (F1 > 0) and the siliciclastic (Li, Be, Zr, K) (F1 < 0) components. (**B**) Distribution of the different factors with depth (below lmsl in cm) in the column. The plots are compared with sedimentary units, archaeological dates, Rb/Sr and D50.

hotplate at 120–130 °C for 48 h, then evaporated to dryness. Perchlorates and any remaining fluorides were converted to chlorides by drying down with 6 M distilled HCl. The samples in solution in 6 M distilled HCl were all clear, indicating complete sample breakdown. The samples were redissolved in 2 ml concentrated distilled HNO_3, from which ~10 percent aliquots were further diluted to 2% HNO_3 and internal standards (10 ppm Sc for ICP-AES and 2 ppb In for Q-ICP-MS) added. Major elements were analyzed by ICP-AES (ICAP 6000) and trace elements by Q-ICP-MS (Agilent 7500 CX). The upper limit of blank contribution is negligible for major elements and <2 percent of the sample content for trace elements. The data are listed in Table S1.

Loss On Ignition (L.O.I.) was measured in a muffle furnace from 10 g sediment heated for 16 h at 375 °C. L.O.I. provides a rough measurement of the organic content of the sediment, which tends to increase when fluvial activity is reduced.

4. Results and discussion

4.1. Assessment of sediment transport processes

Fig. 3A shows CM image representation for all the samples taken from the stratigraphic sections in the harbor basin. The resulting image differs from the original image defined by Passega (1957) and also from the images obtained for other ancient harbor basins such as those of Trajan (*Portus*) (Salomon et al., 2012), *Ostia* (Goiran et al., 2014), *Ephesus* (Delile et al., 2015a) and *Utica* (Delile et al., 2015b).

4.1.1. A new CM image

The atypical image for *Neapolis* arises from the strong contrast between two principal components characteristic of two specific hydrodynamic regimes: (1) Processes of transport and deposition dominated by sand and silt (a mixture of graded and uniform suspensions: US+GS) structured along a vertical dashed line, with values of D_{99} ranging from 200 to 600 μm and low values of D_{50} ranging from 15 to 40 μm; (2) Processes dominated by rolling (R), structured along the dashed horizontal line, with maximum values of D_{99} ranging from 1000 to 3000 μm and values of D_{50} between 70 and 2000 μm (Fig. 3A); (3) The combination of these two principal components defines a third component (US+R), where the two dashed lines intercept each other (Fig. 3A).

4.1.2. Interpretation

In the first case (vertical line), the adjustment variable is the coarsest percentile C (D_{99} or the maximum flow competence), while in the second case, the discriminating variable is the median (D_{50}), providing evidence of average flow conditions. D_{50} makes it possible to distinguish coastal aquatic environments (harbors and lagoons) from continental environments (rivers and terrestrial milieux). Coastal aquatic environments have D_{50} inferior to 150 μm (Fig. 3), implying that processes of transport and deposition are dominated by uniform suspension mixed with both graded suspension and rolling (groups US+GS_{fine}, US+GS_{coarse}, US+R and R+GS+US). Continental environments display a median mostly above 100 μm, meaning that particles were mobilised and deposited principally by processes of pure rolling (group R) or a mixture of rolling and suspension (group R, R+GS and R+US).

Also, group F/A includes poorly classified gravels collected in various environments at the site and characterised by the highest values of C (9–10,000 μm). They are explainable by violent floods and the presence of artifacts.

The presence of uniform suspension in different types of deposits accounts for the absence of sedimentary structure in the stratigraphies (Passega, 1957, 1964). This can be explained by the widespread entry of fine particles into the milieu from the catchment basin of the harbor (Fig. 1B), which led to progressive reduction of energy and sedimentation *en masse* in the water (a form of downstream control of sedimentation).

4.1.3. Similarities and differences between the harbor and the lagoon

In general, the lagoon and the harbor are similar in their hydrodynamics because their M values are less than 150 μm (Fig. 3B, C). This is the case even more so for the deposits of group US+GS_{fine}, which are similar, reflecting inputs subject to the same conditions of flow.

The CM image of the harbor deposits (Fig. 3B) reproduces almost exactly that of the lagoon (Fig. 3C), as the samples align equally along the two mixing lines of maximum and mean flow capacity. However, two specific characteristics emerge from the CM image of the harbor (Fig. 3A, B):

(i) The highest hydrodynamic level within the harbor basin is a function of time because the first deposits dated to between AD 0 and 50 correspond to low values of D_{50} in uniform suspension and decantation (groupe US+GS_{fine}), while later deposits occurred under increasingly turbulent conditions of flow (from group US+GS to group R+GS+US). This last characteristic is clearly visible in the textural diagrams of the eastern section (Fig. 2).

(ii) The D_{99} values of the harbor deposits aligned along the mixing line of maximum flow capacity are higher than 1500 μm, while those of the lagoon locally are lower (<1500 μm) due to a slight difference in flow energy. The high value of C in groups US+GS and US+R attests to the temporary occurrence of a more energetic environment allowing the intrusion of coarse particles into both the harbor basin and the lagoon (Fig. 3B, C). A terrestrial origin of these particles is suspected because of a reduction in the size of the coarsest particles in the lagoon from the western part of the archaeological site towards the eastern sector (Fig. 1).

(iii) Above 100 μm in group R+GS+US, the median discriminates between terrestrial and fluvial environments. Unlike the lagoonal deposits lower in the stratigraphy (<2 m below lmsl), the terrestrial unit presents a bedded sedimentary structure composed of elementary sub-horizontal sequences (Figs. 5 and 6) with inversely graded bedding. Such a structure implies processes of transport and deposition by graded suspension identified by the CM image (group R+GS+US in Fig. 3A).

(iv) Aquatic environments under the influence of terrestrial environment. Part of the deposits of terrestrial origin are relatively poorly sorted (group R+GS+US distanced from the right C = M), probably because of laminar flows of sheet deposits in shallow water over a short time span and because of the presence of uniform suspension in undetermined quantities. However, the sorting of the particles is higher for the terrestrial sediments included in group R, which is situated near the straight line C = M. Good sorting would reflect more constant and regular flows on slopes, unlike those suitable for a mixture of rolling and graded and uniform suspension (sporadic currents of strong intensity, group R+GS+US). Efficient sorting may be related to the evacuation of fine particles due to the energy of regular and sustained tractive currents (Fig. 3C).

The threshold value of the median at 100–150 μm within group R+GS+US also differentiates the relatively poorly sorted fluvial deposits that were sampled in the paleo-channels of the West and South sections (Figs. 5, 6 et 7). Two hypotheses explain the origin of this poor grain size sorting: (1) One is paleogeographic in nature and concerns progression of the terrestrial component into the fluvial deposits (see above); (2) The other is paleohydrological and concerns deposits from flash floods that transported and deposited the entire assemblage of grain size ranges.

The fluvial deposits of the southern section are different from those of the western section (Fig. 3A): (1) South section: progressive reduction of the hydrodynamic level of the flows and better sorting of the particles towards the top of the paleochannel are observed (Fig. 5); (2) West section: poor sorting of particles affecting all the fluvial samples analyzed.

These differences suggest that the paleochannel of the South section must have gone through a period during which it functioned for longer and more regularly, i.e., with a single, relatively stable paleochannel (Fig. 5). In contrast, the paleochannels of the West section (Figs. 6 and 7) contained sporadic and relatively powerful outflow. They were probably responsible for several occurrences of abandonment of original channels during one or more flood phases.

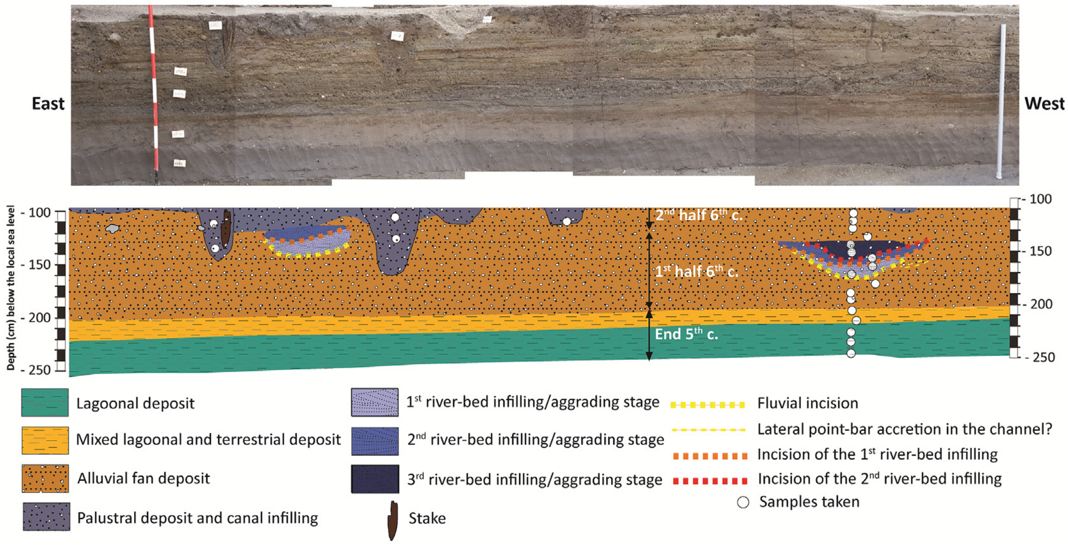

Fig. 5. Interpretation of the South stratigraphic section.

4.2. *Environmental and geochemical conditions in the harbor basin*

Factor analysis of major and trace element abundances (Table S1) in the harbor sediments was applied to identify element clusters related to the environmental conditions prevailing during and after sedimentation (Delile et al., 2014, 2015a). We discriminate three significant factors in order of importance (Fig. 4):

1. *The first factor* (36.5% of the total variability of the geochemical signal, Fig. 4A) comprises the elements associated with authigenic fluxes (redox conditions), which carry evidence of the post-depositional conditions of the deposits, that is, the environment in which they have evolved (Sageman and Lyons, 2003). The principal markers for a deficit in oxygen in the water column (S, Mo) are opposite those that precipitate in oxic environments such as hydroxides of Fe and Mn with which trace metals co-precipitate or are adsorbed onto (As, Cd, Zn, Co, Cu, Sb, Ag). Elements that precipitate as metallic complexes under oxic conditions also have been recorded in sediments of the ancient harbors of Ephesus and Rome (Delile et al., 2014, 2015a), as well as in estuarine sediments from Louisiana (Guo et al., 1997). Classically, anoxic conditions of bottom waters are followed by increase in U concentrations (Tribovillard et al., 2006), as also observed in the ancient harbor deposits of Rome at Portus (Delile et al., 2014). But in some cases this does not happen since known conditions of oxygen depletion in the water column of the ancient harbor basins of Ephesus (Delile et al., 2015a) and Tyre (Elmaleh et al., 2012) did not lead to U enrichment.

   Like the mixing line of mean flow capacity, Factor 1 distinguishes coastal aquatic environments (the harbor and lagoon units between 550 and 200 cm, Fig. 2), in which deficit in oxygen is remarkably stable, from continental aquatic environments, whose principal characteristic is good ventilation of the water column (Fig. 4B).

2. *The second factor* (15.8% of the total variability) opposes elements indicative of detrital fluxes (Al, Fe, Mg, etc.) to those indicative of a biogenic component (L.O.I.). The detrital component (positive F2 values) well reflects the local geological assemblage of the Phlegraean Fields, consisting mainly of felsic pyroclastic rocks, such as trachyte and trachyphonolite (Lustrino et al., 2002; Peccerillo, 2005; Piochi et al., 2005, 2014) of which the primary mineralogical assemblage is alkali feldspars (Mormone et al., 2015). The predominant presence of these minerals in the sedimentological matrix leads to oversaturation of Al, Na and Ba in the positive F2 values (Fig. 4A). Barium feldspars, well known in the Roman Alkaline Province of Italy (Plant et al., 2005), forms by replacement of K^+ by Ba^{2+} in the mineral structure, thereby explaining the depletion of K in Factor 2. The local pyroclastic assemblage also contains some mafic rocks, such as trachybasalts (Peccerillo, 2005), which explains the oversaturation of Mg, Fe and V in the positive F2 values. As for Ba, V also is well known in the Roman Alkaline Province of Italy (De Vos and Tarvainen, 2006). The origin of the local sediments from both mafic and felsic rocks is consistent with the local igneous rocks consisting of both basalts and felsic volcanics (Daly, 1925; Chayes, 1963; Clague, 1978).

   The balance between detrital inputs (positive F2 values) and development of biogenic fluxes (negative F2 values) within the water column reflects the hydrodynamic conditions of the environment. This observation is confirmed by the joint evolution, in the stratigraphy of the East section, of Factor 2, D50 (positive values of F2) and L.O.I. (negative values of F2) (Figs. 2 and 4). The behavior of F2 within the stratigraphy indicates regular increase of the hydrodynamic level within the harbor basin before the end of the 1st c. AD, which was accompanied by a sandy discharge carried by local coastal streams (Fig. 1B). Comparison of the coefficients of correlation between the granulometric fractions and the discriminating elements of the positive values of F2 shows relatively good correspondence between the sandy load and the mafic rocks. The positive correlations between the sand fractions and Mg ($r = +0.40$), Fe ($r = +0.55$) and V ($r = +0.63$) further indicate that these elements are represented in the sand fraction and, hence, that basalt is a significant component of the sand.

3. *The third factor* (10% of the total variability) contrasts elements indicative of the carbonate component (Ca, Sr) with those indicative of the siliciclastic content (Li, Be, Zr, K). The main characteristic of Factor 3 is that it very clearly distinguishes the harbor environment (positive F3 values from 550 to 320 cm) from the lagoonal environment (negative F3 values from 320 to 200 cm) (Fig. 4). For *Neapolis* harbor, the significance of the

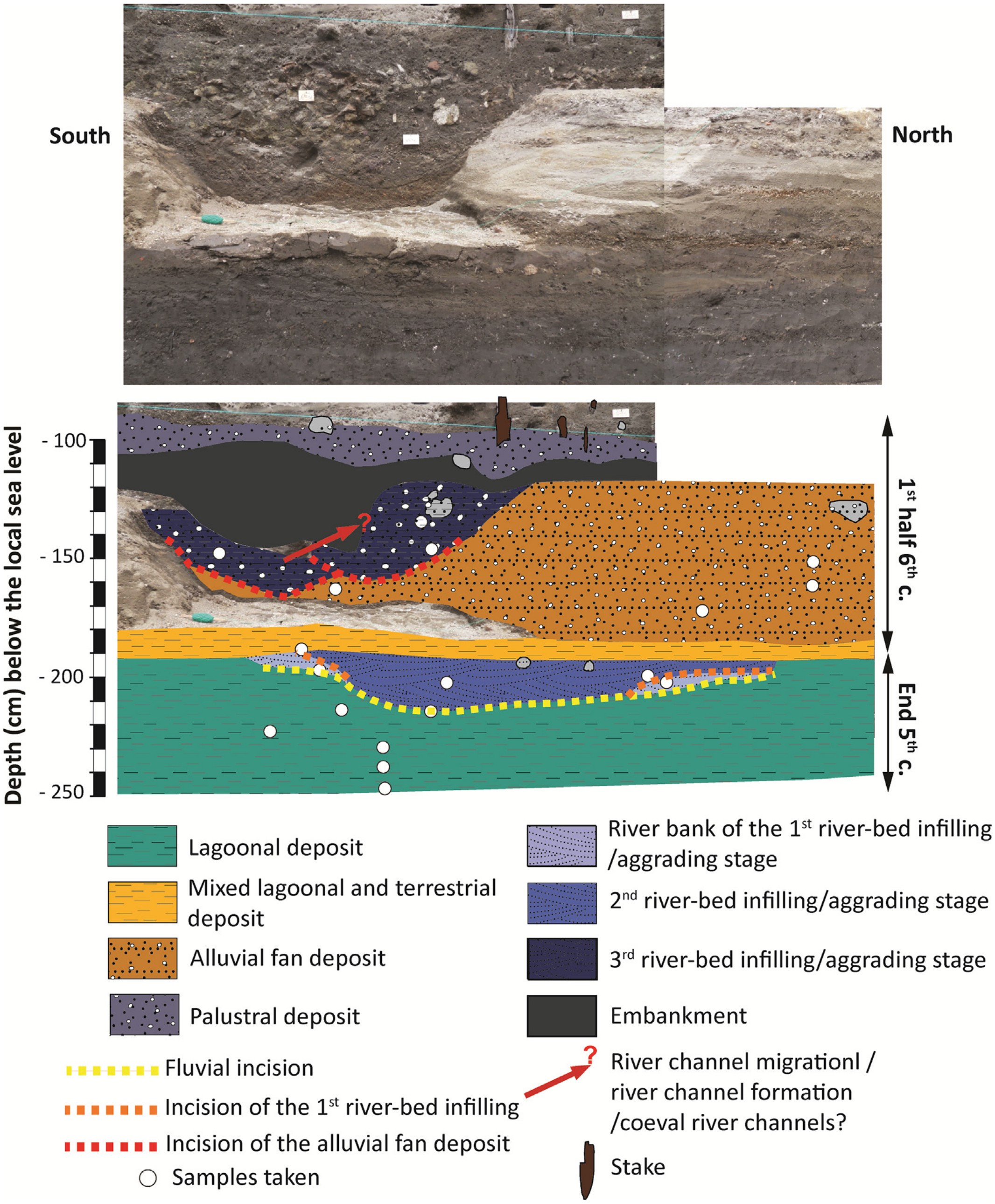

Fig. 6. Interpretation of the bottom part of the West stratigraphic section.

carbonated fraction is explained by the marine nature of this milieu in which shell fragments are numerous. This is not the case for the lagoonal deposits. The positive values of Factor 3 correspond to an enrichment in Na and Mg, both of which are indicative of a marine environment as these two cations are the most common in seawater (De Vos and Tarvainen, 2006). For the lagoon, the siliciclastic fraction reflects eroded particles from surrounding felsic rocks, as Li, Be, Zr and K (the principal elements of the negative values of Factor 3) are generally present in felsic lithologies (De Vos and Tarvainen, 2006). Although a relatively good correlation would be expected between the siliciclastic fraction of Factor 3 and the detrital fluxes of Factor 2, this is not observed because of the differing granulometric distribution in the harbor and lagoonal deposits. The enrichment of the latter in clay particles (5.7% on average) in contrast to the underlying deposits (3% on average) inevitably leads to a significant increase in Li, K and Be, elements that are strongly present in clay minerals, such as illite (Lyons and Welch, 1997) for Li and K and montmorillonite for Be (Marshall and Fairbridge, 1999; Kabata-Pendias, 2011). This is verified by the positive correlations between K (r = 0.44), Li (r = 0.48), Be (r = 0.25) and the clay fraction, reflecting the affinity of these elements for enriched clayey deposits. This indicates that easily weathered feldspars are a significant component of clay. These results stand in contrast to those obtained for Rome, where feldspars are not a significant component of sands (Delile et al., 2014).

4.3. Chronology of the harbor's life cycle

According to the present sedimentological and geochemical

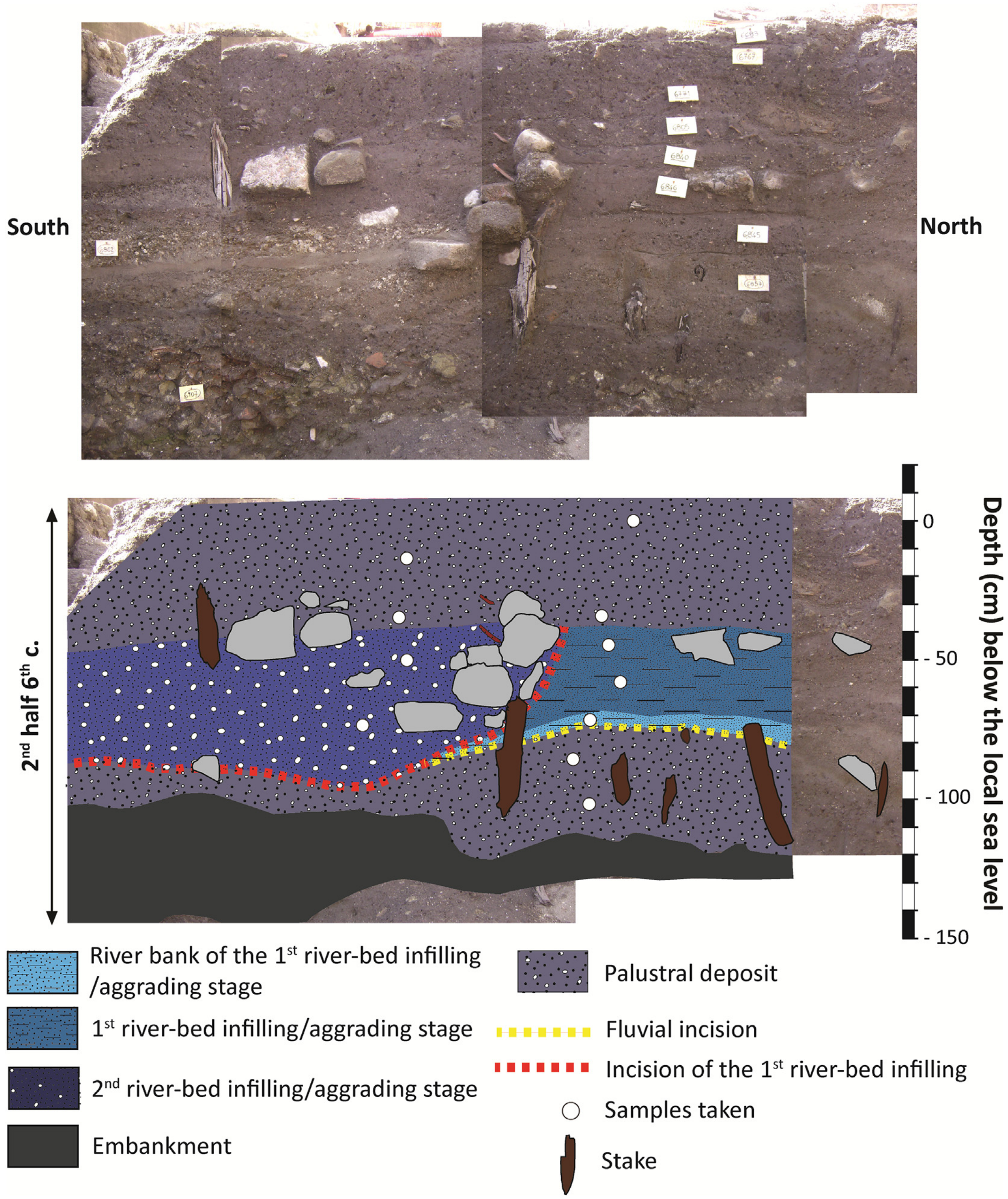

Fig. 7. Interpretation of the upper part of the West stratigraphic section.

results, siltation and infilling of the ancient harbor basin of Naples took place in five stages (see gray and white bands on Fig. 4B).

4.3.1. *A quiet harbor environment until the end of the 1st c. AD*

During the second half of the 1st c. AD (550–440 cm), harbor sediments were deposited in an aquatic environment in which the high values of sodium and magnesium (positive values of F3 in Fig. 4), as well as those of sulphur and organic matter, are evidence of a marine environment (Sageman and Lyons, 2003; De Vos and Tarvainen, 2006). The latter reflects oxygen deficit in the harbor water column brought about by little or lack of renewal of the water masses due to the low hydrodynamic level of the environment. The currents responsible for transport and deposition of particles by uniform and graded suspension were weak enough to ensure the production of organic matter (Hossain et al., 2014).

The marine environment also explains the enrichment in calcium carbonates whose endogenic origin is attested to by both the amount of shell debris in the sediments and the low values of Rb/Sr (Fig. 4B). An exogenic source of strontium is ruled out by the lack of fluctuation of the Rb/Sr ratio within this period's stratigraphy.

4.3.2. *A harbor basin threatened by continuous detrital inputs until the 5th c. AD*

From the end of the 1st c. AD, the conditions of the marine environment (Factors 1 and 3 remain stable) showed continuous progression of detrital fluxes carried by currents that were increasingly energetic in the harbor basin. This sandy discharge into the harbor was achieved by coastal watercourses carrying the products of erosion generated at the scale of the catchment area. The harbor acted as a sediment trap at this time.

This change in regime of the paleo-environmental conditions of the harbor water column occurred at a key point in the history of the Bay of Naples, since it was at that time that the eruption of Vesuvius in AD 79 took place. A sedimentary layer of some 30 cm is attributed to this event in the North section of the archaeological excavation (from −4.22 to −4.50 below lmsl) (Fig. S1). It is composed of heterogeneous sediments, shell debris, numerous wood fragments, *Posidonia* and pottery, as well as large numbers of rolled pumice pebbles, which are characteristic of this event (Plinian pumice lapilli fallout) (e.g. Sigurdsson et al., 1985; Vogel and Märker, 2013 for a review). A recent study by Delile et al. (2016b) showed that this sedimentary unit also is the only one from the stratigraphic section to have recorded a significant shift in the Pb isotope composition of sample residues. This high-intensity layer was probably deposited by a tsunami that accompanied the Vesuvius volcanic eruption in the Bay of Naples. Digital models demonstrating the occurrence of tsunamis of modest amplitude in the Bay of Naples (induced by pyroclastic flows entering the sea) (Tinti et al., 2003), brought on by the volcanic eruptions of Vesuvius, corroborate the account of Pliny the Younger on the AD 79 tsunami in his second letter addressed to Tacitus: "*The sea seemed to roll back upon itself and to be driven from shore by the shaking of the land. The shore became more spacious and was filled by various fish left behind on the sand*." (Pliny the Younger, VI, 20). The AD 79 tephra overlying an erosional surface is recorded for the Bay of Naples by Sacchi et al. (2005) who described, for the Sarno prodelta system, the stratigraphic signature of this layer, deposited, according to them, by a tsunami.

Rather than looking for a direct effect of this high-intensity event on the durable detrital inputs into the harbor basin, we postulate an indirect effect from a combination of factors:

(i) Of much less importance relative to the east of the Somma-Vesuvius, the possible pyroclastic consequences of the eruption of Vesuvius in AD 79 on the hills near the harbor basin could have provided loose material that was not consolidated and thus easily erodable (Sacchi et al., 2009).
(ii) Up to the 3rd c. AD, the steep slopes of the hills of Naples were made more fragile by arboriculture (walnut, chestnut, vines) and horticulture (mainly cabbage) (Russo Ermolli et al., 2014). Thus, Roman land use could also have produced a high supply of sediment, which the local hydrological network (Fig. 1B) would have transported towards the harbor basin.
(iii) A climate component further could have had considerable effect on the siltation of the harbor basin owing to a deterioration of climatic conditions starting in the 1st c. AD. This is manifested by an increase in the frequency of floods that resulted in accumulated sedimentary inputs to the basins of the ancient harbors of Ostia (Goiran et al., 2014), Trajan (Delile et al., 2014) and Pisa (Benvenuti et al., 2006; Lippi et al., 2007).

The simultaneous occurrence of these three factors starting at the end of the 1st c. AD liberated substantial volumes of sediment into the hydrological network of the catchment area of the harbor (Fig. 1B), which were reinforced by the vulnerability to erosive agents of such a small basin (3 km^2) (Delile et al., 2016a). The discharge of sediments inevitably led to progradation of the coastline and, with that, siltation of the harbor reached its highest level (see the positive values of F2 in Fig. 4B) at the beginning of the 3rd c. AD when dredging operations were carried out in an attempt to solve the problem. According to dating provided by archaeological material, a chronological gap is observed between 330 and 350 cm below lmsl (Figs. 2 and 4 B). Rather than referring to a drastic decrease in the rate of sedimentation by an order of magnitude (from ~1 cm/year to 0.1 cm/year), when the sedimentological and geochemical indicators show the opposite, we attribute this chronological gap to numerous dredging operations carried out at the beginning of the 5th c. AD to maintain water in the harbor. For the first time, therefore, we here show that a second series of dredging operations must have taken place in the harbor basin of Naples after those already known of the 4th c. and 2nd c. BC which are visible down to the substratum (Giampaola et al., 2006; Carsana et al., 2009).

4.3.3. From the harbor basin infilling to the establishment of a lagoon during the 5th c. AD

Despite the preventive actions taken against infilling of the harbor basin, the latter was no longer functional starting in the 5th c. AD, when progradation of the coast had led to the formation of a sand bar at the entrance to the harbor, thus transforming the harbor basin into a lagoon (320–200 cm below lmsl in Figs. 2, 4–7) (Giampaola et al., 2006; Amato et al., 2009; Carsana et al., 2009; Giampaola, 2009; Russo Ermolli et al., 2014). These lagoonal deposits, which occurred frequently in the upper part of the Mediterranean harbor stratigraphies, show an intrinsic geochemical specificity related to the anoxic conditions of the bottom water column. Indeed, as quoted by Elmaleh et al. (2012), but also shown at Rome (Delile et al., 2014) and Ephesus (Delile et al., 2015a), this kind of suboxic to anoxic environment can be easily identified because of their high concentrations in S, Mo and U. From these examples we can safely state that increased hypoxia conditions through time in the water column of ancient harbor basins are associated with their silting up. In less than a century, the lagoon filled in rapidly from the action of upstream detrital flows until it reached the coeval sea level of the end of Antiquity (Fig. 2), to become a terrestrial environment at the beginning of the 6th c. AD.

4.3.4. A harbor basin that disappeared beneath a flood-dominated fan delta in the 6th c. AD

The study of the West, South/North and East stratigraphic sections between −2 and 0 m below lmsl shows two principal types of continental aquatic environments: terrestrial and fluvial deposits (Figs. 5–7).

As mentioned above (section 4.1.), the terrestrial unit presents bedded sedimentary structures composed of sub-horizontal elementary sequences with inversely graded bedding. It contains runoff deposits appropriate to sheet flow on slopes, developing freely on a flat surface, with a visible dip of about 5°. It overlies lagoonal deposits starting at a basal surface of gully erosion. The origin of this sedimentary unit is probably a high-intensity regime, specific to the Mediterranean environment where flows are qualified as sporadic. Such characteristics are generally observed on alluvial cones or cones of dejections (Blair and McPherson, 1994; Bertran et al., 1998; Sacchi et al., 2009).

Unlike studies previously carried out on the archaeological excavation site of the ancient harbor of Naples, we have identified several generations of paleo-channels in the West, South and North sections (Figs. 5–7), which we attribute to the southwest and northwest branches of the hydrographic paleo-network of the sector under study (Fig. 1B) (Ruello, 2008; Russo Ermolli et al., 2014). The most noteworthy are situated in the west where fluvial metamorphosis operated between the first paleo-channel, which cut into the lagoon sediments (i.e. the first two riverbed infillings in Fig. 6), and the one observed in the terrestrial deposits (i.e. the 3rd riverbed infilling). The first paleo-channel is close to being a meander with relatively well-developed river beds and asymmetric banks, in which convexity is well distinguished from concavity. The sample taken for granulometric analysis in the convexity of the meander is the only sample resulting from transport and deposition by pure graded suspension (Fig. 3A). The subhorizontal bedded structure of this deposit, observable by the presence of river placers (Fig. S2), reflects transport and deposition by graded suspension in a water column with flow duration long enough to enable segregation of the granulometric fractions. This zone is close to a shore that was little influenced by aquatic turbulence. It could be a paleo-bank or, more precisely, a bank of convexity in the process of lateral accretion. This channel is probably the one responsible for the progressive infilling of the harbor basin.

The second generation of paleo-channels (3rd riverbed infilling, Fig. 6) shows a completely different morphology with two extremely contracted minor beds in which the symmetrical steep banks form gullies in the terrestrial deposits. These features associated with the coalescent character of the two paleo-channels could correspond to the formation of a braided fluvial pattern, although the hypothesis of river channel migration or formation cannot be excluded. In any case, the stratigraphic context of these two paleo-channels reflects a change of environment beginning in the 6th c. AD towards a completely unstable continental environment, in which powerful flows, such as sheet and flash floods, specific to flood-dominated fan deltas, dominated (Blair and McPherson, 1994; Sacchi et al., 2009). The latter ran in incised channels that concentrated the torrential flows.

Such surface formations are also observed in the Riviera di Chiaia west of the study zone in the Bay of Naples (Romano et al., 2013), and on the cliffs of the Amalfi coast southeast of the Sorrentine peninsula (Sacchi et al., 2009). In the first case, authors have attributed the formation of fan deltas to land mismanagement during Late Antiquity, which intensified soil erosion and increased sediment load towards the littoral. In the second case, onset of the climatic cooling phase known as the Early Medieval Cool Period (AD 500–800) is suspected (Sacchi et al., 2009; Violante et al., 2009; Benito et al., 2015; Sadori et al., in press). According to our data, it is difficult to attribute either a strictly human or strictly climatic origin to the alluvial cone. The presence of many centimeter-sized charcoal fragments in the deposits suggests a land-clearing phase intended to increase arable surfaces (Berger et al., 2002; Vannière and Laggoun-Defarge, 2002; Franc, 2005; Bertoncello, 2008; Delile et al., 2016a), which could have exacerbated soil erosion. The abrupt increase of phosphorus concentrations in the sediments starting at −2 m below lmsl (Fig. S3) also suggests agro-pastoral activities. Phosphorus in particular is considered to be a by-product of animal waste and is usually related to intense human activity (e.g. Eidt, 1984; Cavanagh et al., 1988; Lillios, 1992; Sánchez Vizcaíno and Cañabate, 1999; Sullivan and Kealhofer, 2004). However, we posit that despite the increased sediment availability related to possible land use during this period, runoff still must have been sufficient to ensure transport of the sediments in question towards the coast and this was made possible by the increase in flood frequency during the Early Medieval Cool Period.

At the end of the 6th c. AD, the environmental conditions evolved towards a marshy milieu (Figs. 5–7), which presents the same overall geochemical characteristics as the terrestrial deposits (Fig. 4), mainly implying good water body aeration (section 4.2.). However, the conditions of transport and deposition of particles were those that prevailed when the harbor basin was subjected to the first detrital inputs (Fig. 3A). This return to relative stability of the environment is also seen in a new fluvial metamorphosis, as the two riverbed infillings observed in the marshy deposits of the upper part of the West section (Fig. 7) present characteristics close to a meander style: banks with gentle slopes, presence of a bank deposit, river bed enlarged and stabilised, and vertical incision.

The return to more clement conditions led to the taking over by a system of small canals intended to drain the zone (Fig. 5) and thus turn the sector into agricultural land (Russo Ermolli et al., 2014). The high values of the P/Al ratio (Fig. S3) confirm the new agricultural usage of the soils in this sector of the ancient harbor.

5. Conclusions

The present three-dimensional study of the archaeological deposits of the ancient harbor of Naples shows that the combination of granulometric and geochemical analyses provides key information to reconstruct both processes of transport and deposition of sedimentary particles, and paleo-environmental dynamics of the water column. The main factors controlling the environmental conditions of the masses of harbor water are authigenic (oxic vs. anoxic), biogenic, detrital, siliciclastic and carbonated fluxes. The association of these environmental variables with conditions of flow suggests siltation and infilling of the harbor basin in five phases between the 1st c. and the 6th c. AD.

During the 1st c. AD, the harbor basin evolved in a calm and poorly oxygenated environment in which significant biological activity developed. This situation ended after the occurrence of a high-energy event associated with a relatively moderate tsunami that struck the Bay of Naples when the Somma-Vesuvius erupted in AD 79. Afterwards, the harbor basin was subject to increasing and durable detrital inputs caused by the simultaneous action of the supply of sediment growing from the pyroclastic ejections of Vesuvius and intensive land use, as well as by the evacuation of this sedimentary charge towards the coast facilitated by an increase in the frequency of floods from the 1st c. AD onwards. Accelerated siltation of the harbor basin resulted, which caused the Romans to carry out dredging operations between the 3rd and the 5th c. AD. Despite these preventive actions, the harbor was no longer functional in the 5th c. AD, once coastal progradation had transformed the harbor basin into a lagoon.

From the beginning of the 6th c. AD, a completely unstable continental environment came into being, with sheet and flash floods that formed a flood-dominated fan delta under the combined influence of the climatic cooling of the Early Medieval Cool Period and the agro-pastoral activities in the catchment area of the harbor.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2016.08.026.

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