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Abstract

Once trapped in ancient harbor basins, sediments form environmental archives that have been widely studied by geoarcheologists in recent decades, especially to help reconstruct fluvio-marine landscapes of the last millennia. In some cases, classic environmental markers cannot be used for this purpose either because of their scarcity in the sedimentary deposits, or because analytical costs limit the resolution that can be achieved. In order to remedy these shortcomings, and to complement the more commonly used proxies, elemental and isotopic geochemistry has been added to the geoarcheological toolkit. Here we show how to "read" the evolution of the paleo-environmental dynamics in the water column of Ostia Antica (Rome's first maritime harbor) using the geochemical and isotopic record of a 3000-year-old sediment core drilled in the ancient harbor basin. A comparison of the results obtained from Ostia Antica with those of other ancient Mediterranean harbors reveals the nature of the main environmental processes operating during the formation of sedimentary deposits in harbor basins. From this comparative approach, it appears that the respective weight of each control factor is dependent on the coastal geomorphological context of the sites where the harbors were established. Since the discovery of the harbor of Ostia Antica in 2014, this method has provided the means, for the first time, to identify two distinct harbor basin regimes; an initial marine-dominated regime from the middle of the 4^{th} c. BC to ~ the 3^{rd} c. BC, and a later freshwater-dominated regime up to the 2^{nd} c. BC. More generally, we observe the effects of the dynamics of the deltaic progradation of the Tiber, which very early on was subject to a hydro-climatic component, on the processes of alluviation of the harbor basin. Additionally, and also for the first time in harbor geoarcheology, Pb isotope compositions measured specifically on uncontaminated sediments demonstrate their utility for both identifying the geological sources of the sediments of the Tiber delta and discriminating finer from larger particles. The present study further provides an opportunity to test the validity of two hypotheses recently put forward: (1) that a series of three tsunamis is recorded in the harbor silts, and (2) that an initial lagoon-type harbor was constructed at Ostia Antica, which later evolved into a fluvial harbor. Neither of these hypotheses are supported by the present data.

Keywords: Rome, Ostia Antica, ancient harbor basins, geoarcheology, sedimentology, geochemistry, Pb isotopes, Tiber river

1. Introduction

When harbor geoarcheology emerged as a discipline at the beginning of the 1990s following the 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), the analytical and investigative methods used were based on those well known from other domains within the earth sciences, such as micropaleontology (molluscs, ostracods, foraminifera, diatoms, pollen) and sedimentology (texture, granulometry, exoscopy) (Goiran and Morhange, 2003; Marriner and Morhange, 2007; Bravard, 2009; Cubizolle, 2009). Two decades later, while these well-tested methods continue to be used in the field, elemental and isotopic geochemistry has been added successfully to the geoarcheology toolkit, as we show below.

Although geochemistry began to be used in harbor geoarcheology in the mid-2000s to determine human impact based on findings of ancient metal traces (Le Roux et al., 2003, 2005; Véron et al., 2006, 2013, 2018; Marriner and Morhange, 2007; Stanley et al., 2007; Delile et al., 2014b, 2015, 2016b, 2017), it had not so far been used in paleo-environmental studies. It is only very recently that research teams, primarily from Germany, have used elemental geochemistry to improve on paleo-environmental reconstructions in archeological contexts. Important examples of such work carried out on ancient harbors are the studies of Oiniadai (Vött, 2007), Olympia (Vött et al., 2011), Palairos-Pogonia (Vött et al., 2011), Corinth (Hadler et al., 2013a), Kyllini (Hadler al., 2015b), and Alkinoos (Finkler et al., 2018) in Greece; Ephesus (Stock et al., 2013, 2014, 2016; Delile, 2014; Delile et al., 2015) and Elaia (Shumilovskikh et al., 2016) in Turkey; *Portus* and Naples in Italy (Delile et al., 2014a, 2016a); and Magdala (Rossi et al., 2015) in Israel. This recent expansion of geochemistry into geoarcheological research is a direct result of the widespread use of micro-XRF core scanners during the last decade. This technology can rapidly, non-destructively, and automatically scan sediment cores to produce elemental profiles at high resolution, which contribute greatly to the reconstruction of paleo-environments (Croudace and Rothwell, 2015). However, to take full advantage of this technique, it is indispensable to have prior knowledge of the geochemical properties of the sediments in question in order to avoid misinterpretations. One such common mistake consists in using certain elemental ratios capable of tracing the sedimentological (e.g. Zr/Rb and Zr/Ti applied as particle size proxies) or environmental (e.g.

Sr/Al, Mg/Ca or Ca/Al, and Si applied as biological production proxies or Mn/Fe, U, and Mo applied as water ventilation proxies) parameters without taking into account the geological, hydrological, and climate contexts of the sites under study, each of which can significantly modify the meaning of these ratios. Initially, the use of geochemistry for reconstructing environmental processes was applied to (i) marine sediments to decipher paleo-productivity, deep water ventilation, and paleo-temperatures, and (ii) lacustrine sediments to track atmospheric pollution, human impact, paleo-climatic changes, aeolian input, paleo-floods, catchment weathering, and source rock compositions (Boyle, 2002; Croudace and Rothwell, 2015).

Here, we discuss the types of environmental and anthropogenic processes that are most likely to benefit from the use of high-resolution geochemistry applied to the geoarcheological study of ancient harbors. To that end, we identify the geochemical fingerprints of the main environmental and anthropogenic processes that took place in the ancient harbor basin of Ostia Antica and compare them with:

(i) the “classic” environmental archives documented so far by geochemistry (i.e., lacustrine and marine sediments);

(ii) the “traditional” proxies used in harbor geoarcheology (see above), especially those applied to Ostia Antica’s ancient harbor basin, which are well documented from a paleo-environmental perspective (Goiran et al., 2012, 2014, 2017; Hadler et al., 2015a; Sadori et al., 2016; Wunderlich et al., 2018);

(iii) those identified at *Portus* (Delile et al., 2014a for the Trajanic basin and this study for the Claudius basin), Ephesus (Delile et al., 2015), and Naples (Delile et al., 2016a).

Although micropaleontological (ostracods, foraminifera, pollen) and sedimentological (texture, granulometry) studies have been carried out on the harbor deposits of Ostia Antica, the dynamics and paleo-environmental changes in its water column remain poorly understood.

Improving this understanding is all the more important since Ostia Antica had a river harbor located a short distance from the mouth of the Tiber River, which was to subject it to both marine and river influences (Goiran et al., 2012, 2014, 2017; Salomon et al., 2016). As a result, in the present work, we focus in particular on the interaction between fluvial and marine impacts on the harbor water column.

2. Study area

2.1. Archeological and historical background

According to Roman historians, Ostia Antica was founded during the reign of Ancus Marcius in the 7th c. BC. However, the *castrum* (building, or plot of land, used as a fortified military camp) did not appear before the 4th or beginning of the 3rd c. BC (Coarelli, 1988; Martin, 1996; Zevi, 2002; Brandt, 2002). The absence of evidence for the earliest periods has led to hypotheses about the existence of a paleo-Ostia, the location of which remains unknown and would correspond to the city founded by Ancus Marcius (Coarelli 1988; Martin 1996; Zevi 2002; Brandt 2002). Ancient texts reveal that the harbor of Ostia Antica became a commercial and military port during the Punic wars (Livy, 45, 22) and played a vital role in providing Rome with food supplies (especially olive oil from Spain and grain from the North African provinces) during the 1st c. BC (Le Gall, 1953; Zevi, 2001b). Nevertheless, at this time, Puteoli (Pozzuoli) on the Bay of Naples remained the principal maritime port of Rome for trade (Balland, 1965). It was considered to be one of the busiest centers of trade in the Roman Empire, especially for metal ingots, for which a route from the Cartagena/Mazarron and Rio Tinto mines in Spain to Puteoli and Rome was heavily used (Domergue and Rico, 2014; Delile et al., 2016b). The large distance separating the ports of Puteoli and Ostia Antica, as well as a problematic massive siltation of Ostia's harbor basin caused by a succession of floods discharging sediments at the mouth of the Tiber (Strabo, 5, 3, 5), combined with the need to accommodate an increasing number of merchant and military ships arriving from the

Roman provinces, were the main factors that led to the foundation of the new *Portus* harbor complex 3 km north of Ostia Antica in the middle of the 1st c. AD (Keay et al., 2005; Goiran et al., 2014) (Fig.1A).

2.2. *Geography and geology*

The Tiber delta constitutes the outlet for the water and sediment discharges of a river 405 km long which drains a watershed surface area of 17,375 km^2, comprising young sediments from the Apennines and modern volcanic deposits in Latium. The annual deposition of sediment in the Tyrrhenian Sea, estimated at 7.2 million tons per year (Iadanza and Napolitani, 2006), has resulted in the construction of a wave-dominated delta 150 km^2 in extent. The Tiber delta can be divided into (i) the eastern inner deltaic plain, related to the paleo-lagoons of Maccarese in the north and Ostia in the south; (ii) the western outer deltaic plain, where the landscape is composed of accreting dunes to which must be added the submerged area; (iii) the deltaic front (mainly composed of sand and silt); and (iv) the prodelta (mainly composed of mud and clay) (Salomon, 2013; Salomon et al., 2017).

The geomorphological evolution of the Tiber delta during the Holocene period is well documented (Bellotti et al. 1994, 1995, 2007, 2011; Giraudi, 2004; Milli et al., 2013; Salomon, 2013; Salomon et al., 2018). During the periods of the Republic and the Empire, the position of the Tiber mouth likely was located close to the Boacciana Tower (Tomassetti 1897) (Fig.1B). Additional information about the coastline comes from the immediate surroundings of *Portus* (Arnoldus Huyzendveld, 2005; Giraudi, 2004; 2009; Salomon, 2013) and from south of the Tiber delta, on the Laurentine shore (Bicket et al., 2009). However, during the Imperial period, the rapid seaward progression of the coastline recorded by the Tiber delta, which could have been more active at the river mouth, is the cause of relatively poor paleo-geographical knowledge of the Tiber mouth and its dynamics during Roman times. This rapid evolution explains why discovering the exact location of the ancient port of Ostia

Antica has been so controversial until recently (Goiran et al., 2012). The harbor of Ostia Antica, which has been dated to the period of the Republic, was initially difficult to identify, and its infrastructure (i.e., docks for loading and unloading of goods) could have been located anywhere along the riverbanks in direct connection with the city and its storage facilities (warehouses). But since 2012, a large body of multidisciplinary research combining the work of archeologists, historians, geographers, sedimentologists, geomorphologists, micro-paleontologists, and palynologists has confirmed the location of the river mouth harbor basin of Ostia Antica in the northern part of the city, to the west of the "Palazzo Imperiale", founded between the 4th and 2nd c. BC (Goiran et al., 2012, 2014, 2017). The stratigraphy of the cores (Goiran et al., 2014) clearly shows the deposit of harbor silts (dated at their base to the middle of the 4th century BC) at a depth of between 5.7 and 9 m below ground level (m *b.g.l.*) (unit B1, Fig. 2) (i.e., between 3.3 and 6.6 m below present sea level (m *b.p.s.l.*) or between 2.5 and 5.8 m below ancient sea level (m *b.a.s.l.*). The sea level between AD 230-450 was defined locally at 0.8 m ± 10 cm below the current biological sea-level by Goiran et al. (2009)). These harbor silts indicate a calm environment with low-energy currents in which the fluvial influence is reflected in the ostracod assemblages (Fig. 2).

As shown by Salomon et al. (2016), the stratigraphy of the PO2 core can be considered representative of Ostia's harbor area as a whole because of (i) its central location in the harbor basin area; (ii) the limited size of this port basin (~ 0.5 ha) in comparison with that of other ancient harbors (for example the Trajanic basin is ~ 39 ha and that of Ephesus in Turkey ~ 20 ha); (iii) the consistency of its stratigraphic successions deduced from their spatial correlation with other cores drilled in the harbor (Goiran et al., 2014; Hadler et al., 2015); (iv) the spatial extension of these stratigraphic successions to the entire harbor basin area as inferred from geophysical investigations (Hadler et al., 2015a; Wunderlich et al., 2018); (v) its large number of radiocarbon dates; and (vi) the extraction of the PO2 core by using a rotary mechanical corer that provides cores of a quality superior to those extracted by percussion corers.

3. Materials and methods

We analyzed at high resolution one (PO2, Fig. 1B) of the two cores drilled by Goiran et al. (2014) which led to the discovery of the first harbor of Rome at Ostia Antica. This 12 meter long core was drilled in a low-lying area without any archeological structural remains near the present-day Tiber River (Fig. 1B).

3.1. Radiocarbon dates and the age-depth model

The chronostratigraphic framework of the PO2 core is based on 15 radiocarbon dates (Goiran et al., 2014, 2017; Sadori et al., 2016; Delile et al., 2017) for which the age-depth model was created using the Clam software (Blaauw, 2010) (Fig. 2). The details of the age-depth model and the ^{14}C dates, as well as the inherent uncertainties associated with both, can be found in Delile et al. (2017), who exercised great caution in the use of these ages by applying them only to broad historical periods (Republic, High and Late Roman Empire, etc.).

The singular S-shape of the ^{14}C age-depth model of the PO2 core (Fig. 2) is typical of ancient harbor deposits and due to the dredging practices used at the time. This well-known phenomenon in Mediterranean harbors, well documented at Ostia by Goiran et al. (2014, 2017) and Salomon et al. (2016), is discussed in section 4.4.1.

3.2. Analysis of major and trace elements

The geochemical analyses were carried out on the entire core with high sample resolution (86 samples analyzed, i.e., one sample approximately every 14 cm). The data are published in Delile et al. (2017) together with the analytical techniques, which are also briefly summarized here. First, the sediments were sieved at 63 µm with a nylon sieve instead of a metal sieve in order to avoid potential contamination. After drying, 100 mg of sieved sediment from each core sample was dissolved at the Ecole Normale Supérieure de Lyon in a clean laboratory under laminar flow hoods. The samples were digested in a 3:1:0.5 mixture of concentrated double-distilled HF, HNO_3, and $HClO_4$ in Savillex beakers left closed on a hotplate at 120-130 °C for 48 h, then evaporated to dryness. Perchlorates and any remaining fluorides were converted to chlorides by drying down several times with 6 M distilled HCl. The samples in solution in 6 M distilled HCl were all clear, indicating complete sample breakdown. The samples were re-dissolved 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 the blank contribution was negligible for major elements and <2% of the sample content for trace elements. The precision on major and trace elements is between 2 and 5%.

3.3. Analysis of Pb isotopes

The method used is described in detail in Delile (2014) and Delile et al. (2014b, 2015, 2016b, 2017) and the main steps summarized in the following. After sieving at 63 µm as described above, representative aliquots of 500 mg of sediment were leached with Suprapur chloroform to separate the labile (or anthropogenic) component of the Pb. A second mild leaching step was performed with dilute double-distilled HBr to further recover the most easily displaceable (presumably anthropogenic) Pb, not all of which could be assumed to have been retrieved by chloroform. The leftover sample residues, constituting the natural "geological" Pb, were discarded. The two leachate fractions were combined and their Pb separated on anion-exchange columns using HBr to elute the sample matrix and distilled 6 M HCl to elute the Pb. The sample residues were not measured in this study because the isotopic composition of the natural Pb background had already been determined in a previous study (Delile, 2014; Delile et al., 2014b). The Pb isotope compositions were measured by MC-ICP-MS (Nu Plasma 500

HR) at the Ecole Normale Supérieure de Lyon using Tl doping and sample-standard bracketing (Albarède et al., 2004) and the values for NIST 981 of Eisele et al. (2003). The total procedural Pb blank was < 20 pg, far inferior to the multiple μg of Pb leached and separated from each sample. The external reproducibility of the reported Pb isotope ratios as estimated from the repeated (every two samples) runs of NIST 981 are 100-200 ppm (or 0.01-0.02%) for ratios based on 204 ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$) and 50 ppm (or 0.005%) for $^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$, and $^{207}Pb/^{208}Pb$. The Pb isotope data published in Delile et al. (2017) were used exclusively to focus on Pb anthropogenic excesses, while here we use the same data set to understand the natural, as opposed to the anthropogenic, Pb isotopic signal.

4. Results and discussion

4.1. Defining the main geochemical fluxes of harbor basin deposits

As mentioned in the introduction, the main objective of this work is to apply multi-elemental analysis to the silico-clastic deposits of the ancient harbor basin of Ostia Antica in order to identify the main inputs and processes involved in their formation. Because the composition and relative weight of different geochemical fluxes reflects the environmental conditions at the time of deposition, we can associate them with environmental variables whose evolution over time enables reconstruction of the paleo-environmental changes that occurred at the scale of the harbor site. For these purposes, the identification of the geochemical fluxes and their associated elementary compositions is a critical aspect requiring great caution.

4.1.1. The three main geochemical inputs and their arbitrarily associated elements

According to Sageman and Lyons (2003), three main inputs are involved in the formation of sedimentary deposits: (i) detrital, (ii) authigenic, and (iii) biogenic materials (Fig. 3).

(i) *Detrital material* (Fig. 3A) is derived from erosion of continental crust and volcanic rocks. These erosion products are carried by the hydrological network from their sources at the watershed to the marine environment. The principal elemental components of the particle flux transported by modern fluviatile sources are, in order of decreasing abundance, Si, Al, Fe, Ca, K, Mg, Na, Ti, P, Mn, and Ba, according to Martin and Whitfield, 1983. However, inter-comparison of these elements within the PO2 core shows stratigraphic distributions (see panel showing detrital elements in Fig. 3A) that differ from those predicted. This qualitative observation is reproduced quantitatively using the correlogram (Fig. S1) which displays relatively weak levels of correlation between, for example, Al and K (r = 0.31), Mg and Fe (r = 0.06), and Ti and Ba (r = 0.2), even though positive correlations between some elements qualified as detrital, such as Al, Mg, Zr, and Ti, are also observed. These first-order observations demonstrate that it is incautious to use *sensu stricto* certain elements considered to be universal markers of detrital origin. These differences between observation and theory in the chemical composition of the detrital fraction are accounted for by the relative weight of the local specificities that directly affect the factors controlling the composition in question: the mineralogy of the enclosing rocks, the erosional regime which itself depends on regional climate conditions (temperature, precipitation, and runoff), and the reactivity of eroded material during transport (Sageman and Lyon, 2003).

(ii) *Authigenic material* (Fig. 3B) is controlled by the redox state of the system, which depends on the ventilation conditions of bottom waters which in turn determines organic and inorganic reactions by which dissolved constituents are precipitated as minerals, either as metal oxyhydroxides (O_2 enrichment) or metal sulfides (O_2 depletion). The control factors of authigenic material in sediments depend mainly on the water-column mixing rate and the production of organic matter. The redox state usually is tracked by certain elements such as Fe, S, V, Mo, and U (Sageman and Lyon, 2003), which are assumed to be enriched under reducing conditions and depleted under oxidizing conditions. All of them correlate negatively with Mn because Mn is enriched under oxidizing conditions and depleted under reducing conditions. However, as seen in Fig. 3, the behavior of these elements as a function of stratigraphy does not show such a distribution. This qualitative observation is consistent with the quantitative observation as the correlogram in Fig. S1 shows relatively weak correlations between, for example, Mo and U (r = 0.07), V and Mo (r = 0.2), and U and S (r = 0.2), even if positive correlations are also observed, especially between Mo and Fe (r=0.55), Fe and U (r=0.51), Fe and V (r=0.75), and Fe and S (r=0.8) (Fig. S1). None of these elements, therefore, can be used as universal markers of authigenic inputs.

(iii) *Biogenic material* (Fig. 3C) reflects the photosynthetic production of organic material and the presence of remains of skeletal material, the latter being composed of calcite ($CaCO_3$) or silica (SiO_2). Biogenic fluxes in the sedimentary system depend on the concentration and supply of nutriments from surface waters (nitrate, phosphate, and micro-nutriments such as Fe). They are produced by chemical erosion and terrestrial biogenic activity or biological processes in the water column. Usually, the biogenic flux is tracked by Si, Ca, Sr, P, or Loss on Ignition (L.O.I.) (Sagement and Lyons, 2003; Sánchez Vizcaíno and Cañabate, 1999; Delile et al., 2016a). However, as observed for the detrital and authigenic fluxes, neither the qualitative nor the quantitative observations (Figs. 3C and S1) show clear systematic positive or negative correlations between, for example, Ca and Sr (r = 0.04), Ca and P (r = -0.3), and Sr and P (r = 0.3).

This attempt at classification, or grouping, of chemical elements taken individually according to the three principal inputs involved in the formation of sedimentary deposits (Fig. 3) has revealed the limits of the approach. First, assigning a given element to a specific category of inputs is not supported by robust statistic correlations, hence calling for caution in automatically using geochemical proxies traditionally considered to be robust tracers for particular inputs. Second, the individual observation of several dozen chemical elements is fastidious work without any real added value. For these reasons, the reading of the underlying causes of geochemical variation and their number is difficult.

4.1.2. A new way to define the main geochemical fluxes of harbor basin deposits

In order to examine in-depth the thousands of data acquired by multi-element analysis (39 chemical elements measured) at high resolution (86 samples analyzed in the present study), we use factor analysis in order to convert data into uncorrelated and limited variables, also known as factors. The factors resulting from the statistical treatment of the full data set (39 elements for 86 samples) carry a large part (>75%) of the total geochemical variability of the depositional system. These factors in turn correspond to variables that are equivalent to the principal components deduced from the PCA statistical procedure (see Appendix A in Delile et al., 2014a). Based on the loading values of each factor (Fig. 4A), the distribution of the chemical elements, which results from positive (element clusters located in the same position relative to the y-axis) and/or negative (element clusters located in the opposite position relative to the y-axis) correlations, enables us to determine the environmental variable expressed behind each factor.

Based on this method, we discriminate four main factors controlling the bulk of the geochemical composition of the PO2 core (Fig. 4):

(i) *The first factor* (47% of the total variability of the geochemical signal, Fig. 4) comprises elements associated exclusively with a siliciclastic detrital flux (Th, Zr, U, K, REEs, etc.) and is marked with negative F1 values. All these elements are known to be enriched in the Roman Alkaline Province in Italy, including the downstream volcanic rocks of the Tiber River watershed, where they show the highest abundances in floodplain sediments (De Vos and Tarvainen, 2006). This volcanic province is also known under the name of the

Roman Magmatic Province – Latian District (RMP-LD) (Mattei et al., 2010) which regroups the Colli Albani, Vulsini, Cimini, Vicano, Ceriti, and Sabatini volcanoes, all very close to the Tiber delta. The RMP-LD region, which is one of four major volcanic provinces of the Tyrrhenian margins of peninsular Italy, consists of mafic ultrapotassic rocks with a remarkably homogeneous elemental composition characterized by high abundances of Pb, Th, U, Ce, and La and low abundances of Ti, P, Ta, and Nb (Mattei et al., 2010). These geochemical features distinguish all the volcanoes close to the Tiber delta. This is shown in Fig. 4A where elements with affinities for the RMP-LD mafic ultrapotassic rocks show strongly negative values (ranging between -0.7 and -1), whereas elements depleted in the same rocks display significantly lower negative values (ranging between -0.5 and 0).

The main characteristic of Factor 1 is that it tracks the sedimentary units with the coarser particles, since the lowest F1 values occur in the sandy units A and B2 (Figs 2, 4B). The correlogram for elementary and granulometry data (Fig. S2) from harbor units only (units B1 and B2) shows that the sandy fraction is clustered within these elements (Th, Zr, U, K, REEs, etc.). We conclude from this that Factor 1 reflects siliciclastic terrigenous influence which, in terms of depositional environment, corresponds to the ancient hydrodynamic conditions of the harbor water column.

(ii) *The second factor* (13% of the total variability of the geochemical signal, Fig. 4) opposes elements indicative of detrital fluxes (other than the siliciclastic detrital flux of F1) (Ga, Al, Rb, Li, Ti, Mg, etc.) to elements indicative of a carbonate component (Ca). The detrital component (positive F2 values) clearly reflects another type of terrigenous influence, that related to aluminosilicates. Al, Ga, Rb, Li, Mg, and Ti are strongly correlated among themselves (Fig. S1) because they are all constituents of clay minerals (De Vos and Tarvainen, 2006). Figure S2 confirms the predominance (weight) of fine particles in Factor 2 because the hierarchical clustering shows good correlations between clays and silts containing these elements. Factor 2 reflects the terrigenous influence of aluminosilicates which, interpreted in terms of an environmental variable, corresponds to the ancient quiet hydrodynamic conditions of the harbor water column.

(iii) *The third factor* (10% of the total variability of the geochemical signal, Fig. 4) presents with negative F3 values elements associated with authigenic fluxes (redox conditions), especially those tracking oxygen depletion in the water column (S, Fe, Mo, V). Factor 3 also includes chalcophile elements that precipitate as sulfides under anoxic conditions (Pb, Cu, Co, Sb). This factor also has been recorded in the ancient harbor deposits of Ephesus (Delile et al., 2015).

(iv) *The fourth factor* (7% of the total variability of the geochemical signal, Fig. 4) opposes Na to heavy metals such as Sn, Cd, and Pb. The strong influence of Na within the stratigraphy reflects either the salinity of the harbor itself or the invasion of the sediments by the salt wedge. For the Trajanic harbor as well as for that of Ostia Antica, the association of the ostracodal marine group with high sediment Na content unambiguously reveals a marine-dominated environment (Delile et al., 2014b; Goiran et al., 2014; Sadori et al., 2016) for the basal part of core PO2 (Figs. 2, 4B). This marine influence is opposed mainly to the inputs of heavy metals derived from human activities (Sn, Cd and Pb). Since marine influence is not associated with any trace metal pollutants, we conclude that anthropogenic pollutants were carried by the freshwater of the Tiber River (Delile et al., 2017). This is supported by the ostracodal freshwater group, which increases greatly in the upper part of unit B1 (Fig. 2). Owing to Factor 4, we can show for the first time that the functional harbor unit B1 recorded two distinct regimes (gray dotted line in Fig. 4B): a harbor basin under marine influence at a depth of about 9 to 7 m *b.g.l.* (i.e., 4.6-6.6 m *b.p.s.l.* or 3.8-5.8 m *b.a.s.l.*) followed by an increasingly fluvial-dominated regime at a depth of about 7 to 6 m *b.g.l.* (i.e., 3.6-4.6. m *b.p.s.l.* or m 2.8-3.8 m *b.a.s.l.*).

4.2. Synthesis of the main environmental factors leading to the formation of ancient harbor basin deposits in the Mediterranean

The methodological tool associating elemental geochemistry with factor analysis in order to improve the reconstruction of paleo-environments has been applied to four other roman harbor basins in the Mediterranean besides that of Ostia Antica used as an example above: that of Ephesus in Turkey (Delile et al., 2015), that of Naples in Italy (Delile et al., 2016a) and those of Trajan (Delile et al., 2014a) and Claudius (this study) at *Portus*. Table 1 presents the first synthesis of this method in describing the different environmental variables (that is, the factors identified by factor analysis) that affected the paleo-environmental dynamics of the water columns of these ancient harbor basins, as well as their respective weights expressed in percentages. F1 corresponds to the most important control factor, often representing around 50% of the variance, while F4 constitutes the least significant environmental variable with values of less than 10% (Table 1).

According to Table 1, the first environmental component (42%) that affects the paleo-environmental dynamics of harbor water columns corresponds to detrital fluxes, that is, sedimentary discharge from an outlet. This is not surprising as all these harbor sites, except that of Naples, are located on deltas that are sub-aqueous and sub-aerial coastal accumulations of river-derived sediments. The process of construction of these complex coastal landforms is based on the terrigenous detritus of fluvial origin, the effectiveness of which increases at river mouths, where the ancient harbor basins are located. This principal environmental characteristic of harbor environments is also present in the typology of ancient harbors produced by Giaime et al. (2016). According to the statistical applications (Principal Component Analysis and Hierarchical Ascendant Classification) on which their typology rests, the major natural process that distinguishes between specific types of harbors is the rate of sediment supply. This process moreover is responsible for the major constraint on navigation as it reduces the draught for ships in the harbor basins because of siltation and alluviation (Goiran and Morhange, 2003; Marriner and Morhange, 2007; Salomon et al., 2016; Goiran et al., 2017). The predominance of detrital fluxes in the paleo-environmental evolution of the water column in harbor basins is subject to the coastal geomorphology of the sites where these harbors were established, as only those located at deltas are dominated by this environmental parameter. Indeed, the paleo-environmental changes of the water column of the ancient harbor of Naples, located in a small coastal bay, were affected more by aeration (Factor 1 = redox conditions = 36%) than by terrigenous contributions (Factor 2 = 16%) (see Table 1 and/or Delile et al., 2016a). In general, these detrital fluxes are composed of siliciclastic and aluminosilicate minerals which cause enrichment in Al, Zr, Ti, Th, Mg, Ba, K, Co, Zn, and REEs in the sediments. This category of flux generally reflects the ambient hydrodynamics of harbor basins in which the recrudescence of currents is produced either by the activity of canals connecting the harbor basins to the river (in freshwater-dominated harbor environments), or by the acceleration of deltaic progradation (on floodplains, coastal alluvial fans, paleo-channels, delta-fronts, and prodeltas) (Table 1).

Generally, these allochthonous particle fluxes are anti-correlated with the second source of sedimentary particles in harbor deposits, the biogenic fluxes (34%, Table 1). This negative correlation is due to the nature of these fluxes which are considered autochthonous as they are produced *in situ*. This is why this environmental variable is so predominant in the water columns of the harbor basins of Trajan and Ephesus (Table 1). The grouping of elements representative of biogenic fluxes (L.O.I., Ca, and Sr) is usually found on the axis of Factor 1, in a position opposite to that of the constituent elements of detrital fluxes. They are most often evidence for relatively calm hydrodynamic conditions as these favor the production of biomass, whether plant (organic matter) or carbonated (skeletal remains). While the production of biomass depends on paleo-geographic changes that in turn encourage environments with weaker water currents (swamp, marine, enclosed harbor, peat, lagoon, epilimnic, brackish, or eutrophic), eutrophication and urban sewage inputs also participate effectively in the production of these biogenic fluxes.

In order of importance, authigenic fluxes (20%) are next; these correspond to the redox conditions of the environment. This environmental parameter expresses the conditions of the ventilation of the harbor water column, that is, its speed of renewal, which is rapid for well-oxygenated milieus (Mn, K, Ti, Zn, Cr, Co, Cd), and slow in environments deficient in oxygen (S, Mo, U, Pb, Ag, Cu). In the first case, deltaic progradation (on floodplains, freshwater-dominated harbors, coastal alluvial fans, paleo-channels, delta-fronts and prodeltas) and breaking of waves on the shore (on delta-fronts and beaches) are the principal processes of oxygenation identified. In the second case, the processes limiting the presence of dissolved oxygen in the harbor waters are peat formation arising from enclosing harbor basins, interflood periods, urban sewage inputs, and eutrophication (in enclosed harbors and peat bogs). The range of anoxic environments is relatively extensive, as we have identified marine, lagoon, marshy, peaty, and harbor environments. In terms of paleo-environmental reconstructions, this factor is particularly instructive for evaluating the degree to which the environments encountered are open; the more the milieu is open, the higher the proportion of dissolved oxygen, and vice versa.

The following factor, which can sometimes be intermixed with Factor 1, expresses the mineralogy and the lithology of the sediments (11%). This factor therefore characterizes rather well the granulometric distribution of the stratigraphic sequences studied, in which the fine sediments are dominated by alumino-silicates (Al, Ti, Mg, Rb, Ga, Li) and the coarsest by siliciclastic minerals (Zr, Th, REEs, Si). Besides this characteristic useful for reconstructing variations in the hydrodynamics of harbor currents, this environmental variable also provides unique information on the geological sources of sediments from a given watershed.

The fifth variable revealed by factor analysis represents the pollutants of anthropogenic origin (10%) (Table 1). This component is made up of heavy metals (Pb, Cu, Sn, Ag, Cd) which have been exploited by humans in various ways for millennia. However, it is necessary to be cautious in using this factor because the precipitation and thus the enrichment of these metallic trace elements depends on the intensity of human activity, but also on the physico-chemical conditions (Delile et al., 2015) and the turbulence of the aquatic milieus (Delile et al., 2017). In order to be free of these two environmental constraints that can bias the reading of human influence over time, we normalize the trace elements of interest to an element representative of the terrestrial crust (Al, Th, REEs, etc.) and calculate the enrichment factor on the basis of representative crustal values specific to the local context in question. These are easily obtainable from the pre-harbor levels of the studied sites.

The last factor of environmental control, which completes the total geochemical variability in a given harbor deposit sequence, is the marine influence (10%) in the sediments based on their enrichment in Na (Table 1). This factor is particularly useful when the absence of microfauna renders reconstructions of paleo-environments difficult. Generally in the case of a harbor milieu open to the sea, the increase in the proportion of seawater compared to freshwater leads to the formation of a harbor milieu under marine influence (i.e., a marine-dominated harbor). A large range of harbor facies depends on the degree of opening of the harbor basin to the sea and its distance from the river mouth (if present). In contrast, an increase in the values of this factor generally characterises pre-harbor levels of the delta front type.

Once these environmental variables have been identified, combining their respective information enables determination of paleo-environments and the processes that produced them.

4.3. The sources of the Tiber river-mouth sediments inferred from Pb isotopes

Within the scope of previous studies focusing on lead pollution generated by Rome and trapped in (recorded by) its harbor basins during the Roman and medieval periods (Delile et al., 2014b, 2017), Pb isotope compositions were measured on four harbor sediment cores. In the following, we proceed with an in-depth study of the natural Pb isotopic signal to understand its meaning. Of the total of 177 samples analysed, 75 were considered uncontaminated (Figs. 5 et 6). The Pb isotopic compositions of these samples reflect the natural background of Pb in the waters of the Tiber whose characteristics are related to the geology of the Tiber River watershed.

In order to optimize the reading of the geological signal from the Pb isotopes, we converted the Pb isotope compositions into their corresponding geochemically informed parameters, which are the Pb model age T_{mod}, the $^{238}U/^{204}Pb$ (μ) and the $^{232}Th/^{238}U$ (κ) ratios (Fig. 5B) (Albarède et al., 2012). In short, T_{mod} (Ma = million years) is a proxy tracking the tectonic age of crystalline rocks and their associated ore deposits, and thus closely maps the distribution of the Alpine, Hercynian, and early Paleozoic provinces of Europe. Mu (μ) and kappa (κ) delineate collision belts or tectonically stable areas, and thus divide Europe into coherent regions (Blichert-Toft et al., 2016).

In Fig. 5, uncontaminated harbor sediments from Ostia Antica (core PO2) and Portus (cores TR14, CN1, and PTXI-3) include one main source of natural Pb labeled "component α" (Delile et al., 2014b, 2017). This natural component α consists of two sub-components α' and α" connected by a mixing line (grey dotted line in Fig. 5). As recently demonstrated by Delile et al. (2014b, 2017), these uncontaminated sediments represent a mixture of two local low-^{204}Pb/^{206}Pb sources, reflecting the geology of the Tiber River watershed. One source is the upstream, erodible recent Apennine limestones (component α”), which are very similar to Pb dissolved in modern Mediterranean seawater (Stumpf et al., 2010), and the other is the recent volcanic rocks of the Alban Hills (component α’) (Conticelli et al., 2002; D’Antonio et al., 1996). As mentioned in section 4.1.2., the elemental composition of the volcanic rocks of the Alban Hills is similar to that of the RMP-LD. This geochemical homogeneity of the volcanic districts located in the vicinity of the Tiber Delta (Colli Albani, Vulsini, Cimini, Vicano, Ceriti, and Sabatini) is also observed for their Pb isotopic compositions (Conticelli et al., 2007; Mattei et al., 2010). In other words, the Pb isotopic fingerprint of the Alban Hills (component α’) reflects that of the RMP-LD as a whole. Furthermore, in the trend α’−α” uncontaminated sediments split distinctly into two groups according to their kappa values (Fig. 5A) or ^{208}Pb/^{206}Pb ratio (Fig. 5B). The sandy pre-harbor sediments show high values, while the harbor sediments dominated by clays and silts are characterized by lower values. It thus appears that a particle size gradient can be inferred from the Pb isotopic compositions of the sediments.

To test this linear relationship, we calculated two indices labeled *f*α’ and *f*α” that measure the proportion of the natural sub-components α’ and α” in all uncontaminated sediment samples (equation details in the Materials and Methods section of Delile et al., 2017). In Fig. 6, where these index values are plotted against the sand, silt, and clay percentages of the same samples, it is clear that the particle size distribution of the Tiber delta sediments largely correlates with the proportions of the two main natural sedimentary sources of the Tiber’s watershed. On the one hand, sandy particles correlate positively with the volcanic component (*f*α’) ($r = 0.69$) and, on the other hand, fine particles correlate well with the Apennine limestones (*f*α”) ($r = 0.68$) (Fig. 6). Such a distinction is not unexpected, as the changes in mineral sorting processes that result from varying levels of hydrodynamic activity modify the mineralogy and thus the geochemistry of the transported sediments. According to Garçon et al. (2014), a “heavy mineral effect” alters the Pb isotopic budget of both coarse and fine fluvial sediments. Some heavy minerals concentrated in coarse sediments are extremely radiogenic, allowing sandy sediments to grow in more radiogenic $^{208}Pb/^{206}Pb$ values (Garçon et al., 2014) and, thereby, acquire elevated values of κ (r between $^{208}Pb/^{206}Pb$ vs $\kappa \sim 0.7$). The sandy deposits of the Tiber delta's littoral facies are strongly enriched in heavy minerals (Belfiore et al., 1987) that take the form of placers (Salomon, 2013) (Fig. S3) derived from the erosion of the Monti Sabatini or the Colli Albani (Funiciello, 1995; Ventriglia, 1971). The presence of such minerals requires a source close to the deposit area (Carling and Breakspear, 2006), located less than 20 km away according to Thomas and Thorp (1993).

A primarily volcanic origin for the sandy particles of the Tiber delta, which would have derived from erosion of the volcanic rocks in the Alban Hills, but also from the other volcanic districts that are part of the RMP-LD surrounding the Tiber delta (Vulsini, Cimini, Vicano, Ceriti, and Sabatini), is reinforced by a particularly significant correlation coefficient between F1 and $f\alpha$’ measured in core PO2 (r = -0.7).

4.4. Chronology of the life cycle of the harbor

According to the present sedimentological, geochemical, and Pb isotopic results, the paleo-environmental evolution of the water column of Rome’s first harbor took place in five stages (gray and white bands in Fig. 4B) as described further below. First, however the chronostratigraphic framework of the PO2 core will be discussed.

4.4.1. Comments on the chronostratigraphic model of the PO2 core

The S-shape of the ^{14}C age-depth model obtained for the PO2 core (Fig. 2) testifies to a well-known and well-documented phenomenon in harbor geoarcheology resulting from multiple dredging operations. These practices, observed in many ancient Mediterranean harbor basins, consist in removing part of the sedimentary thickness of the harbor deposits in order to preserve a sufficiently deep draught to guarantee the circulation of ships and thus maintain the operation of the port. This phenomenon is generally detected on the basis of (1) sharp drops in apparent sedimentation rates and (2) chronological inversions due to removal and mixing of part of the harbor deposits (Marriner and Morhange, 2006). At Ostia, such dredging markers have been identified several times and have been the subject of specific studies by Salomon et al. (2016) and Goiran et al. (2017). To sum up these studies, the chronostratigraphic model of the ancient port basin of Ostia contains four chronological gaps reflecting three potential dredging phases. These gaps are distributed as follows (red stars in Fig. 2):

Gap 1 is identified by a sharp drop in sedimentation rate between the last date from unit A at 1050 cm depth (835-736 BC) and the first date from unit B1 at ~ 870 cm depth (358-113 BC). This chronological gap either testifies to the excavation of the harbor basin of Ostia or to a later dredging phase that occurred around the middle of the 4th c. BC.

Gap 2 is identified by a chronological inversion recorded at 815 cm depth (728-265 BC) reflecting the mixing of part of the harbor deposits where older deposits are mixed in with younger deposits. Since this date lies within the chronological ranges of the sedimentary units A and B, this older date may refer to the same dredging event described above. Another explanation could be that this date, which is based on terrestrial material (charcoal), was part of reworked material coming from the Tiber.

Gap 3 is identified by a sharp drop in the sedimentation rate between the last date of unit B1 at ~ 585 cm depth (387-204 BC) and the first date from unit B2 at 526 cm depth (163 BC-AD 16). This chronological gap reflects a second potential dredging phase that took place at the earliest before the mid-2nd c. BC.

Gap 4 is identified by a last sharp drop in the sedimentation rate between the date at 378 cm depth (158 BC-AD 24) and that at ~ 550 cm depth (AD 80-231). This chronological gap reflects a third and last potential dredging phase that took place at the latest during the 1st c. AD.

4.4.2. The pre-harbor environment

The pre-harbor unit A is composed of bedded and shelly grey sands with *Posidonia*, attesting to a depositional environment of deltaic progradation. According to the age-depth model of the core (Fig. 2), this unit dates from the early 1st millennium (modeled dates are situated between the end of the 9th c. and the early 8th c. BC) to the middle of the 4th c. BC (Goiran et al., 2014, 2017; Delile et al., 2017). Figure 4 shows a relatively high-energy environment revealed by the negative values of Factor 1, faithfully reporting the rather coarse grain size of this unit (Fig. 2). The main geochemical aspects of this unit are the high salinity (high Na, F4 in Fig. 4B) and the oxygen depletion (negative values of the Factor 3 in Fig. 4B), consistent with the marine-to-brackish lagoonal ostracod groups observed by Goiran et al. (2014). Also reported in this work are freshwater inflows (Fig. 2) that explain the turbulent conditions attested to by the siliciclastic flux (Factor F1). While the main mineralogical and geochemical characteristics of these pre-harbor deposits are like those recorded at *Portus* (Delile et al., 2014a), the freshwater influence on the site of the ancient harbor basin of Ostia Antica strengthens the hypothesis of the presence of an estuarine river mouth, whose fluvial sand inputs were remobilized by the marine swell. Due to the continuity and regularity of the seawater influence during almost five centuries, as well as the dramatic oxygen depletion (F3 negative values in Fig. 4) and the freshwater influence, it is difficult to posit this pre-harbor deposit as a credible "tsunami event I" as has been postulated between 800 BC and 400 BC by Hadler et al. (2015a). In the somewhat more realistic and less catastrophic perspective taken here, the assemblage of observed and measured faunal, sedimentological, and geochemical indicators rather converge towards a pre-harbor deposit typical of a classic deltaic front sequence, which is well recorded both at the scale of the site itself and of the Tiber delta as a whole (Mazzini et al., 2011; Goiran et al., 2012; 2014; Salomon, 2013; Salomon et al., 2012, 2018; Delile et al., 2014a; Sadori et al., 2016)

4.4.3. The lower harbor sequence

From the middle of the 4th c. to the beginning of the 2nd c. BC, the environmental conditions change markedly towards a quiet milieu between -9 and -5.7 m *b.g.l.* (i.e., between 6.6 and 3.3 m *b.p.s.l.* or between 5.8 and 2.5 m *b.a.s.l.*) (Fig. 4), as suggested by the compact dark grey silt deposits (Goiran et al., 2012, 2014, 2017; Sadori et al., 2016). Classically, this unit B1 resulted from the creation of the harbor basin of Ostia Antica, a typical well-protected harbor, still connected to fluvial-marine environments. The significant reduction of the hydrodynamic conditions of the currents leading to the deposit of unit B1 is clearly indicated by Factor 1, which shows a drastic decrease in siliciclastic fluxes (Fig. 4B). Inversely, the same process led to an increase in the proportion of fine particles in the deposit as seen in the positive values of Factor 2 (aluminosilicate flux in Fig. 4B). The third geochemical characteristic of unit B1 is the distinction of two regimes in the paleo-environmental dynamics of the harbor water column. Based on the seawater influence (Factor 4 in Fig. 4B), unit B1 can be divided into two subunits:

- Subunit B1a (from -9 to -7 m *b.g.l.*; i.e., between 6.6 and 4.6 m *b.p.s.l.* or between 5.8 and 3.8 m *b.a.s.l.*) reflects a marine-dominated regime since the F4 values (seawater influence) always remain positive, although being lower than those of unit A due to the connection of the harbor basin to the Tiber river;
- Subunit B1b (from -7 to -5.7 m *b.g.l.*; i.e., between 4.6 and 3.3 m *b.p.s.l.* or between 3.8 and 2.5 m *b.a.s.l.*) reflects a freshwater-dominated regime since the F4 values (seawater

influence) are negative. This is corroborated by the ostracodal freshwater group in this subunit (Fig. 2).

According to the ^{14}C age-depth model of the PO2 core (Fig. 2A), the passage from subunit B1a to B1b took place around the middle of the 3rd c. BC. This change in the paleo-environmental dynamics of the harbor water column at this particular time is not surprising, and even rather consistent with the known progradation phases of the Tiber river delta. Giraudi et al. (2009), Bicket et al. (2009), Giraudi (2011), and Salomon et al. (2018) recorded intense Tiber delta progradation between the 4th c. BC and the 5th c. AD which began after a sudden paleo-geographic event. Indeed, a major step of the Tiber delta construction occurred between the 8th and the 3rd c. BC due to the sharp southward migration of the river mouth, in the direction of the harbor basin of Ostia (Bellotti et al., 2011; Milli et al., 2013; Salomon et al., 2018). Over this time period, the rate of the progradation of the river mouth is estimated to be around 5-6 m/year (Milli et al., 2013). According to Milli et al. (2013) a strong Tiber flood event that occurred during the climate cooling phase of the Iron Age (Bond cycle B2, Bond et al., 1997, 2001) probably led to the shift of the Tiber mouth location. In this new paleo-geographical context of the Tiber delta, the increasing fluvial inputs into the harbor basin of Ostia Antica between the 4th and the 2nd centuries BC (the chronological range of unit B1) caused the paleo-environmental dynamic change of the harbor water column towards a freshwater-dominated regime in about the early 3rd c. BC.

This gradual and continuous increase of the freshwater influence in the harbor muds is not consistent with the surge of a tsunami deposit in the “lagoonal harbour” which is referred to as “event II” by Hadler et al. (2015a). Such a “high-energy event layer” should present a sudden break and a sustainable return of seawater influence in this deposit, and not the reverse.

4.4.4. The upper harbor sequence

Between the 2nd c. BC and the 3rd c. AD, a new harbor sequence called unit B2 became established at a depth of between 5.7 and 3.2 m *b.g.l.* (i.e., between 3.3 and 0.8 m *b.p.s.l.* or between 2.5 and 0 m *b.a.s.l.*; Figs. 2 and 4). This unit presents sedimentological and geochemical characteristics that are different from the lower harbor sequence as the deposit of coarse sands (Fig. 2) led to a retreat of aluminosilicate minerals (negative values of Factor 2) in favor of siliciclastic particles (negative values of Factor 1). In unit B2, three major pulses of siliciclastic flux reflect periods of strong hydrodynamic currents in the harbor basin; they are evidence of high-energy floods of the Tiber (Goiran et al., 2014, 2017, Salomon et al., 2016). These phases were followed by periods of relatively calm currents in which anoxic conditions were established (negative values of Factor 3 in Fig. 4B). Finally, unit B2 reflects infilling of the harbor basin, which appears to have been subject to the hydrological rhythms of the Tiber. During periods of major inundations, the currents renewed the oxygenation of the water masses, while in periods of low water level, the less energetic currents led to the development of anaerobic conditions.

According to Hadler et al. (2015a) and Wunderlich et al. (2018) unit B2 would incorporate yet a third tsunami event dated to between AD 1 and 50. As speculated above for their second tsunami event, our geochemical analyses should show a sudden break illustrating a sustainable return of seawater influence in this deposit. However, exactly the opposite is recorded, since the influence of seawater is becoming increasingly absent in unit B2 (Fig. 4B). Moreover, the occurrence of a tsunami would have been observed at different places in the delta, such as the Ostia lagoon (Bellotti et al., 2011; Vittori et al., 2015) and the Maccarese lagoon (Bellotti et al., 1994, 2007; Giraudi, 2002, 2004, 2011; Di Rita et al., 2010; Jouannic et al., 2013), since the sediment-transport distances for tsunamis vary from several hundred meters to a few kilometres from the shore (a regional signature) (Minoura et al., 1997; Gelfenbaum and Jaffe, 2003; Morton et al., 2007). However, none of the studies carried out on the sedimentary deposits of the Tiber delta have mentioned any such event. This is not surprising as the three high-energy events of tsunamigenic origin were recorded in a single core (core OST 3), among eight cores taken by Hadler et al. (2015a). Thus the tsunamigenic fingerprint appears to be local rather than regional. However, as pointed out by Sadori et al. (2016), if such a catastrophic event had taken place during the 1st c. AD, no doubt it would have been recorded by Roman historians, who paid close attention to natural phenomena; this is, however, not the case. Rather than assuming a scenario including a third tsunami event as speculated by Hadler et al., (2015a), we present below in three steps using an integrated approach (i.e. combined hydro-climatic, historical, and sedimentological and geochemical data) an alternative scenario that takes into account the environmental context of this period.

(i) During the time period covered by unit B2 (2nd c. BC to 3rd c. AD), a major hydro-sedimentary event, which is characterized by an increase in the frequency of floods, occurred during the period of the 1st c. BC to the 2nd c. AD approximately at several places in the western Mediterranean region (Berger and Bravard, 2012). Based on the flood events of the Tiber River in Rome recorded by Bersani and Bencivenga (2001), corroborating the work of Le Gall (1953), such an increase in the flood frequency of the Tiber took place between approximately the 2nd c. BC and the 2nd c. AD.

(ii) During this major hydro-sedimentary crisis, several coastal sites experienced an acceleration of deltaic progradation on the Mediterranean coast due to the erosion and transport of substantial amounts of sedimentary loads. This was the case for the Rhône delta between the 1st c. BC and the end of the 2nd c. AD (Arnaud-Fasseta, 2000, 2002), the Argens delta in eastern Provence (Excoffon et al., 2010, 2016) and the Küçük Menderes delta in Turkey from the 2nd c. BC to the 1st c. AD at least (Delile et al., 2015). In the case of the Tiber delta, the work of Giraudi et al. (2009) distinctly shows an acceleration phase of progradation that occurred between the 3rd c. BC and the 3rd c. AD.

(iii) This rapid progression of the progradation of the deltas stimulated by a sporadic deterioration of hydro-climatic conditions brought on the accelerated siltation of numerous harbor basins in the Mediterranean such as that of the great Roman harbor of Narbonne in the 1st c. (Rescanières, 2002), and those of Frejus (Excoffon et al., 2010), Ephesus (Delile, 2014; Delile et al., 2015), Naples (Delile et al., 2016a), Pisa (Benvenuti et al., 2006; Mariotti Lippi et al., 2007), as well as that of Trajan at *Portus* (Delile et al., 2014a). For all these reasons, we consider that at this period the acceleration of the deltaic progradation of the Tiber, partly controlled by climate, but partly also by humans, moved the river mouth of the Tiber even further downriver, and thus even further from the harbor basin (Fig. 2), on the one hand, and mechanically caused an aggradation of the alluvial floor, on the other hand. This process thus favored the evacuation of the strongest floodwaters accompanied by their sands in the harbor basin of Ostia Antica. This scenario also emphasises the importance of consulting contemporary sources such as the Roman author Strabo (64-58 BC / AD 21-25), who wrote: "Ostia had the inability to maintain or consider a convenient sheltered harbor due to the amount of Tiber sediments transported down to the seashore" (Geography, 5, 3, 5, translated by H. L. Jones).

4.4.5. The abandonment of the harbor basin

The yellow bedded silts of unit C (Figs. 2 and 4) from the 3rd c. AD onward represent floodplain deposits which definitively isolated the harbor basin from the sea. Unit C presents the same geochemical characteristics as the floodplain deposits recorded in the uppermost unit (unit C) of the Trajan basin at *Portus* (Delile et al., 2014a). In both cases, the depositional environment was freshwater (negative values of F4), oxygenated conditions prevailed (constant positive values of F3), and the detrital particles dominated by the aluminosilicate minerals demonstrate the fineness of these sediments (high positive values of F2 and F1) (Fig.

4). These characteristics indicate that the abandoned harbor had finally been overrun by the floodplain around five centuries before the harbor of Trajan suffered the same fate.

This abandonment phase of the harbor basin appears to have been mistaken with the establishment of a fluvial harbor (Hadler et al., 2015) called the "younger fluvial harbour phase" in Wunderlich et al. (2018). Indeed, these authors argue for a shift from a harbor of lagoon type towards a fluvial harbor phase (or "harbour generation II") located between - 0.5 and - 1 m *b.p.s.l.* (see Fig. 7 in Hadler et al., 2015), that is to say between - 0.2 m *b.a.s.l* and + 0.3 m *above a.s.l.* These values, inferred from the ancient biological sea level dated to AD 230-450 by Goiran et al. (2009), show unambiguously that the water column disappears at these depths because the environment became terrestrial. Consequently, the establishment of a river harbor at these depths is strictly impossible. For this reason, we strongly suggest using ancient sea levels to characterize harbor levels and phases rather than the simple measurement of present sea level.

5. Conclusions

The 3000-year-old geochemical record preserved in the sediment core from the ancient harbor basin of Ostia Antica located in the Tiber delta has provided new insights into some of the aquatic paleo-environmental conditions, insights that had not been gleaned by the "classical" proxies used in the geoarcheological studies carried out in this harbor basin thus far. Associated with factor analysis, elemental geochemistry applied at high resolution to some forty chemical elements has enabled discrimination of the main environmental factors leading to the formation of the harbor basin deposits, classified in order of importance as (i) strong hydrodynamics (i.e., high-velocity currents) (the siliciclastic terrigenous signal ~ 47%), (ii) quiet hydrodynamics (the aluminosilicate terrigenous signal ~ 13%), (iii) water column ventilation (the authigenic fluxes ~ 10%), and (iv) seawater vs. freshwater influence (~ 7%). A first comparison of these environmental variables affecting the harbor water column at Ostia Antica with those identified using the same method in the ancient harbors of Trajan and Claudius (*Portus*), as well as those of Ephesus and Naples, has shown that the formation of the harbor basin deposits took place by means of similar geochemical fluxes, whose respective weights were relatively constant from one harbor basin to the other. This observation is not surprising as all these harbor sites, except for that of Naples (situated in a small coastal bay north of the gulf of Naples) are located on deltas. Thus the paleo-environmental evolution of the water column of the harbor basins was conditioned by the coastal geomorphology of the sites where the harbors were established.

By focusing on sediments uncontaminated by anthropogenic lead, the study of Pb isotopes has shown that it is possible to both identify the geological sources of sedimentary particles of the Tiber delta and distinguish the fine from the coarser particles. The particle size distribution of the Tiber delta sediments largely correlates with the proportion of the two main natural sedimentary sources of the Tiber's watershed: The sandy particles correlate positively with the volcanic rocks, while the fine particles are subject to rough correlations with the Apennine limestones.

The present study also sheds new light on the chronology of the life cycle of the harbor at Ostia Antica. First, the Na enrichment of pre-harbor level sediments, indicating, as at *Portus*, an environment dominated by marine influence, remained when the harbor basin was dug out around the middle of the 4th century BC, but to a lesser degree. Then, starting around the 3rd c. BC, the initial marine-dominated regime of the harbor basin shifted towards a freshwater-dominated milieu due in part to intense Tiber delta progradation caused by a short phase of climate deterioration, and due in part to human action. This influence of Tiber waters in the water column of the harbor basin reached a threshold of no return between the 2nd c. BC and the 3rd c. AD because the harbor basin was affected by the high-energy floods of the Tiber river. During this period, the geochemical signal of the coarse harbor deposits carefully recorded the hydrological rhythms of the Tiber, marked by the alternation of major inundation phases and pronounced low-water phases. Again during this period a phase of increased progradation of the Tiber delta occurred, resulting from an increase in the flood frequency of the Tiber between approximately the 2nd c. BC and the 2nd c. AD. While Hadler et al. (2015a) and Wunderlich et al. (2018) have advocated for a high-energy event to interpret the coarsest B2 unit, our geochemical data are more consistent with the scenario proposed by Goiran et al. (2014), Sadori et al. (2016) and Salomon et al. (2016) who call on an upsurge in the frequency of floods, which carried the sands into the harbor basin of Ostia Antica that led to its abandonment. This final phase of abandonment cannot be replaced by a river port environment, as argued by Hadler et al. (2015a) and Wunderlich et al. (2018), since these deposits are located in part above ancient sea level (- 0.2 to + 0.3 m *b.a.s.l.*); the harbor water column no longer existed at that time.

Finally, this study has also provided the opportunity to test the hypothesis of Hadler et al. (2015a) that argues for three high-energy events ascribed to a tsunamigenic origin, which would have thrice greatly affected the harbor basin of Ostia Antica. There are many arguments against this hypothesis, whether historical (absence of historical accounts of such events), geomorphological (inappropriate morphology of the coastline south of the Tiber River mouth), stratigraphic (no traces of tsunami deposits in the area) (Sadori et al., 2016), or anthropic (highest Pb abundances (anthropic contamination) recorded in the deposits of the most recent so-called tsunami) (Delile et al., 2017). While the earliest tsunami appears to have been mistaken for a classic deltaic front sequence of the Tiber, the other two high-energy layers should record a sudden change to a sustainable return of seawater influence in these deposits. However, our multi-elemental geochemical signal records the exact opposite, a strong freshwater component that increases towards the top of the stratigraphy.

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Figure captions

Figure 1. (**A**) Location of the harbor basins of *Portus* and Ostia in the Tiber delta and position of cores PO2 and PTXI-3 (orange circles) analyzed in this work, and core TR14 analyzed by Delile et al. (2014a) (beige circle). (**B**) Map showing the archeological area of ancient Ostia with the location of core PO2, as well as the old (before AD 1557) and current Tiber river courses (modified from Gorian et al., 2014). The blue area is the location of the Ostia Antica harbor basin.

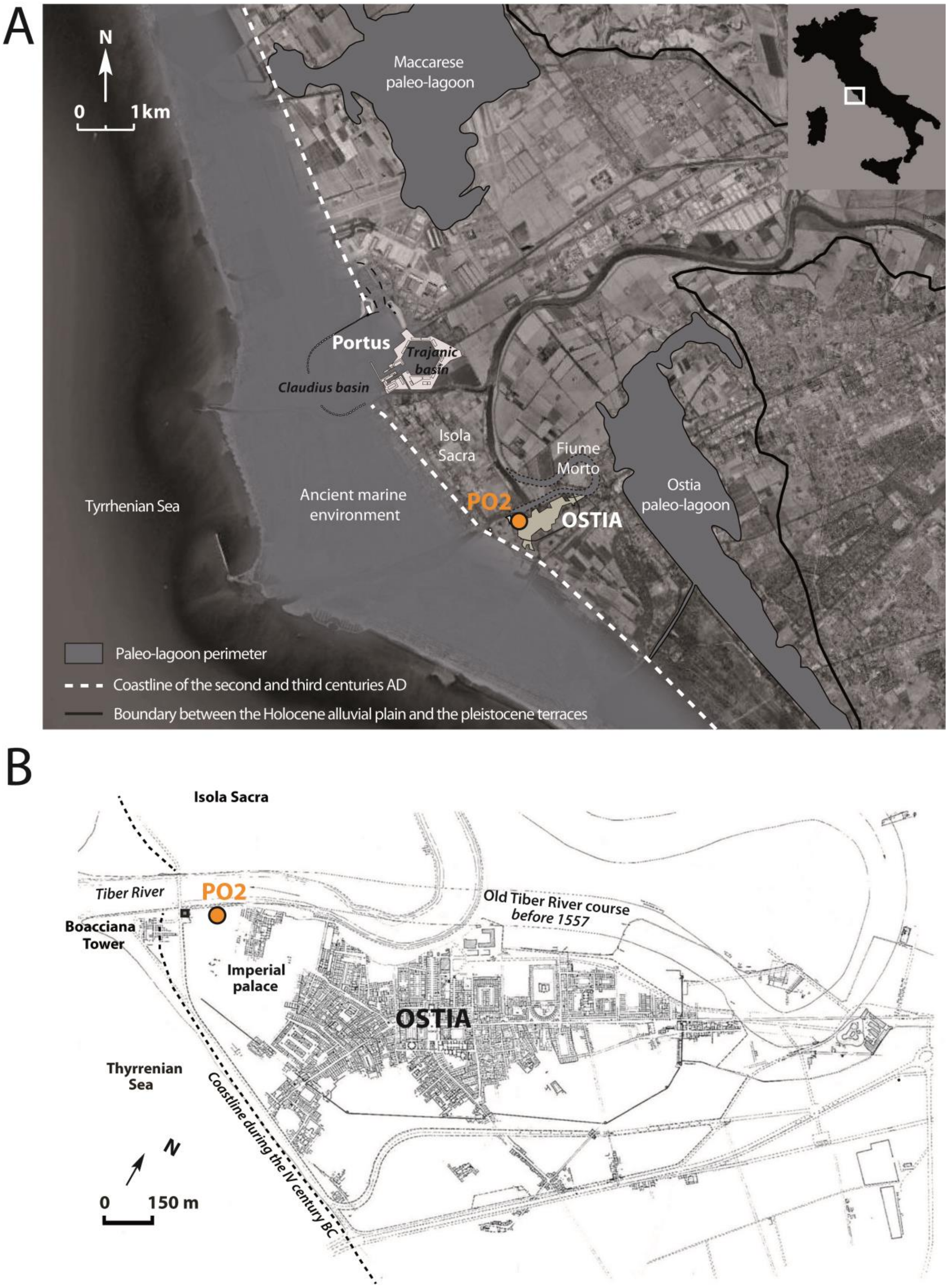


Figure 2. Stratigraphic log of core PO2 showing the age-depth model, stratigraphic and environmental descriptions, magnetic susceptibility values, the 50 percentile (D 50) grain

size, the granulometric diagram, Loss on Ignition (L.O.I.), $CaCO_3$ content, and ostracod assemblages divided into five ecological groups: marine, phytal marine, coastal phytal (i.e. phytal species requiring algae or higher plants for their life cycle), brackish lagoonal, and freshwater (modified from Gorian et al., 2014).

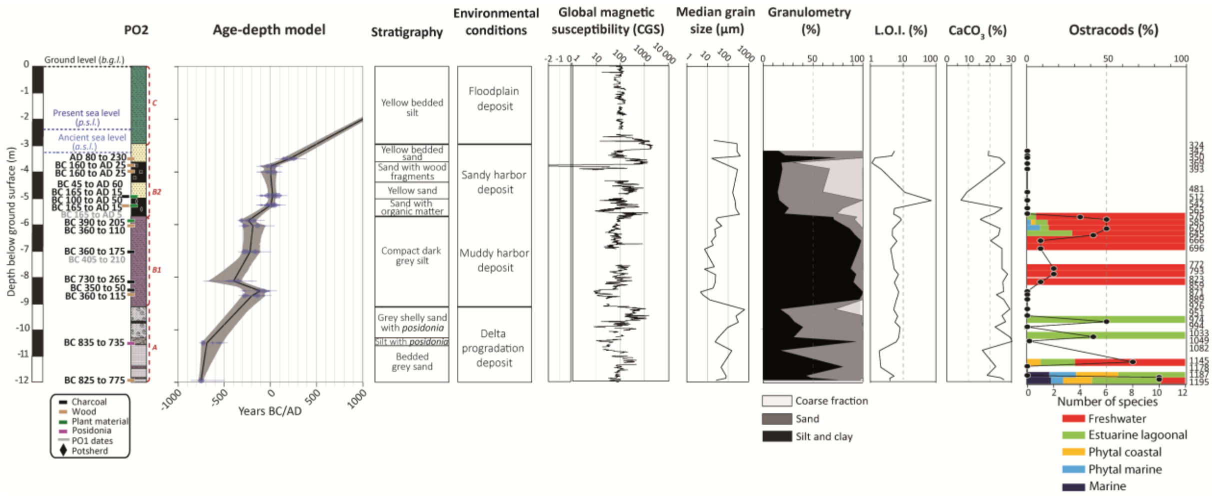


Figure 3. Geochemical logs of elemental concentrations of the PO2 core classified according to their supposed belonging to the main geochemical fluxes: (A) Detrital elements, (B) Authigenic elements, (C) Biogenic elements. Section 4.1.1. discusses how this approach of classifying elements according to their presumed affiliation with the main geochemical inputs is arbitrary.

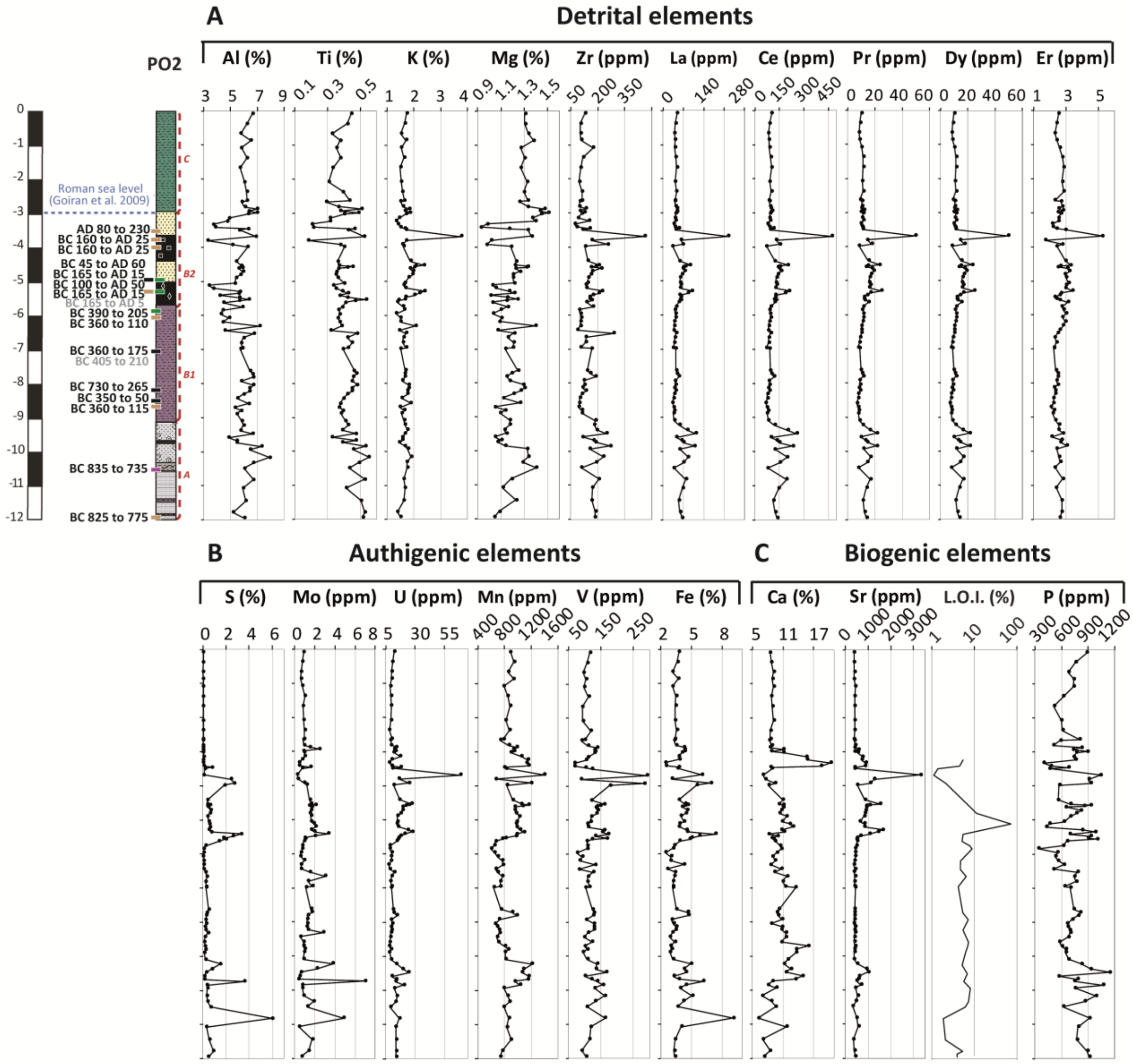


Figure 4. (**A**) Factor analysis of elemental concentrations in core PO2. The number of factors is limited to four: (1) Silicate detrital fraction (47%); (2) aluminosilicate detrital fraction versus carbonate fraction (13%); (3) anoxic conditions (10%); (4) seawater influence versus polluted freshwater (7%). (**B**) Distribution of the different factors with depth in the column. The gray and white shadings and the gray dotted line highlight the main geochemical units of the core discussed in section 4.4.

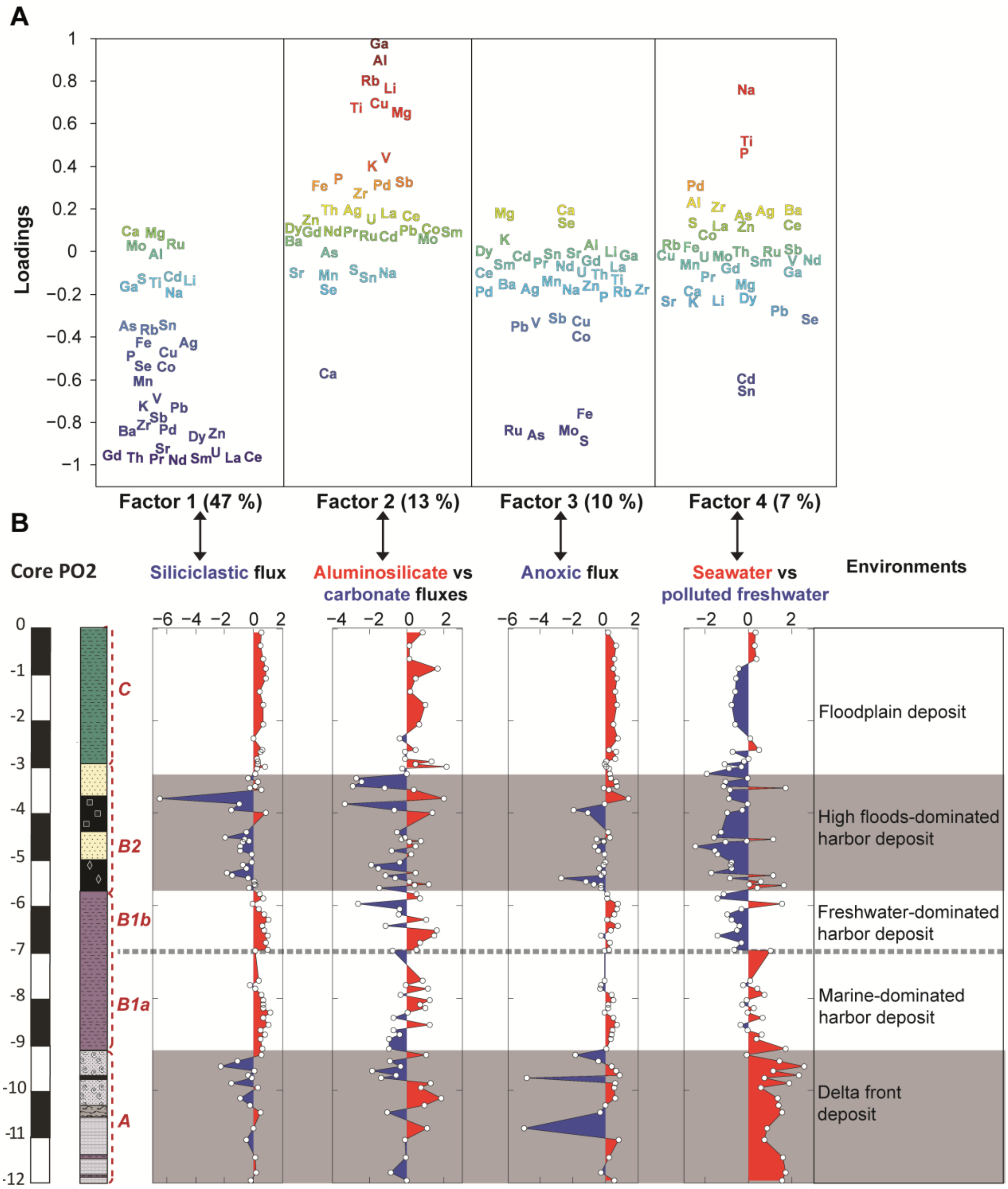
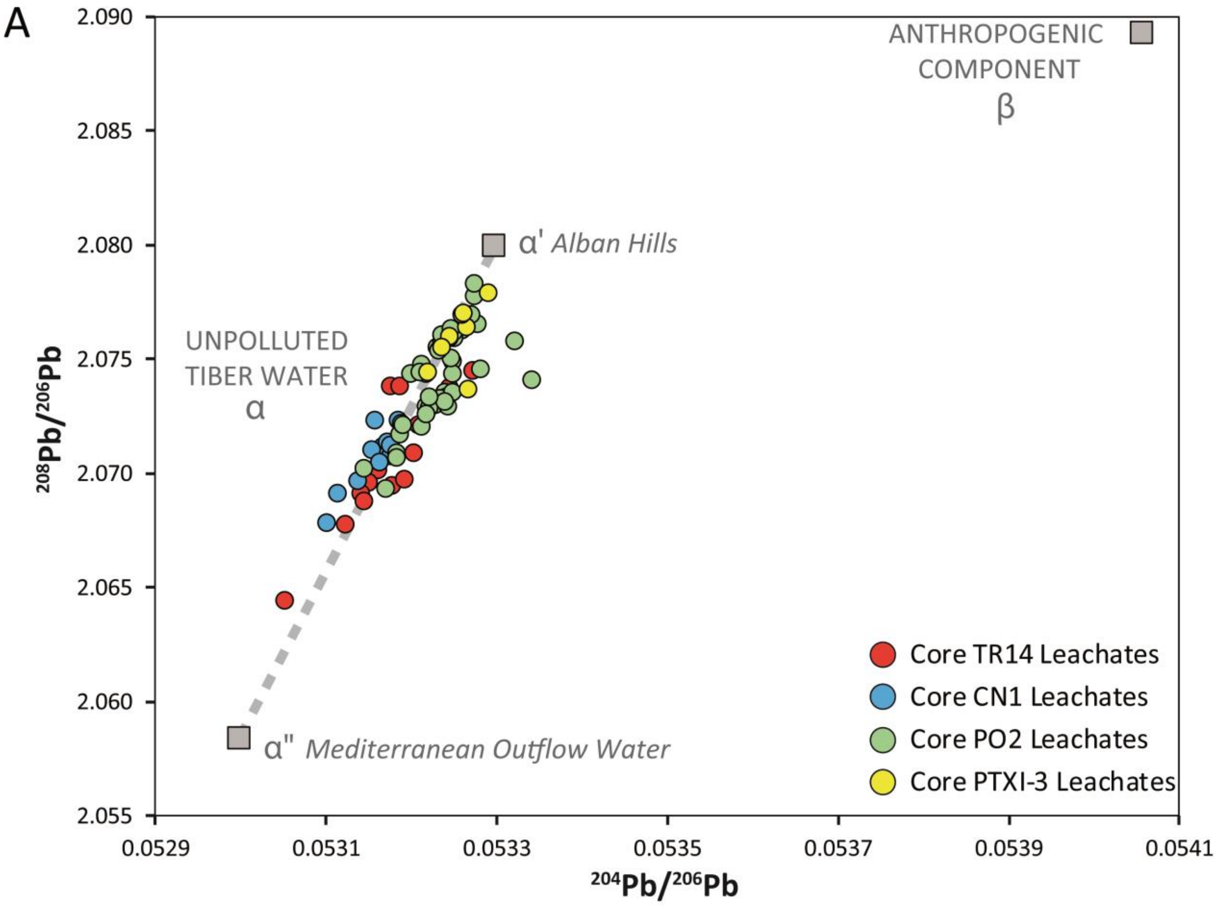
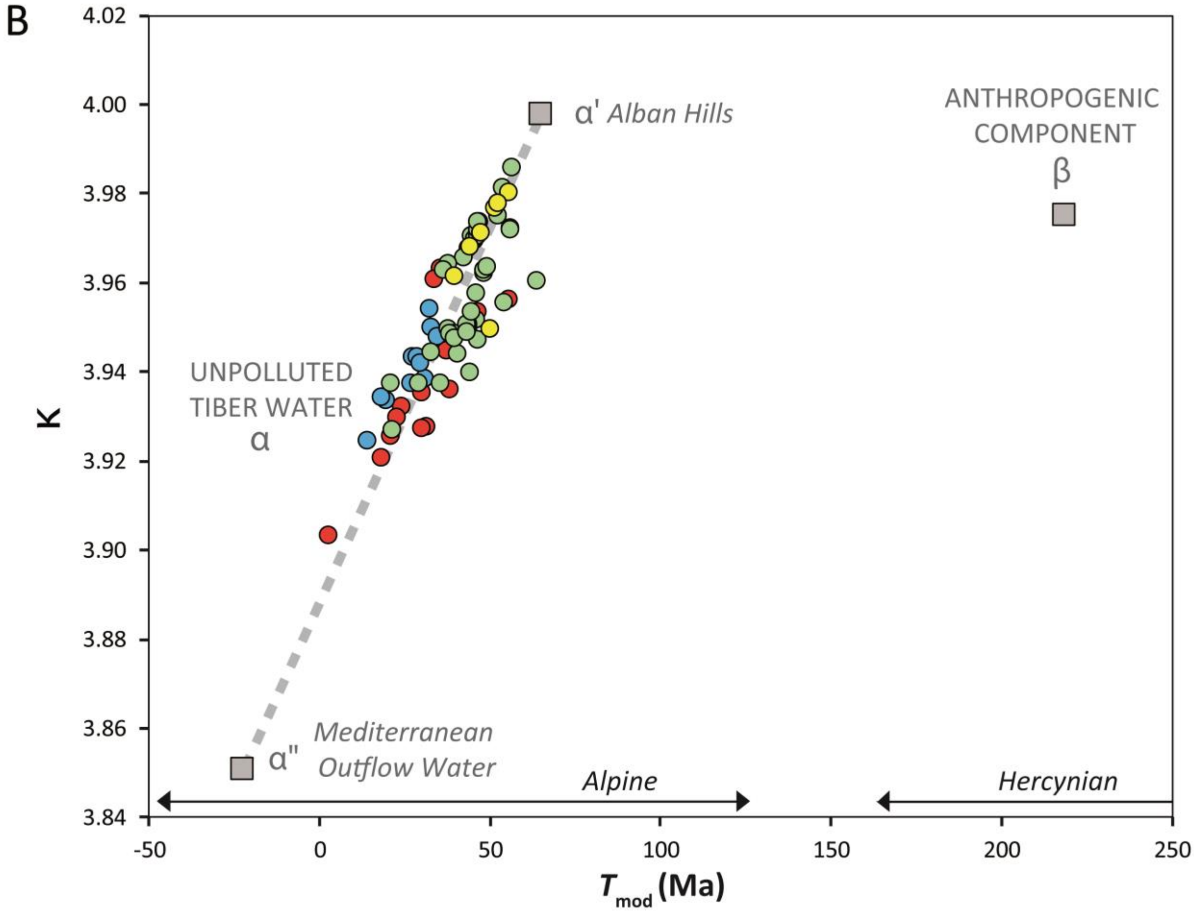


Figure 5. (A) Lead isotope ratios ($^{204}Pb/^{206}Pb$ vs. $^{208}Pb/^{206}Pb$) and (B) geochemical parameters (T_{mod} vs. κ) for leachates from the uncontaminated sediments of the *Trajanic* (in red), Claudian (in yellow), and Ostia (in green) harbor deposits, and of the *Canale Romano* (in blue). Together, these samples define a geological mixing line between the α' component composed of volcanic rocks from the Alban Hills (Conticelli et al., 2002; D'Antonio et al.,

1996) and the α" component related to the erodible recent Apennine limestones, which are very similar to Pb dissolved in modern Mediterranean seawater (Stumpf et al., 2010) (modified from Delile et al., 2017).


A
2.090
2.085
2.080
2.075
2.070
2.065
2.060
2.055
0.0529
0.0531
0.0533
0.0535
0.0537
0.0539
0.0541
$^{208}Pb/^{206}Pb$
$^{204}Pb/^{206}Pb$
ANTHROPOGENIC
COMPONENT
β
α' Alban Hills
UNPOLLUTED
TIBER WATER
α
α" Mediterranean Outflow Water
Core TR14 Leachates
Core CN1 Leachates
Core PO2 Leachates
Core PTXI-3 Leachates


B
4.02
4.00
3.98
3.96
3.94
3.92
3.90
3.88
3.86
3.84
K
-50
0
50
100
150
200
250
T_{mod} (Ma)
α' Alban Hills
ANTHROPOGENIC
COMPONENT
β
UNPOLLUTED
TIBER WATER
α
α" Mediterranean
Outflow Water
Alpine
Hercynian

1163

Figure 6. Plot of *f*α’ and *f*α” values (proportion of the natural sub-components α’ and α” in all uncontaminated sediment samples) against sand, silt, and clay percentages for leachates (in green) and residues (in black) from core TR 14 and leachates from cores PTXI-3 (in grey) and PO2 (in yellow).

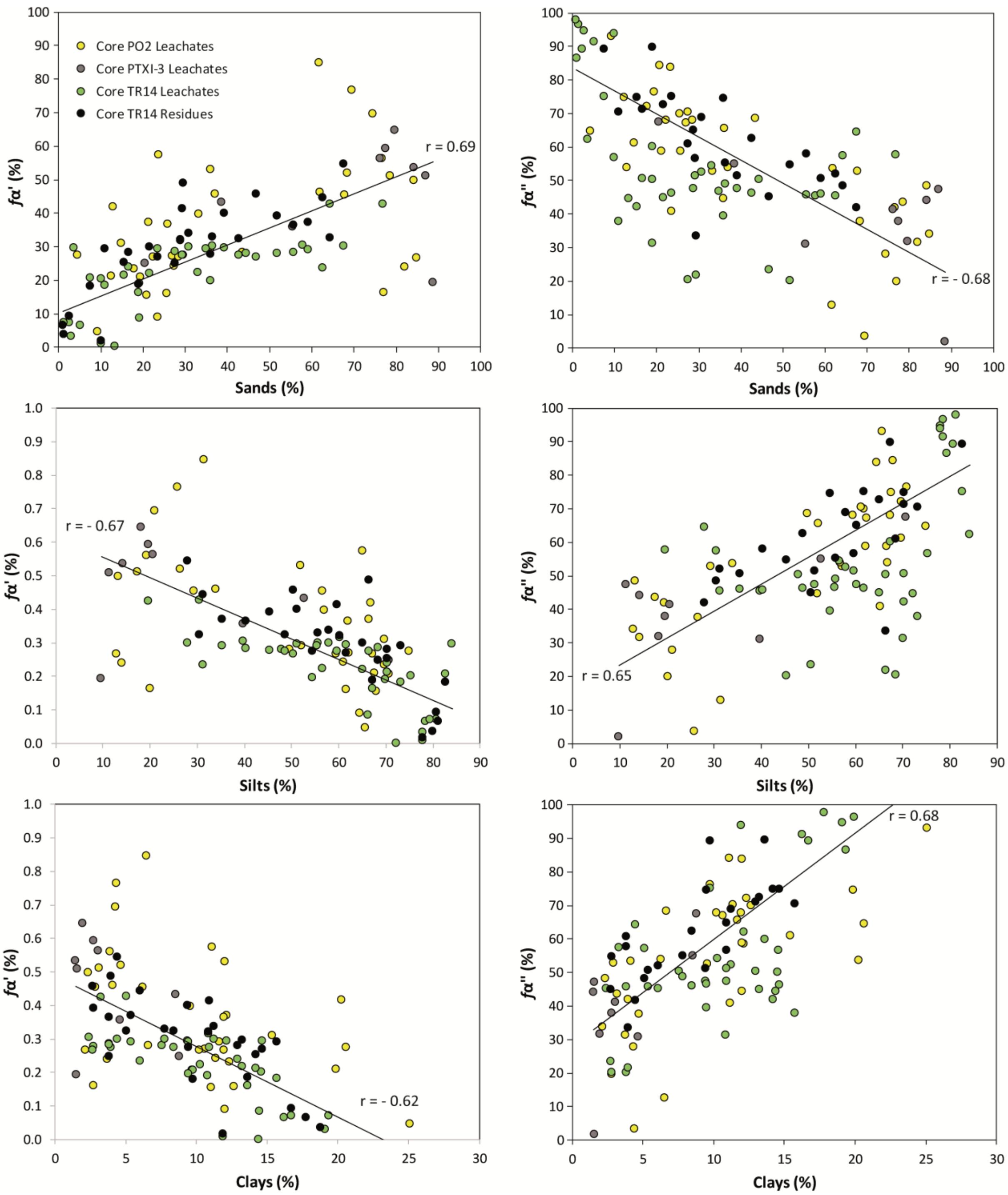


Table 1. Environmental factors involved in the formation of sedimentary deposits in the ancient harbor basins of Ostia (Factor analysis in Fig. 4), Claudius (Factor analysis in Fig. S4 and data in Table S1), Trajan, Ephesus, and Naples. These environmental variables, organized in order of relative importance, have been identified by factor analysis of element concentrations. For each of these variables, the chemical elements concerned, the associated processes, and the types of environments involved are given.

			ENVIRONMENTAL FACTORS SORTED ACCORDING TO THEIR SIGNIFICANCE (F1 TO F4 IN %) AND INFERRED FROM FACTOR ANALYSIS						
Harbor site	**Reference**	**Coastal geomorphology**	**Detrital flux (42%)**	**Biogenic flux (34%)**	**Oxic condition (20%)**	**Anoxic condition (20%)**	**Mineralogy/lithology (11%)**	**Anthropogenic flux (10%)**	**Seawater flux (8%)**
Ostia	This study	Delta	F1 (47 %)	N/A	F3 (10 %)	F3 (10 %)	F2 (13 %)	F4 (10 %)	F4 (7 %)
Portus (Trajanic basin)	Delile et al. (2014a)	Delta	F1 (55 %)	F1 (55 %)	F2 (17 %)	F2 (17 %)	N/A	F4 (5 %)	F3 (9 %)
Portus (Claudius basin)	This study	Delta	F1 (44 %)	F2 (16 %)	N/A	N/A	F3 (12 %)	N/A	F4 (6 %)
Ephesus	Delile et al. (2015)	Delta	F1 (49 %)	F1 (49 %)	F2 (19 %)	F2 (19 %)	F3 (8 %)	N/A	N/A
Naples	Delile et al. (2016a)	Coastal bay	F2 (16 %)	F2 (16 %)	F1 (36 %)	F1 (36 %)	F3 (10 %)	F2 (16 %)	F3 (10 %)
SYNTHESIS		**Significant elements**	Al, Zr, Ti, Th, Mg, Ba, K, Co, Zn, REEs	LOI, Ca, Sr	Mn, K, Ti, Zn Cr, Co, Cd	S, Mo, U, Pb, Ag, Cu	Al, Rb, La, Se, Ce, Ga, Li, Be, Zr, K, Ti, Mg	Pb, Ag, Sn, Cu, Cd,	Na
		Process	Fluvial hydrodynamics: - Canal networks - Coastal and delta progradation	Biomass production: - Organic matter - Skeletal remains - Eutrophication - Urban sewage inputs	- Delta progradation - Swell	-Enclosing harbor basin -Weak water-column ventillation -Interflood period -Urban sewage inputs and eutrophication	- Erosion of the local and regional geological basement	- Heavy metal inputs - Using of lead pipe networks - Metallurgic activities	- Seawater influence - Infiltration of the littoral salt wedge
		Paleo-environment	- Floodplain - Freshwater-dominated harbor - Coastal alluvial fan - Paleo-channel - Delta front - Prodelta environment	- Swamp - Marine - Enclosed harbor - Peat - Lagoonal - Brackish and eutrophic environments	- Floodplain - Freshwater-dominated harbor - Coastal alluvial fan - Paleo-channel - Delta front - Prodelta environments - Beach	- Marine - Enclosed harbor - Peat - Lagoonal - Swamp	In all environments	In all environments	- Marine dominated harbor - Delta front

Figure S1. Color-coded correlation matrix (correlogram) for all measured chemical elements in core PO2.

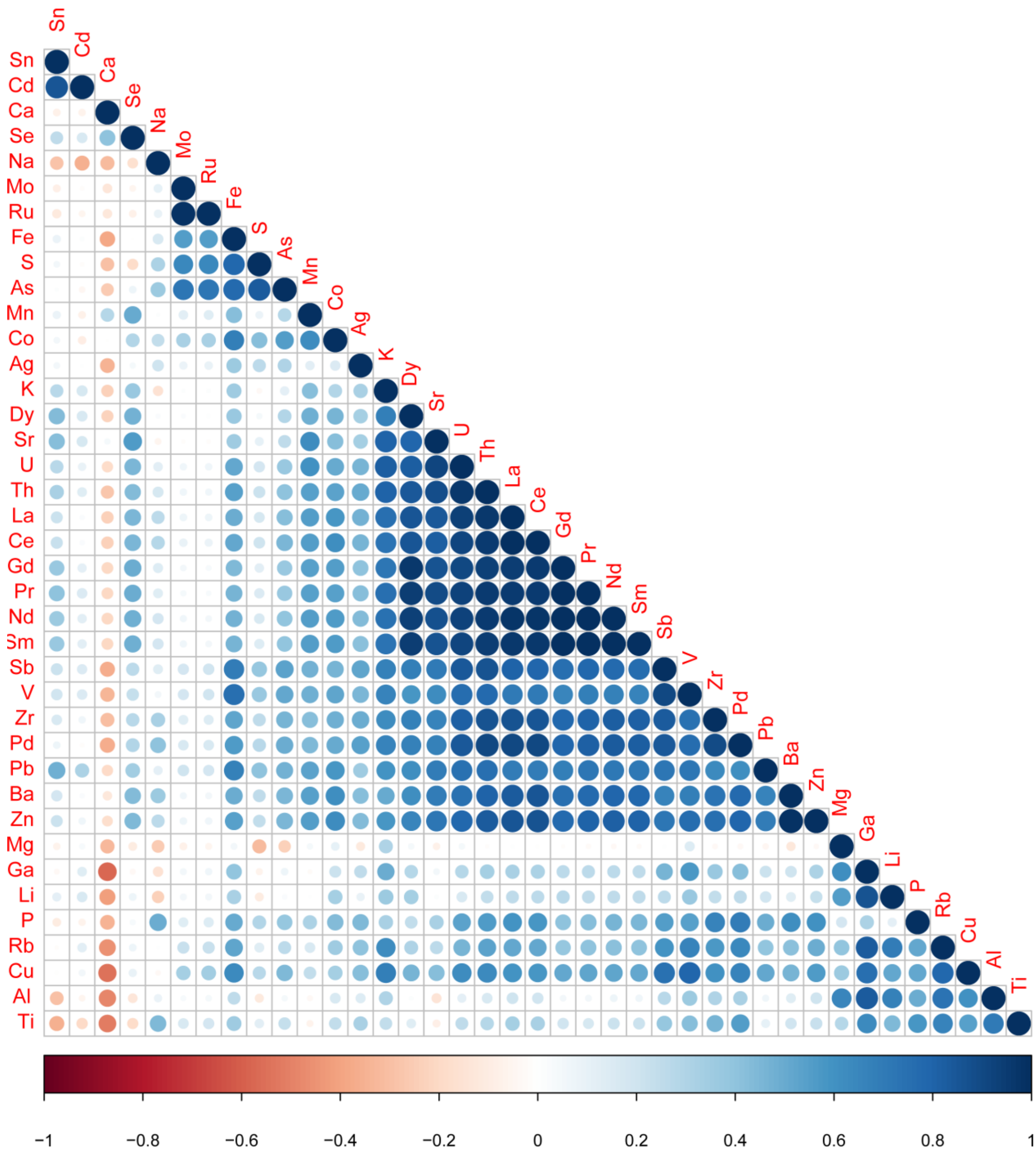


Figure S2. Color-coded correlation matrix (correlogram) for all measured chemical elements and granulometric fractions in the harbor subunits B1 and B2 of core PO2. Two groups have been identified by hierarchical clustering.

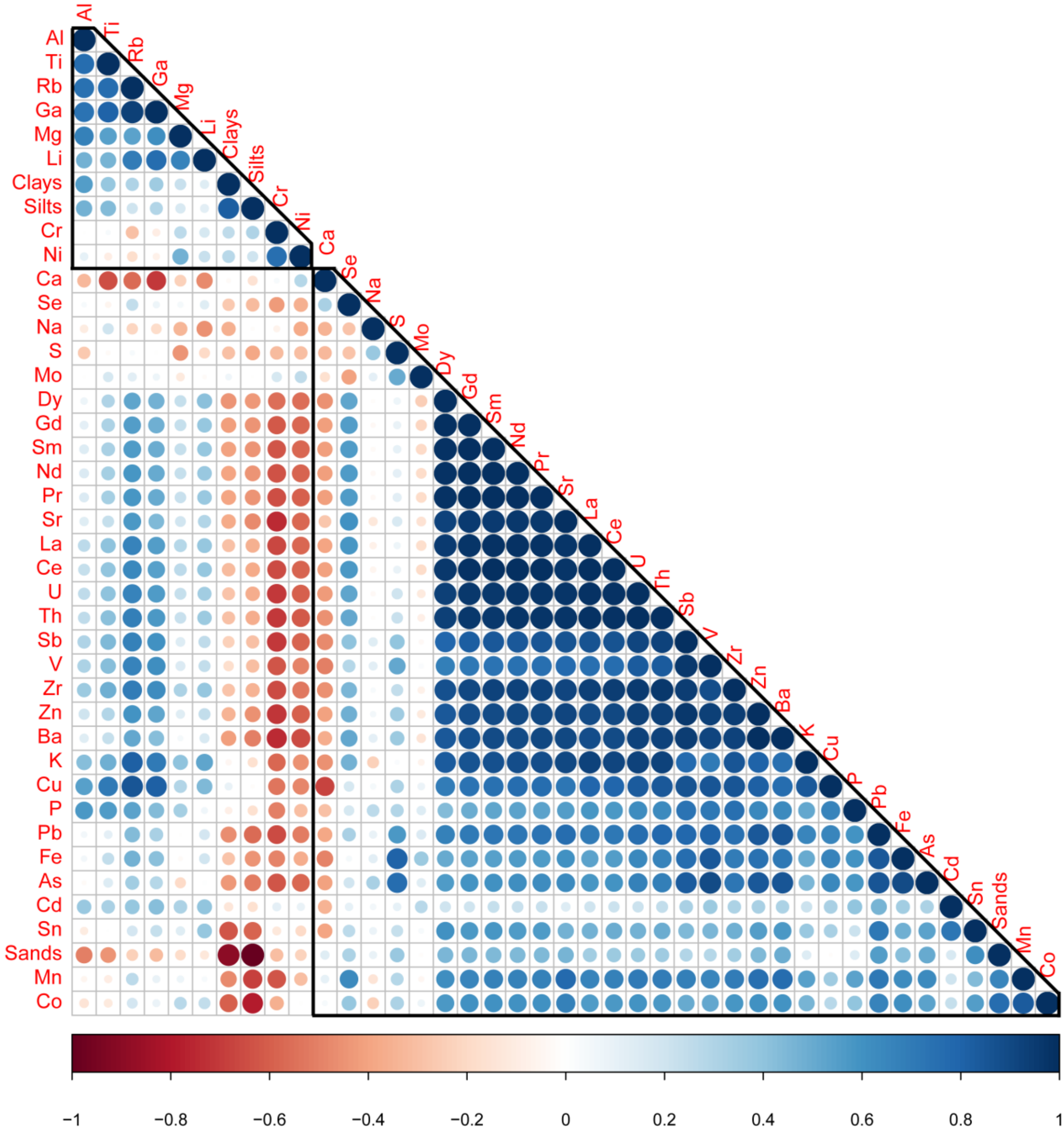


Figure S3. (**A**) Photo showing subhorizontal bedding formed by placers on the current coastline of the Tiber delta (modified from Salomon, 2013). (**B**) Close-up of a pluricentimetric layer containing placers.

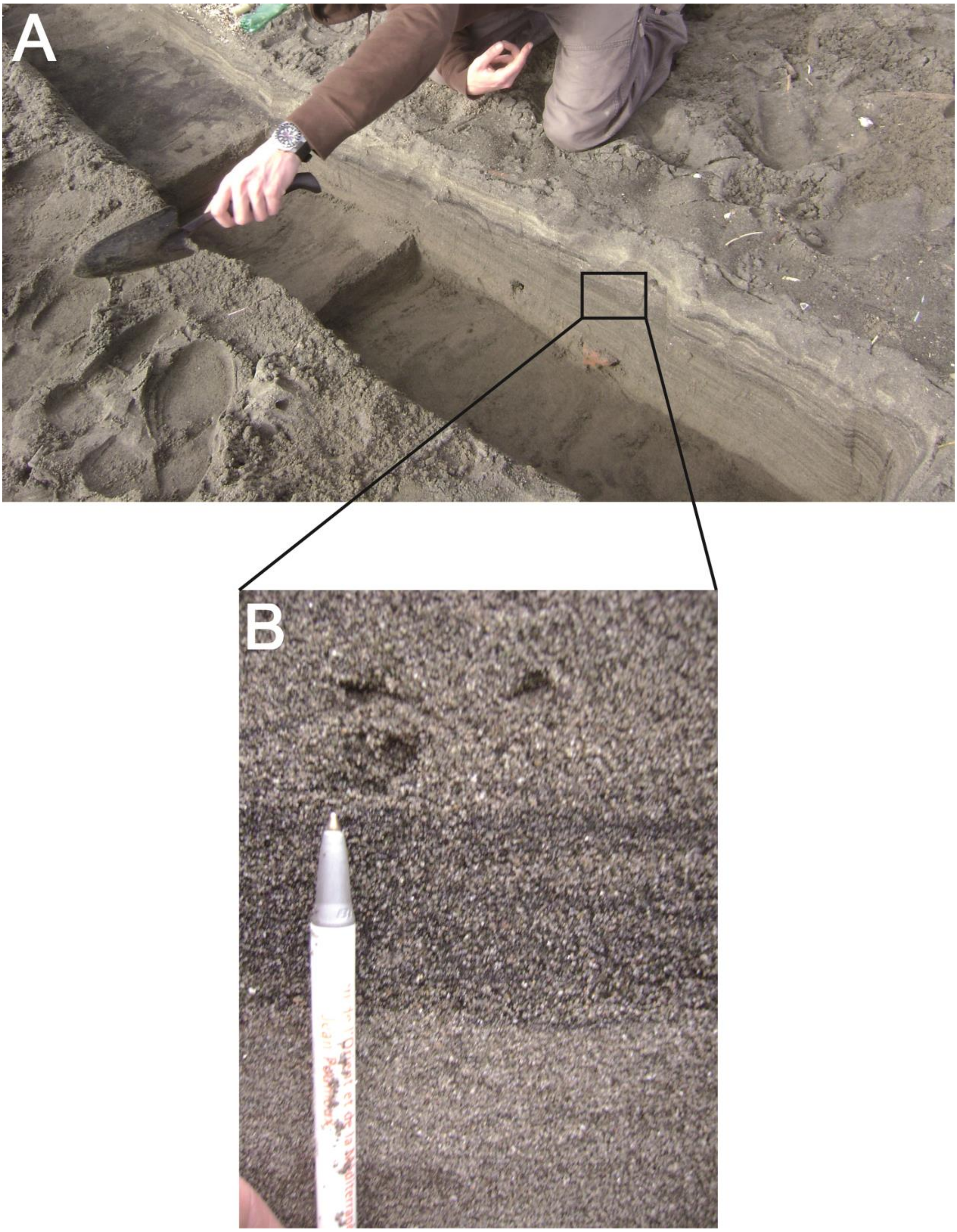
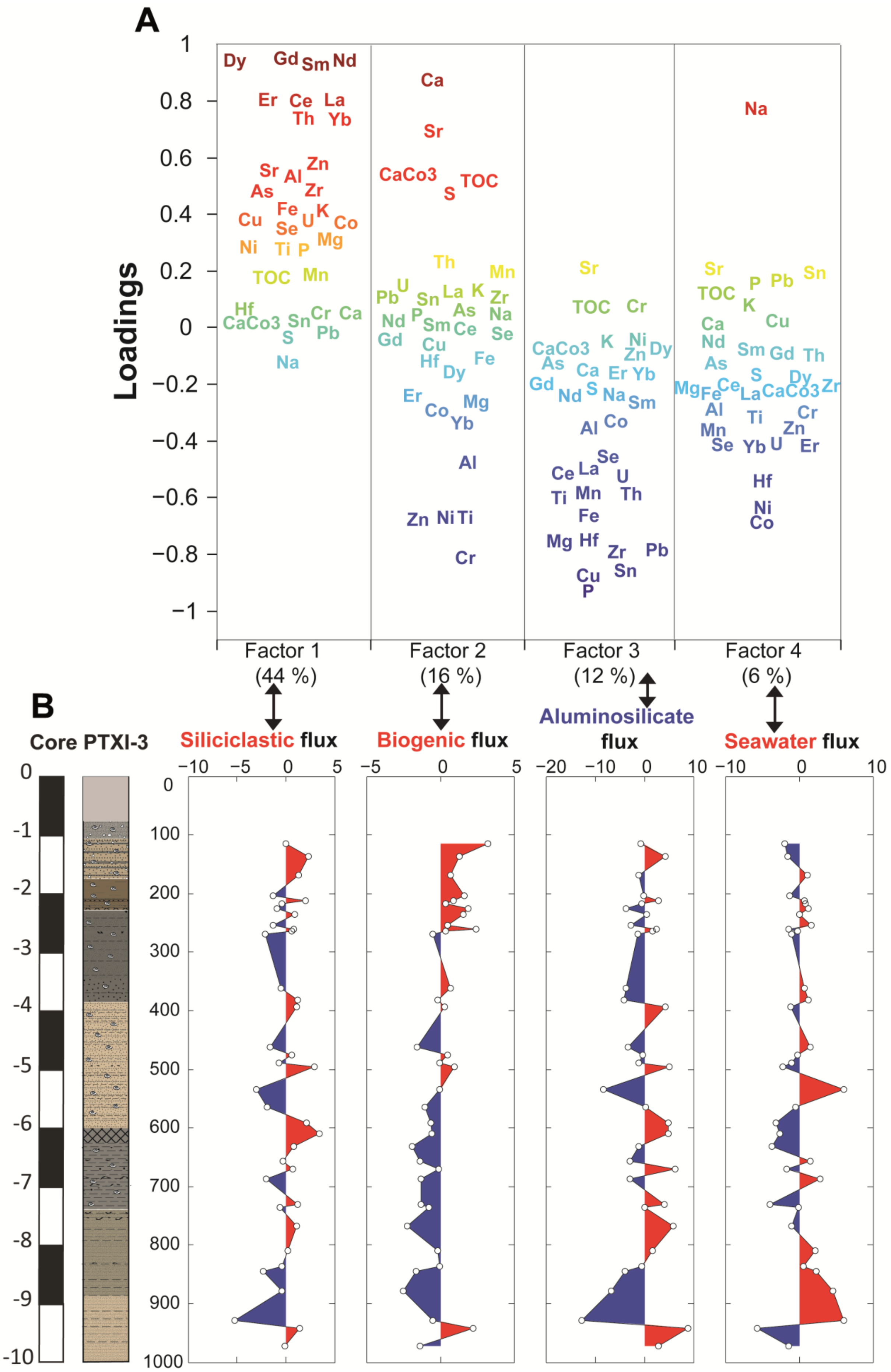


Figure S4. (**A**) Factor analysis of elemental concentrations in core PTXI-3 taken in the ancient harbor basin of Claudius. The number of factors is limited to four: (1) Silicate detrital fraction (44%); (2) biogenic fraction (16%); (3) aluminosilicate detrital fraction (12%); (4) seawater influence (6%). (**B**) Distribution of the different factors with depth in the column.



A
Loadings
Factor 1 (44 %)
Factor 2 (16 %)
Factor 3 (12 %)
Factor 4 (6 %)
B
Core PTXI-3
Siliciclastic flux
Biogenic flux
Aluminosilicate flux
Seawater flux

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Table S1. Major and trace element concentrations in core PTXI-3. Values in wt.% for major elements and in ppm for trace elements.

	wt.%												ppm																					
Depth (cm)	L.O.I.	CaCo3	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	TiO_2	P_2O_5	MnO	SO_2	Zr	Cr	Co	Ni	Cu	Zn	As	Se	Sr	Sn	La	Ce	Nd	Sm	Gd	Dy	Er	Yb	Hf	Pb	Th	U
115	5	33	8.76	3.37	19.66	1.28	2.15	1.49	0.30	0.14	0.10	0.39	146.16	34.88	13.64	28.65	25.72	41.07	28.02	9.86	652.26	2.94	57.31	111.69	49.62	8.62	6.91	4.48	2.30	1.92	161.11	44.12	25.89	3.16
136	6	40	7.84	2.63	20.67	1.42	2.09	1.37	0.24	0.10	0.12	0.41	121.39	35.68	12.24	31.88	25.10	52.89	22.17	3.22	981.79	2.73	52.05	100.85	54.40	9.88	7.41	5.23	2.43	1.88	59.21	47.06	23.72	3.29
169	30	13	8.25	2.36	17.88	1.46	2.20	1.26	0.27	0.11	0.12	0.78	134.73	38.27	7.11	23.51	29.19	57.61	17.48	4.69	1037.52	3.81	56.46	112.99	61.41	10.94	8.65	6.00	2.76	2.42	63.92	55.27	26.82	4.38
205	8	26	6.26	3.93	18.14	1.01	1.51	0.91	0.22	0.09	0.10	11.14	139.48	29.97	9.63	22.03	20.40	35.09	19.90	7.80	577.20	1.07	36.17	70.02	32.11	5.92	4.83	3.45	1.81	1.59	127.19	38.09	16.41	2.68
213	14	23	9.08	3.80	16.51	1.53	2.45	1.03	0.23	0.10	0.07	0.84	84.42	37.02	9.39	26.95	16.23	54.87	23.13	5.29	908.35	3.08	48.67	95.10	51.77	8.68	6.98	4.85	2.10	1.82	46.36	35.02	22.59	3.51
218	16	26	8.28	4.20	18.97	1.35	2.28	0.99	0.22	0.10	0.07	3.10	97.62	26.88	7.82	19.98	18.68	46.45	25.03	3.47	902.39	2.64	45.63	87.70	47.59	7.84	6.41	4.04	1.89	1.62	45.28	34.33	20.79	3.45
226	23	15	8.50	5.12	14.76	1.53	2.11	1.18	0.25	0.11	0.11	3.92	138.14	43.83	7.86	28.31	21.37	56.93	19.39	3.59	827.42	2.70	44.63	86.17	47.76	8.41	6.46	4.43	2.05	1.77	58.44	41.19	23.73	3.77
235	17	27	8.81	2.99	18.65	1.41	2.30	1.24	0.25	0.10	0.06	2.30	88.53	42.18	9.92	32.18	18.00	61.85	21.94	7.95	1073.60	3.31	51.25	98.90	55.19	9.53	7.46	4.87	2.34	1.85	53.49	38.47	23.36	3.74
255	2	34	8.40	2.65	17.00	1.49	2.37	1.06	0.23	0.10	0.06	1.74	88.06	27.78	8.53	19.94	15.64	44.85	20.43	3.90	842.42	4.40	41.52	81.16	42.96	7.73	6.35	4.04	1.82	1.55	44.53	39.55	18.95	6.41
262	11	28	9.15	3.46	17.78	1.40	2.32	1.31	0.30	0.11	0.14	2.08	111.33	34.77	13.28	25.11	13.54	40.69	19.01	6.56	609.94	1.18	45.82	87.19	40.23	7.02	5.42	3.84	1.83	1.52	137.32	36.62	21.38	8.71
265	4	33	8.74	3.40	15.39	1.45	2.24	1.25	0.27	0.10	0.06	2.65	97.61	43.23	9.17	25.41	19.58	56.97	18.58	5.96	758.57	3.59	43.56	83.38	48.71	8.19	6.38	4.40	2.11	1.80	53.04	37.13	19.52	4.98
270	13	26	8.35	2.92	17.10	1.45	2.29	1.18	0.26	0.11	0.12	1.89	98.31	28.42	10.42	19.22	11.40	34.98	12.76	6.90	567.53	1.48	37.20	73.88	32.21	5.86	4.71	3.40	1.61	1.25	110.13	36.47	18.09	5.51
362	7	25	9.19	5.77	19.91	1.58	1.63	2.14	0.48	0.27	0.14	3.98	204.82	41.62	12.54	24.44	73.43	54.09	16.69	8.05	571.24	111.75	60.79	124.43	53.74	9.44	6.97	4.33	2.00	1.71	215.25	2100.79	30.22	6.30
382	4	23	10.90	6.16	16.28	1.73	2.63	3.11	0.55	0.35	0.16	2.08	274.70	42.85	16.58	29.13	117.46	65.84	25.63	11.75	678.14	47.82	77.05	159.96	66.02	11.72	8.67	5.22	2.56	2.12	286.91	562.95	43.26	8.39
393	10	25	7.61	2.96	17.83	1.24	1.88	1.54	0.33	0.10	0.05	0.33	74.98	85.89	11.18	35.67	16.34	57.35	7.33	9.91	709.48	2.40	36.13	79.71	42.45	8.11	6.26	4.40	2.07	1.68	49.58	28.58	12.55	2.59
463	6	34	7.23	2.95	15.83	1.23	1.76	1.83	0.34	0.11	0.05	0.44	87.22	93.57	17.94	40.24	19.85	63.36	9.17	1.51	651.93	1.94	35.48	81.67	46.99	8.29	6.61	4.38	2.08	1.69	56.01	30.16	11.97	2.59
475	3	25	8.57	3.06	14.67	1.34	1.93	1.40	0.35	0.11	0.09	0.23	99.40	56.60	11.29	36.73	18.95	63.35	7.64	7.06	709.13	3.76	49.74	110.23	53.51	9.06	7.71	5.17	2.39	2.03	59.45	39.51	19.08	5.03
490	1	21	8.14	3.26	16.03	1.26	1.79	1.39	0.35	0.10	0.11	0.09	108.00	74.28	11.95	42.11	16.74	58.20	8.62	7.43	608.66	0.77	49.15	106.25	46.55	8.38	6.56	4.43	2.37	1.95	202.93	37.29	18.89	5.80
496	1	21	9.25	3.51	14.92	1.36	2.12	1.42	0.36	0.12	0.10	0.28	122.63	54.55	11.70	30.04	21.84	71.99	8.41	7.92	887.80	2.63	52.83	115.08	58.60	10.62	7.92	5.20	2.17	1.83	65.20	47.48	22.51	3.79
535	1	21	7.67	2.82	13.50	1.37	1.81	1.45	0.34	0.10	0.09	0.19	90.28	67.39	9.22	28.28	16.50	54.45	5.26	3.22	566.48	2.14	31.73	72.48	39.94	7.49	5.87	4.16	1.92	1.58	47.67	27.62	12.08	2.50
564	1	14	8.09	2.79	16.58	1.41	2.23	1.23	0.25	0.08	0.05	0.23	73.16	47.03	9.18	27.49	13.05	44.91	4.79	2.87	606.56	1.24	26.93	58.22	30.93	5.81	4.49	3.43	1.47	1.26	35.08	25.98	9.37	1.55
591	1	19	8.49	3.59	15.02	1.27	1.92	1.54	0.42	0.12	0.06	0.33	111.94	116.68	11.88	39.37	22.06	76.78	8.77	7.67	682.82	3.16	50.57	114.34	59.54	10.22	7.72	5.19	2.40	1.96	70.02	41.09	21.14	3.32
611	1	13	9.95	5.02	10.09	1.37	2.00	1.24	0.37	0.12	0.04	4.00	141.79	55.51	14.62	44.00	33.03	75.24	52.61	8.64	621.30	3.19	65.71	133.91	71.13	12.07	9.44	6.12	2.73	2.23	70.37	61.35	27.14	4.30
633	1	19	13.56	5.38	8.47	0.93	2.23	2.17	0.62	0.11	0.13	0.30	171.31	119.39	33.17	94.70	46.05	125.25	19.62	10.58	345.19	4.01	65.24	131.49	58.35	10.39	8.31	5.92	3.18	2.90	289.57	48.00	26.87	9.51
657	2	11	10.17	4.45	10.50	1.31	2.17	1.52	0.40	0.11	0.12	1.40	139.98	86.28	14.14	45.09	31.44	80.76	67.09	4.95	559.47	3.55	45.11	99.90	49.55	8.72	7.13	5.39	2.47	2.15	66.00	43.10	19.86	4.05
670	10	10	7.91	2.28	12.03	1.50	2.05	1.07	0.26	0.08	0.04	0.21	62.44	64.37	7.08	24.31	13.92	45.46	7.40	2.80	499.08	2.06	25.22	58.02	29.82	5.09	4.31	3.08	1.45	1.22	35.67	24.76	10.13	1.92
688	5	12	7.99	2.53	10.88	1.53	1.90	1.17	0.32	0.09	0.09	0.15	65.11	54.42	6.75	35.52	13.64	49.49	9.80	8.01	408.44	1.11	34.54	75.85	34.08	6.28	5.32	3.76	1.86	1.69	117.41	26.90	10.25	2.14
731	5	18	11.32	4.84	10.23	1.30	2.13	2.06	0.50	0.11	0.13	0.28	110.78	102.58	12.87	61.21	29.09	85.63	17.70	7.60	346.67	2.14	42.14	87.74	39.62	7.26	6.04	4.57	2.54	2.21	177.41	35.79	17.28	3.30
736	1	14	9.15	3.39	11.41	1.45	1.96	1.36	0.40	0.12	0.05	0.28	99.40	71.20	8.37	32.28	20.51	63.49	15.35	4.52	476.60	2.19	35.98	82.03	42.00	7.73	5.82	4.16	2.04	1.92	57.94	32.65	15.97	2.40
768	8	22	8.55	3.07	11.40	1.55	1.93	1.22	0.33	0.11	0.09	0.15	96.40	61.84	8.28	25.69	18.27	60.80	7.65	4.55	477.03	1.66	31.44	69.01	38.18	6.92	6.04	4.21	2.06	1.80	48.59	27.54	14.64	2.37
809	2	12	8.84	2.90	11.95	1.52	2.13	1.11	0.28	0.10	0.04	0.14	75.35	67.83	8.55	30.78	18.10	55.69	8.73	2.06	504.85	1.55	31.30	68.00	37.41	6.55	5.56	3.81	1.79	1.52	43.48	30.15	13.48	1.96
837	1	13	8.57	2.98	11.74	1.60	1.88	1.25	0.35	0.12	0.05	0.16	77.27	75.11	9.39	31.38	18.24	61.56	7.74	2.47	446.30	2.26	31.64	68.22	38.17	6.54	5.77	4.07	1.93	1.69	49.22	24.16	12.87	2.49
845	2	20	8.22	2.93	11.88	1.54	1.91	1.19	0.38	0.10	0.09	0.05	80.95	71.42	8.18	33.82	12.29	49.10	9.98	6.23	449.30	1.55	33.30	71.41	34.79	6.19	5.03	3.70	1.98	1.68	136.89	25.80	12.58	2.31
879	1	17	11.82	4.36	12.35	1.28	2.29	1.36	0.43	0.13	0.05	0.16	132.24	69.86	12.26	44.82	29.43	89.69	18.60	8.06	609.53	2.59	61.77	125.12	63.32	10.71	8.06	5.39	2.40	2.11	74.81	61.45	29.79	3.34
928	3	22	7.89	2.48	13.56	1.51	2.04	1.08	0.28	0.08	0.04	0.14	54.95	68.45	8.16	29.54	13.48	52.44	7.47	6.35	553.82	1.41	30.63	65.05	35.85	6.54	5.43	3.87	1.82	1.46	37.72	22.84	10.68	1.72
942	1	21	7.52	2.25	12.65	1.45	2.01	1.00	0.25	0.08	0.04	0.13	57.06	52.04	6.92	23.65	12.74	47.00	6.95	1.67	506.07	1.04	23.20	49.78	28.72	5.35	4.52	3.29	1.54	1.35	35.31	20.16	8.46	1.40
973	1	22	7.63	2.40	11.86	1.55	1.76	1.09	0.36	0.09	0.08	0.07	75.65	60.11	7.60	45.66	10.49	50.08	10.07	5.39	405.26	0.64	34.49	70.03	33.34	6.40	5.51	3.87	1.98	1.81	122.32	21.42	11.12	2.45