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► To cite this version:

Hugo Delile, Ferréol Salomon. Palaeotsunami deposits at the Tiber River mouth (Ostia Antica, Italy): Do they really exist?. *Earth-Science Reviews*, 2020, 208, pp.103268. 10.1016/j.earscirev.2020.103268 . hal-03045769

HAL Id: hal-03045769

<https://hal.science/hal-03045769>

Submitted on 21 Sep 2022

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Palaeotsunami deposits at the Tiber River mouth (Ostia Antica, Italy): do they really exist?

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Keywords: palaeotsunamis, pluridisciplinary proxies, geoarchaeology, Mediterranean Sea, Ostia, Tiber delta, coastal research, Pb palaeopollution

Abstract

In this paper, we test the recent hypothesis of the occurrence of five to seven tsunami generations, that would have struck the ancient harbour basin of Ostia (Italy), and the lower channel of the Tiber River during the last three millennia. Because these steady disaster events would have deep implications on our knowledge of the history of Rome, we reviewed the pluridisciplinary data available at the Tiber River mouth. Considering sedimentological, geomorphological, micropalaeontological, geochemical, chronological and historical evidence, there is no conclusive palaeoenvironmental evidence to suggest past tsunami inundations near Ostia yet. River mouths are not the best contexts to identify tsunami deposits. High fluvial and coastal mobility generated by regular floods and storms hardly records single high-energy event (HEE) from a flood, a storm, or a tsunami. Sediments are

regularly reworked at the river mouth both in the river channel and on the close shoreface. Mixed fluvial and marine influences and the seasonal formation of a salt wedge at the mouth of the Tiber create specific estuarine assemblages for micro- and macrofauna. The layer called High-Energy Event 1 (HEE-1) on the palaeo-shoreface close to the river mouth and HEE-4 / 5 in the point bars of the Tiber channel are most probably layers reworked several times by fluvio-coastal events (storms and/or floods). HEE-3 sealing the Republican harbour of Ostia is clearly related to flood deposits. Complementary analyses would be necessary to definitely identify the origins of the HEE-2 and HEE-7 in the harbour, and HEE-6 in the palaeochannel or floodplain. Based on the data available, we show how other processes than tsunami inundations could be just as accountable for these coarse-grained sediment layers (storm deposit, flood deposit, or riverbank deposit). This review puts into question the use of pluridisciplinary proxies to identify palaeotsunami deposits. In addition, we demonstrate how high Pb concentrations constitute a robust proxy to definitively refute the presence of palaeotsunami deposits. As such, this study will be beneficial to a large community of specialists in coastal research.

1. Introduction

Scientific interest in palaeotsunami research has increased since the 2004 Indian Ocean Tsunami (2004 IOT) and the following similar disastrous hazards, like those of the 2011 Tohoku-oki Tsunami (2011 TOT) and more recently of 2018 Palu Tsunami (Indonesia), for which human losses were huge. This has resulted in a large range of methods developed in different disciplines to characterise and assess the effects of these kind of high-energy events (HEEs) on past human societies, as well as their ability to deal with it (e.g., their vulnerability and resilience). One of the best area to explore this specific short-lived human-environment interaction is the Mediterranean due to its long urban history of occupation over the last

millennia and its intense seismic activity. In this regard, coastal geoarchaeology is involved in tracking palaeotsunami impacts along Mediterranean shores, promoting interdisciplinary approaches including sedimentology, geomorphology, micropalaeontology, geochemistry, archaeology, and history. Among the sites and stratigraphic tsunami deposits documented all around the Mediterranean (e.g., Maramai et al., 2014; Reicherter et al., 2019; Marriner et al., 2017), one of them involves the iconic city of ancient Rome. Because tsunami inundations would not be without significant impacts on our understanding of the history of Ancient Rome, we have paid a special concern to them.

During the last ten years, several geoarchaeological research were conducted in the area of the archaeological site of Ostia, the ancient port of Rome at the mouth of the Tiber River. Two research teams applied similar or complementary methods to analyse and interpret fluvio-coastal dynamics dating from the Roman period.

In the early 2010's, Goiran et al. (2012, 2014) published definitive chronostratigraphical and palaeoenvironmental evidence for the location of the harbour of Ostia (Fig. 1). Later, complementary analyses were conducted on these cores (Goiran et al., 2012, 2014, 2017; Sadori et al., 2016; Salomon et al., 2016; Delile et al., 2017, 2018), while the second team conducted more extended surveys in the area involving complementary cores and geophysical surveys (Hadler et al., 2015; Wunderlich et al., 2018; Vött et al., 2015, 2020). In parallel, geoarchaeological research was conducted in the palaeomeander of Ostia that was flowing in the city of Ostia during the Roman period. The first team conducted studies in the area of the *Castello Giulio II* and in the area of the *Castrum* of Ostia (Salomon 2013; Pepe, et al., 2016; Salomon et al. 2017, 2018), although the second team studied two cross-sections of the palaeomeander of Ostia between these two locations (Wunderlich et al., 2018; Hadler et al., 2020).

76 The presence of these two teams contributed to produce a lot of essential new data to
77 reconstruct the evolution of the landscape of this important city-port from the Roman period.
78 However, the two teams propose different interpretations of the deposits. On the basis of
79 geomorphological, sedimentological, geochemical, geophysical and microfossil analyses,
80 Hadler et al., (2015, 2020), Wunderlich et al. (2018) and Vött et al. (2020) hypothesize the
81 existence of seven palaeotsunami deposits (High Energy Event 1 to 7 spelled thereafter HEE-
82 1 to 7) attributed to five to seven different events (Table 1). Amongst these tsunami events,
83 three to four would have hit the active port-city of Ostia during the Roman period. In contrast,
84 none of these deposits were interpreted such as tsunami by the other team (Goiran et al., 2012,
85 2014, 2017; Sadori et al., 2016; Pepe et al., 2016; Salomon et al., 2016, 2017, 2018; Delile et
86 al., 2017, 2018).

87 For this reason, it seems crucial to test these palaeotsunami hypotheses by focusing on
88 all pluridisciplinary data available at the mouth of the Tiber River. This paper reviews
89 sedimentological, geomorphological, micropalaeontological, geochemical, archaeological,
90 chronological, and historical accounts that were gathered these last years on the study area.
91 This study is based on (i) a re-examination of evidence published in Hadler et al. (2015 and
92 2020) and Vött et al. (2020), together with other palaeoenvironmental data from other cores
93 drilled in the area (Goiran et al., 2014; Sadori et al., 2016; Salomon et al., 2016, 2017; Delile
94 et al., 2017, 2018), (ii) a discussion of a complementary approach using lead (Pb)
95 concentrations as a reliable exclusion indicator of the extreme wave event hypothesis, and (iii)
96 a critical comment on the chronology proposed by Hadler et al. (2015, 2020) and Wunderlich
97 et al. (2018), based on radiocarbon dates. Finally, this work highlights pitfalls that should be
98 avoided while identifying palaeotsunami deposits in fluvio-coastal environments, including
99 ancient harbours.

2. Sedimentary features

Usually, the first evidence suggesting a palaeotsunami deposit within a stratigraphy is the presence of a coarse-grained layer trapped in finer deposits, which are separated by a basal erosional surface at the base of the palaeotsunami deposit (Dawson et al., 1988 ; Morton et al., 2007 ; Engel and Brückner, 2011 ; Shanmugam, 2012 ; Rubin et al., 2017 ; Rübke and Vött, 2017). Ideally, low energy palaeoenvironments such as lagoons, coastal freshwater lakes, and mangroves, are the most appropriate places in which to identify palaeotsunamis deposits. In such contexts, HEEs are expressed by a short-time disturbance in the ambient low-energy milieu. Theoretically, if the protected palaeoenvironment is away from direct fluvial or coastal influence, it limits the number of natural processes that are able to settle into distinct coarse layers. A compilation of different sedimentological signatures (presence of rip-up clasts, fining upward sequence, mud cap, reworked underlying sediment, basal load structure), together with palaeoenvironmental indicators (palaeoecological markers, geochemical signatures) have to be considered before suggesting any interpretations. All of this evidence will be reviewed in this paper.

The first high-energy event (HEE-1) identified by Hadler et al. (2015) was observed in a pre-harbour deposit around 6 m below sea level (b.s.l.) (6.36 to 5.61 m b.s.l.) in Core OST-3 (HEE-1 - Fig. 2 and Table 1). The environmental context (shallow marine environment with fluvial influence, shoreface) is dated to at least to the 9th - 8th c. BC in Core OST-1 at 8.81m b.s.l. and before the 4th c. BC (oldest radiocarbon dates for the establishment of the harbour of Ostia). A coarse-grain layer is observed in Core OST-3, together with a basal erosional surface, a fining upward sequence with a mud cap, rip-up clasts, and gravels (Table 1). For this first event, all sedimentological indicators observed could support the tsunami hypothesis, but do not exclude flood or storm hypotheses. Along with Goiran et al. (2012, 2014) and Sadori et al. (2016), we insist on the depositional context. All research teams agreed on the

existence of a shallow marine / shoreface environment with fluvial influence from the river mouth near Ostia in this area at the beginning of the 1st millennium BC (Goiran et al., 2014; Hadler et al., 2015; Sadori et al., 2016; Delile et al., 2018; Salomon et al., 2018). The Tiber delta is a wave-dominated delta. However, at the scale of the river mouth, the promontory alternate between river and wave dominated morphologies. River mouth environments are known to be fast changing environments. River mouth bars form and change regularly. Sandy shoreface morphologies close to a river mouth are highly mobile and constantly exposed to floods and storms. Additionally, it has been demonstrated that the Tiber River mouth was particularly dynamic during the first part of the 1st millennium BC: quick progradation shaping a large promontory and river channel migrating toward the south (Bellotti et al., 2011; Milli et al., 2013; Delile et al., 2018; Salomon et al., 2018; Salomon, 2020).

Hadler et al. (2015) hypothesise that “fluvial sediments were dislocated by a high-energy event within a near-shore deltaic marine environment”, and attest to the difficulty in identifying the fluvial and coastal balance in such environments. Since the sedimentological signature of this deposit could also be attributed to a fluvial or a storm event, we suggest leaving all interpretations open to the origin of this HEE-1. No sedimentological evidence alone should definitively proves a paleo-tsunami signature. Alternatively, we would suggest that the layer identified could be related to through/bar deposits near the palaeoriver mouth of the Tiber River (Salomon, 2013, 2020). Deposits similar to HEE-1 can be identified in almost all cores drilled between Ostia and Fiumicino in depths ranging between 4 to 9 m below the current sea level and related to different progradational phases (Salomon, 2013). These layers offer badly sorted silty sand with some little gravels, cross-bedded structure often trapping organic layers, and the D50 is systematically finer than 200 µm below this layer and coarser than 200 µm above the same layer. Current D50 distribution along the coasts of the Tiber delta demonstrates similar grain-size pattern associated to the lower, middle (breaker zone,

longshore bars), and upper shoreface (Noli et al. 1996; Tortora, 1999; Tentori et al., 2018). In this interpretation, several events, several seasons and longer-term evolution would have occurred to form HEE-1 layer involving fluvial inputs (floods) and coastal reworking (mainly littoral drift and storms). Afterward the progradation of the Tiber River mouth definitely trapped these reworked shoreface deposits. A tsunami could have happened, but its imprint would not be properly distinguishable amongst other processes involved in the marine side of the palaeo-river mouth.

In the harbour of Ostia, three coarse sandy layers were assigned to palaeotsunami events: HEE-2 (3.28-3.05 m b.s.l.), HEE-3 (1.45-0.12 m b.s.l.), and HEE-7 (0.65-0.15 m b.s.l.) (see Fig. 2 for Core OST-3; complementary information from Core PO-2 in the Fig. 3 in which the gray bands refers to the high siliciclastic inputs associated to the palaeotsunami events HEE-1, HEE-3 and HEE-7; and Table 1). Generally, enclosed harbour environments are good traps for palaeotsunami deposits. HEE-2 and -3 layers clearly expose a change in the facies with increasing grain-size, the presence of basal unconformities, and rip up clasts, but no clear mud caps. However, no specific grain-size grading is observed. Unfortunately, in the light of the above mentioned, we cannot definitively exclude marine strong storms and fluvial major floods as potential sources of these coarse layers, since these processes could imply sedimentological characteristics similar to tsunamites. In our opinion, the hypothesis of a storm reaching the harbour cannot be totally excluded considering current strong storms (Noli et al., 1996), and the geography of Ostia during the Roman period. According to the palaeogeographical reconstructions, the mouth of the Tiber River was ca. 200 m to the northwest and the coastline ca. 200m to the south in the second part of the 1st millennium BC and the beginning of the 1st millennium AD (Salomon et al., 2018) (Fig. 1).

The HEE-7 layer is located in the area of the ancient harbour of Ostia, in a chamber of the shipshed (or navalia-temple complex) with pillars built in the 2nd c. AD (Vött et al. 2020;

Heinzelmann, 2020). HEE-7 layer (Fig. 4 and Table 1) demonstrates a change in the facies with a normal grading. However, the absence of a basal erosional surface and rip up clasts, and no clear mud caps do not argue in favour of a palaeotsunami deposit. This sandy deposit is located within the range of the relative ancient sea levels identified in Ostia and Portus (Goiran et al. 2009; Heinzelmann, 2020). The context and the facies of the sediment could suggest a deposit related to a sandy riverbank of the Tiber close to the river mouth and semi-sheltered in the shipshed building.

The harbour basin of Ostia was located close to the river mouth. Consequently, the action of fluvial and marine processes makes the identification of tsunami deposits more complex.

Finally, three deposits were considered most likely from palaeotsunami origin in the palaeomeander of Ostia – HEE-4/5 in Core TEV-4A and HEE-6 in Core TEV-1A (Hadler et al., 2020) (Figs. 5 and 6, and Table 1). The precise depths of the HEEs are not reported in the original publication, but their estimates were reported in the figures 5 and 6. Again in this context, no clear sedimentological evidence supports the tsunami hypothesis. All of the HEE deposits observed in Core TEV-4A were identified during the period of activity of the palaeochannel. In such environments, the preservation of tsunami deposits is poor due to high post-depositional disturbances derived from fluvial processes. In this respect, an active riverbed is regularly re-shaped according to events (floods), or season (flood period). Additionally, based on the data provided by Hadler et al. (2020), there are no changes in the facies, no basal erosional surface, no visible rip-up clasts, no normal grading and no mud cap. In this highly dynamic fluvial dynamic environment, grain-size is considerably changing and no clear event can be identified for palaeotsunami deposits (Figs. 5 and 6, and Table 1).

The high-energy event identified in Core TEV-1A (HEE-6) was dated to a later period (Table 1), and trapped in floodplain deposits on top of the infilled palaeochannel formed after the cut-off started in 1557. It is a better context in which to look for tsunamites. However, Hadler et al. (2020) do not describe any sedimentological marker suggesting a palaeotsunami deposit. Grain-size change seems progressive more than abrupt, and the facies is rather homogeneous. Based on these observations, we would interpret the progressive increase and decrease of the grain-size, such as a manifestation of a period of higher flood activity.

In general, the facies of the three high-energy events identified in the palaeochannel of Ostia are similar to their depositional context (see photos in Figs. 4 and 5 from Hadler et al., 2020). The identification of the HEEs is based on single analysed samples (TEV4A/11 for HEE-4; TEV4A/4 for HEE-5; and Sample TEV1/9 for HEE-6) and rely mainly on foraminifers.

To conclude this part on sedimentological evidence, storms or floods along with palaeotsunami origins should still be considered as valid hypotheses for the deposits identified in the harbour of Ostia (HEE-2, -3 and -7) and in the 1st millennium BC shoreface close to the palaeoriver mouth (HEE-1) (Hadler et al., 2015). However, the sedimentary facies of HEE-3 is similar to a fluvial bedload-derived deposit identified in the palaeomeander of Ostia (Salomon et al., 2017) and the canals of Portus (Salomon et al., 2014).

In the palaeomeander of Ostia, no sedimentological evidence supports the hypothesis of a palaeotsunami (Hadler et al., 2020). Complementary indicators are discussed here below.

3. Geomorphological features

One of the most used geomorphological fingerprints of tsunamites in the literature concern the fining-landward sequence (e.g., Goff et al., 2001 ; Paris et al., 2007 ; Engel and

Brückner, 2011 ; Röbbke and Vött, 2017), and the great spatial distribution of these deposits (e.g., Morton et al., 2007; Pignatelli et al., 2009; Marriner et al., 2017).

We should first observe that the distribution of the sedimentary cores is not appropriate to look at this evidence, especially in an urbanised river mouth such as Ostia. The diversity in the palaeoenvironments and the complexity of the topography in a city would clearly affect the distribution of the deposits and their preservation. As a result, thickness correlations between the HEEs identified in the harbour of Ostia and the palaeochannel of Ostia would be hazardous, since there are completely different depositional contexts.

In accordance with Hadler et al. (2015), only HEE-3 deposit will be discussed in this section (Fig. 2 and 3): the upper thick high-energy event deposit was recorded in the whole harbour of Ostia by all research teams. In contrast, HEE-2 trapped in the harbour (e.g., observed in Core PO-1 and OST-3, but not in PO-2 and OST-5, OST-8) was not observed in all the cores.

HEE-7 is for now only restricted to the area of the shipshed chambers. According to Vött et al. (2020) “this event is interpreted as a tsunami that hit the wider coastal region”. However, for now, Tyrrhenian coasts do not provide any evidence of the spatial expansion of this youngest tsunamite recorded into the harbour basin.

In the harbour of Ostia, while it was argued that the “thinning landward and uphill” criterion is fulfilled for the HEE-3 deposit recorded at Ostia, the NW-SE oriented-cross-section provided by Hadler et al. (2015) is roughly perpendicular to the Tiber palaeochannel and toward uphill, but not perpendicular to the coastline (Fig. 1). The first cross-section displays cores OST 8, 3, 5 and 4 with an associated-event HEE-3 thickness of about ~ 1.5 m, 1.5 m, 2 m and 1.5 m, respectively. These values are therefore indicative of a regular thickness of the high-energy event deposit, but do not express a landward fining sequence.

Thickness of the layers would have made sense in a wider spatial context with more regular topography.

4. Micro-faunal features

The hypothesis of the occurrence of seven tsunamis deposits at Ostia is mainly supported by the foraminifera contents in Hadler et al. (2015, 2020) and Vött et al. (2020), which are known to contribute to the identification of such events (Hawkes et al., 2007). However, bioindicators should be interpreted carefully since there is no absolute evidence using foraminifers that attests to tsunami origin of deposits (Mamo et al., 2009).

Considerations reported here are based on the data provided by Hadler et al. (2015, 2020) and Vött et al. (2020). In Figures 2, 4, 5 and 6, only few parameters related to foraminifers are reported. For the full tables of foraminifers, we refer to the original publications.

4.1. Indigenous and autochthonous foraminifers at the mouth of the Tiber River

The clear attribution of a coarse deposit to a tsunami using foraminifers usually needs the presence of deep water assemblages (pelagic and/or benthic species and/or deep water species) in coastal environments (shallow water, brackish) and/or, to a lesser extent, a sudden change in the assemblage, and a higher species diversity (Dawson et al., 1995; Hindson and Andrade, 1999; Hindson et al., 1996, 1998; Hawkes et al., 2007; Mamo et al., 2009). For the Tiber delta, this would be finding offshore foraminifers assemblages (Di Bella et al., 2013) in the coastal area. Additionally, taphonomic characters, breakage of tests, nature and importance of the abrasion should be considered.

According to the synthesis produced by Mamo et al. (2009), “it seems to be easier to distinguish displaced ”open” or “fully marine” assemblages within a marsh setting than it is to

distinguish a displaced marine assemblage in an estuarine or lagoonal setting”. Considering the palaeoriver mouth of Ostia, the depositional contexts (shoreface, harbour and river channel all close to the palaeo-river mouth of the Tiber) are definitely not ideal to identify a clear assemblage suggesting a tsunami (Table 1).

In its lower reach, the Tiber River built a delta with accumulation of fluvial sediments partially reworked by the sea (Bellotti et al., 2007; Milli et al., 2013). However, the river mouth channels offers an ecological context similar to estuaries (Mikhailova et al., 1999; Capelli and Mazza, 2008; Manca et al., 2014). A salt water wedge forms seasonally in the delta and the maximum of sea water intrusion can penetrate at least ca. 9 km inland (Mikhailova et al., 1999). The Tiber delta is formed in a microtidal area, and the more probable cause of salt wedge intrusion might be the wind action (Manca et al., 2014).

Consequently, *autochthonous foraminifers* can develop within the lower course of the Tiber River similarly to other estuarine environments (Wang, 1992; Wang and Chappell, 2001; Ruiz et al., 2005). This estuarine context can explain the presence of marine foraminifers in a good state of preservation recorded within the ancient harbour of Ostia or in the palaeochannel (see below).

Additionally, in accordance with Hadler et al. (2015), it should also be reminded that *allochthonous foraminifers* can derive from the erosion of recent or much older deposits. *Globigerinoidae* are the most represented in the core OST-3 (harbour of Ostia), and “most likely derives from the local bedrock within the hinterland of the Tiber River (Bellotti et al., 2007)” (Hadler et al. 2015).

4.2. Estuarine environments observed in the palaeoriver mouth

In Core OST-3, the most obvious change of assemblage occurs from the pre-harbour to the harbour environment. Pre-harbour shoreface / river mouth deposits display a large range of foraminifers developing in marine to shallow marine environments in important quantities (Fig. 2). Except for the allochthonous planktonic foraminifers, *Ammonia beccarii*, *Cassidulina* spp., *Nonion* sp., *Ammonia tepida* and *Trioculina* sp. are the most frequent taxa. In contrast, less species and less quantities of foraminifers are recorded in the harbour deposits (Fig. 2). *Ammonia beccarii*, *Cassidulina* sp., and *Bolivina* sp. are the most represented taxa in the harbour. Interestingly, between the river mouth shoreface environments and the harbour of Ostia, the diversity of foraminiferal species decreases, but most of the species in the harbour are also present in the pre-harbour deposit. Only *Adelosina* sp. and *Eponides* sp. are observed in the harbour, but their quantity is not representative. Accompanying taxa of *Ammonia tepida* and *Trioculina* sp. seem to characterise more the shoreface / river mouth environment in OST-3, while *Bolivina* sp. is more present in the harbour. However, *Ammonia* sp. and especially *Ammonia beccarii* are highly represented in all the stratigraphies studied. The fluvio-coastal stratigraphy from Core OST-7A is only of 2 m (Vött et al., 2020) (Fig. 4) and it should have been compared with other cores. HEE-7 (Units VII and VIII in Core OST-7A in Vött et al., 2020) demonstrates a clear increase in the quantity and the diversity of foraminifers. However, there is no clear shift of the assemblage. *Ammonia* sp. is still highly represented along with *Cassidulina* sp., *Cibicidoides* sp., *Bulimina* sp., *Nonion* sp., but also *Haynesina* sp. This layer can be related to another variation of the estuarine environments of the Tiber River mouth.

The foraminiferal assemblage of the palaeomeander of Ostia (Cores TEV-4A and TEV-1A) (Figs. 4 and 5) is largely similar to the ones observed on the shoreface / river mouth and the harbour. *Ammonia beccarii*, *Cibicidoides pseudoungerinus* (*Cibicidoides pseudoungeriana*?), *Cassidulina* spp. are the most represented (again excepting reworked

Globigerinoidae). *Cibicidoides pseudoungerinus* are more representative in the depositional environment of the palaeochannel, but *Cibicidoides* sp. were largely observed in the coastal river mouth environments in Core OST-3 and in HEE-3 trapped in the harbour of Ostia. Accompanying taxa such as *Melonis barleeaanum*, *Pullenia* spp., *Bulimina* spp., *Cibicides refuigens*, *Quinqueloculina seminula* are also more specific of the palaeochannel environments.

Diversity between foraminifer assemblages expresses different estuarine conditions. The different assemblages observed at the mouth of the Tiber River display some differences but overall, all ecological contexts are related to estuarine environments. Except allochthonous foraminifers, *Ammonia* sp. / *Ammonia beccarii* are the dominant taxa/species observed in all depositional contexts, and are characteristic of estuarine environments (Wang, 1992; Wang and Chappell, 2001; Ruiz et al., 2005; Di Bella et al., 2011). The common presence of *Haynesina* sp. (characteristic of brackish environments) in all environments suggest the same conclusion. It confirms that the coastal river mouth, the harbour, and the palaeochannel of Ostia all express fluctuations of the estuarine environments of the Tiber River (Fig. 2, 4 and 5).

4.3. What are the foraminiferal characteristics of the high-energy events?

In our opinion, for each of these high-energy layers identified around Ostia, the foraminifers never display deep water assemblage inputs and/or sudden displaced assemblages suggesting a palaeotsunami deposit. Also, no discriminant species specifically characterise the seven high-energy events from their context.

HEE-1 in Core OST-3 demonstrates a sharp quantitative change expressed by a lower quantity of foraminifers on the shoreface / river mouth (Fig. 2). The diversity of species is very low considering each three samples picked in the HEE-1 by Hadler et al. (2015) (11 to

15 species). However, no distinct assemblage characterises HEE-1 (Fig. 2). In consequence, these evidence could support the hypothesis of fluvial sediments reworked by coastal processes (Hadler et al. 2015), and the hypothesis of a river mouth to coastal trough/bar context (Salomon, 2013). However, we consider that a distinct deposit attributed to a single flood, a single storm or a potential tsunami would be unlikely (Table 1).

The pattern is different for the two upper high-energy events (HEE-2 and 3) recorded in the harbour (Fig. 2). A rise in quantity and diversity comparing to the average harbour environments (HEE-2 = 16; HEE-3 = 18) can be observed. However, the assemblage is not distinct from the other estuarine environments of the area of Ostia – *Ammonia sp.* or *Ammonia beccarii* are still dominant and accompanied with *Cassidulina sp.* Additionally, the quantity of foraminifers never reaches abundant quantities (except allochthonous planktonic taxa) (according to the semi-quantitative data from Hadler et al. 2015). It should be noted that between HEE-2 and 3, two samples in Units IVb display the presence of 15 different species recorded in silt and clay deposits, also with a similar assemblage (Hadler et al. 2015). Since there are no coarser sediment, there are not a high-energy events. Few to common quantities are also observed, similar to HEE-2 and 3 (Hadler et al. 2015). Again, in our opinion, this demonstrates the complexity of the estuarine environments affected by the salt water wedge.

A shift in quantity and diversity is observed in HEE-7 in regards to the 2-meter stratigraphy from Core OST-7A (Fig. 4), but with no specific assemblage considering all cores (OST-3, TEV-1A, TEV-4A). According to Vött et al. (2020), species and taxa of “*Ammonia beccarii*, *Neoconorbina sp.*, *Nodosaria sp.*, *Nonion sp.*, *Rosalina sp.*, *Valvulineria sp.*” (error - *Valvulineria sp.*?) seems to be almost exclusively found in HEE-7. However, similar foraminifers are found also in important proportions in the lower part of Core OST-7A (abundant and dominating *Cassidulina sp.*, *Ammonia sp.*, *Nonion sp.*). Additionally, these taxa and species are also found in other estuarine environments in cores OST-3, TEV-4A, and

TEV-1A. *Neoconorbina* sp., *Nodosaria* sp. are present but remain low in all samples analysed in these cores including in HEE-7. *Rosalina* sp. seems to be the only outlier of HEE-7 in the context of all the cores analysed in the Tiber River mouth. However, it is not sufficient to define a shift in the assemblage. Since HEE-7 is located close to the Roman relative sea levels (Goiran et al. 2009 or Heinzelmann, 2020), we suggest to consider floating and swashing on the riverbank such as important factors that would have enriched this unit in foraminifers. These hypotheses should be tested.

In Core TEV-4A, HEE-4 and HEE-5 do not display the most species diversity of foraminifers nor the lowest (Fig. 6) (Hadler et al., 2020). Additionally, changes related to foraminifers are rather progressive and do not demonstrate abrupt events. Surprisingly, fluvial deposits (even in bedload-derived deposits) trapped many foraminifers of different species in the stratigraphies. Even more surprising, after Hadler et al. (2020), these foraminifers are in a good state of preservation. This suggests that in the lower reach of the Tiber River the presence of foraminifers in coarse sediment is not a good indicator for distinguishing marine or fluvial high-energy events.

Again, in Core TEV-4A, there is no assemblage of foraminifers specific to the suggested high-energy events compared to the depositional environments of the palaeochannel of Ostia. The most represented taxa are *Ammonia Beccarii*, *Cassidulina* spp., *Cibicidoides pseudoungerinus* (except allochthonous taxa) accompanied by *Melonis barleeanum*, *Pullenia* spp., *Bulimina* spp., *Cibicides refuigens*, *Quinqueloculina seminula* (Hadler et al., 2020). They are also the most common within the full sequence of Core TEV-4A (Fig. 6). In our opinion, the intrusion of the salt wedge controls the developments of foraminifers within the channel (see above).

Interestingly, Hadler et al. (2020) observe “some juvenile articulated specimens of the marine bivalve *Lentidium mediterraneum*” and “(articulated) brackish ostracods” in Sample

TEV 4A/11, i.e., in the sample interpreted such as the HEE-4. They suggest that it is “associated with shallow water and frequently occurring in sandy estuarine environments” (Hadler et al., 2020), which corroborate the estuarine interpretation of these foraminifers (Wang, 1992; Wang and Chappell, 2001; Ruiz et al., 2005). In this regards, Hadler et al. (2020) observe “the foraminiferal content of deposits from high-energy environments frequently decreases with increasing grain size and is mostly restricted to few large, abraded individuals, clearly reflecting assemblages disturbed by strong flow dynamics”. This remark matches the hypothesis of autochthonous foraminifers developed within the river channel when energy is lower. Combining the foraminiferal data (no specific assemblage, no specific increase or decrease in quantity) and the sedimentological data (“macroscopically no changes were observed for the respective events” - Hadler et al., 2020, - with no particular grain-size coarsening) (Table 1), identifying tsunami or storm deposits in the active river channel in Ostia seems unlikely.

Finally, the influence of the salt wedge cannot affect Core TEV-1A / Unit D (Fig. 5) since the depositional context might have been already disconnected from the river and the sea when the HEE-6 occurred. In TEV-1A, Unit D is interpreted as a floodplain deposit. Considering (i) the homogeneity of the facies of Unit D, (ii) the gradual increase and decrease of grain-size in Unit D, (iii) the presence of *Cassidulina* spp., *Cibicidoides pseudoungerinus*, *Ammonia Beccarii* also dominant in TEV-4A (estuarine markers), and (iv) the occurrence of all these foraminifers in Unit D (common to very common), we would interpret Unit D such as an increase/decrease of flood activity during the last centuries with a peak in HEE-6 (Table 1). In this scenario, well preserved foraminifers would have been transported by floods. Since we observe a certain amount of foraminifers (common) in all floodplain deposits analysed in Unit D, this hypothesis is not impossible. However, it should be explored in more details.

4.4. Conclusive remarks about the foraminifers at the mouth of the palaeo-Tiber River

The reinterpretation of the foraminiferal data provided in Hadler et al. 2015 and 2020 and in Vött et al. (2020) suggests no clear evidence for a single marine HEE such as a tsunami around Ostia. This reinterpretation applies to a major tsunami, which should have been clearly marked by the foraminiferal assemblage, and to a minor tsunami, which is even more difficult to track in estuarine environments. In our opinion, all the cores (OST-3, OST-7A, TEV-4A, TEV-1A) display different expressions of the estuarine environment. The development of autochthonous foraminifers in the river mouth environments of the Tiber, their reworking and transport during floods, and the floating and the swashing of some species on the riverbanks should be considered seriously and tested. More precise species identification of foraminifers would help to better characterise the depositional environments and interpret the HEE identified. Additionally, statistical treatments would be helpful to bring more information about the foraminiferal assemblages and the depositional contexts - freshwater influence, organic matter content (like in the publication of Di Bella et al. (2011) for the harbour of Portus located a few kilometers in the north).

Determination of fluvial / marine origins of the HEE deposits should also be tested against geochemical evidence.

5. Geochemical evidence

As reported by the number of publications related to tsunami and chemistry since 2005 (Chagué-Goff et al., 2017), the use of geochemical proxies in the tsunami research field has evolved exponentially over the past few years. This trend is explained both by recent devastating tsunamis (e.g., 2004 Indian Ocean Tsunami (2004 IOT), 2011 Tohoku-oki Tsunami (2011 TOT), and 2018 Palu Tsunami), and by the increasingly recognized value of this powerful tool for the identification of historical and/or prehistorical deposits (Chagué-

Goff et al., 2017; Rübke and Vött, 2017). In this section, we will explain how elemental geochemistry and Pb isotopes in sediments provide substantial value in the debate related to the record or absence of multiple palaeotsunami deposits in the ancient harbour basin of Ostia.

5.1. Elementary geochemistry

Recently, the elemental geochemistry of siliciclastic deposits of Ostia's harbour basin has been documented by measuring the concentrations of 39 chemical elements on 86 samples regularly distributed in the harbour stratigraphy. In order to explore the thousands of data, a Factor Analysis was performed, which is a statistical treatment consisting of converting data into uncorrelated and limited variables known as factors (Fig. 3) (Delile et al., 2018). This approach combining geochemistry and statistics was recently discussed to identify tsunami deposits based on specifically saltwater inputs indicators (Chagué-Goff et al., 2017). Amongst them, Na is considered a sensitive chemical proxy to identify palaeotsunami deposits (Shanmugam, 2012 ; Chagué-Goff et al., 2017; Rübke and Vött, 2017).

The results obtained by the mean of this method at Ostia (Fig. 3) identifies environmental factors leading to the formation of the harbour basin deposits. In order of importance these factors are (in %) (Delile et al., 2018): (i) the velocity of currents (the siliciclastic terrigenous signal ~ 47%), (ii) the low hydrodynamics conditions (the aluminosilicates signal ~ 13%), (iii) the harbour water column ventilation (the authigenic fluxes ~ 10%), (iv) the seawater vs. freshwater influence (~ 7%). Factors 1 and 4 are particularly relevant to recognize palaeotsunamis deposits because they trace the ambient hydrodynamics and the river/marine origin of the currents, respectively. The red bands in Figure 3B (Units A, B2 and C) indicate the sedimentary deposits interpreted as tsunamis-related HEE-1 and 3 by Hadler et al. (2015).

Negative values of F1 (in blue) in Figure 3B confirm strong currents involved in HEE-1 and 3, but not in HEE-2 (positive values of F1 in red). For HEE-1 recorded in the upper part of Unit A, the marine origin of the water is demonstrated by the positive values (in red) of F4 (Fig. 3B), which is used to support a tsunamigenic origin (or strong storm) in this unit. However, the dramatic oxygen depletion (tsunami or storm events imply well oxygenated water column) (see negative values in blue of F3 in Fig. 3B), and the over-representation of estuarine lagoonal ostracod groups (Goiran et al., 2014 ; Sadori et al., 2016; Delile et al., 2018) do not support the tsunamigenic hypothesis. Unit A displays all characteristics of a classic pre-harbour deposit typical of a deltaic front sequence, which is widely documented at the scales of the site itself, as well as 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., 2014 ; Delile et al., 2014a,b, 2018 ; Sadori et al., 2016).

The second coarse Unit B2 of Core PO-2 corresponds to the HEE-3 inferred from the study of Hadler et al. (2015). The Factor Analysis of the geochemical signal suggests strong currents (see negative values in blue of F1) from fluvial origin (see negative values in blue of F4) (Fig. 3B). This freshwater signal in the harbour basin is the strongest recorded in the stratigraphy. Unit B2 records the peak of a dynamic initiated in Unit B1a (Fig. 3B). This gradual and continuous regression of seawater in favor of freshwater influence recorded in the harbour stratigraphy is visible with Factor 4 (Fig. 3B).

5.2. Trace metal palaeopollutions: a powerful tool to identify palaeotsunami deposits

5.2.1. Conceptual model of the trace metal palaeopollutions recorded before, during, and after a palaeotsunami into the sedimentary archives of ancient harbour basins

According to Hadler et al. (2013), allochthonous materials composing of tsunamigenic deposits are “characterized by decreased lead concentrations”. Processes associated with this

view are described below and illustrated in Figure 8 through a simple conceptual model that can only be applied to older periods.

Stage 1: Pre-harbour environment

Under coastal pre-harbour conditions (i.e., before the development of port infrastructures associated with the foundation and development of ancient port-cities or activities dealing with lead) no anthropogenic metal excesses are recorded in marine sediments. They can be considered uncontaminated.

Stage 2: Functional enclosed harbour environment

The development of port-cities and harbour infrastructures thoroughly change the prevailing natural coastline landscape. The decreasing water current velocity induced from the enclosed harbour basin results in lower hydrodynamism that modify in turn the depositional and transport processes of sediments, as well as the geochemical content.. Consequently, finer sediment with higher organic content starts to settle (Fig. 8). During this stage, particle-bound trace metal elements released from urban areas reach the closest urban hydrographic network and, then, reach the harbour basin water column through flows, channels, and canals. In contact with sea water, metallic cations are formed from organo-mineral aggregates (transported on the suspended particulate matter from the river) with the flocculants ions Ca^{2+} and Na^+ from a marine environment. As a result, they massively precipitate at the bottom of the harbour basin. This mixing of fresh and salty waters leads to increase concentrations of trace metal elements into the harbour sediments. In contrast, offshore deposits during ancient periods are uncontaminated due to a significant and fast dilution effect from the uncontaminated open sea water (Fig. 8).

Stage 3: Enclosed harbour environment disturbed by a tsunami inundation

The tsunami waves trigger the erosion and resuspension of the offshore sediments, which are transported inland and deposited into the harbour basin in the form of an

allochthonous coarse layer devoided of anthropogenic metals excesses. The re-suspended sediments from the inner shelf do not contain anthropogenic Pb excesses (“clean” sediments) because it includes sediments deposited prior to the Late Modern Period (post AD 1750) widespread contamination of the seabed (as it is the case during the stage of the pre-harbour environment). At the same time, the landward seawater inundation prevents the river reaching the sea, increasing the intensity of flooding inland, and canceling any chance for heavy metals to be deposited in the harbour basins. Consequently, the allochthonous coarse layers set up by palaeotsunamis in the harbour deposits are characterized by lead concentration levels (also valid for other heavy metals) similar to those of the local environmental Pb background. In all likelihood, the presence of Pb palaeopollutions (anthropogenic Pb excesses) in these coarse deposits definitively dismisses the tsunamigenic hypothesis.

Stage 4: Return to a functional harbour environment

Once the extreme event is past and stable environmental conditions have been restored, the palaeotsunami deposit is fossilized under a new generation of harbour muds enriched in anthropogenic metal excesses. Stratigraphically, the palaeotsunami deposits trapped into the ancient harbour basins are characterized by a sharp geochemical hiatus.

5.2.2. The example of the ancient harbour basin of Ostia

In Figure 3A, Factor 4 indicates the freshwater inflows in the harbour of Ostia (symbolized by negative values) are correlated with metallic pollutants clusters (Pb, Cd, Sn). This specific geochemical fingerprint of the ancient urban waters has been also found in the infilling of the ancient harbour basins of *Portus* (Delile et al., 2014a) testifying its wide coastal extension throughout the Tiber River delta. Their origin has been demonstrated as coming from upstream and related to activities happening in watershed of the Tiber River, including Rome (Delile, 2014 ; Delile et al., 2014b, 2017, 2018). More specifically, Delile et

al. (2017) have shown that the direct source of lead contamination trapped in the harbour sediments was solely from the lead pipe system used upstream in the water supply network of Rome and Ostia. Delile et al. (2017) also identified that uncontaminated seawater had diluted contaminated river water. In other words, the Tiber's freshwater transported the upstream originated Pb excesses towards its outlets, including the riverine-coastal harbour basins (Ostia and *Portus*) (Fig. 3B). Downstream uncontaminated marine water inflows diluted the contaminated harbour water columns (Delile et al., 2017, 2018). This process is consistent with the conceptual model described above (Fig. 8). As evidenced by Delile et al. (2017), this marine dilution effect (e.g., Muller and Förstner, 1974) leading to depleted heavy metal concentrations in sediments also concerns “the local coastal environment” of the “Tiber delta deposits” (Hadler et al., 2019), which were likely reworked by smaller high-energy events. For example, in the former Bay of Utica in Tunisia, in which the Medjerda delta was built, based on two deep-sediment cores transects taken towards the ancient offshore environment (Medjerda delta deposits), Delile et al. (2019) observed within 3 km from the outlet, anthropogenic lead (Pb) excesses released into the ancient marine environment are no longer perceptible. Even in the case of a smaller high-energy marine event, a tsunamigenic source of the HEE-3 deposit should be characterized by the lack of Pb excesses in sediments. Clearly, this is not the case (Fig. 3B).

Recently, Kolaiti et al. (2017) refuted also the hypotheses of palaeotsunamis deposits proposed by Hadler et al. (2013) based on the high Pb contents recorded in the HEE layers trapped in the sedimentary archives of the Lechaion's ancient harbour basin (ancient Corinth, Greece). Delile et al. (2017) reported that the sedimentary profile of Pb palaeopollution recorded in Unit B2, which is suspected by Hadler et al. (2015) and Wunderlich et al. (2018) to have been deposited by the tsunami HEE-3, “does not fluctuate randomly but displays robust peaks and troughs” (see the curve of the proportion of Pb palaeopollution in Fig. 3B).

For all of these reasons, the highly contaminated coarse Unit B2 cannot have been formed by a tsunami event, but instead from increasing fluvial inputs.

6. Inconsistencies in the dating of the tsunamis-related HEEs deposits trapped in the harbour basin infilling

In this review, we paid particular attention to the radiocarbon and archaeological dates provided by Hadler et al (2015) and Vött et al. (2020). The most important information deduced from radiocarbon dates in palaeotsunami research to strengthen the recognition of tsunamites is the presence of significant chronological inversions inside the high-energy layers (e.g., Nigam and Chaturvedi, 2006 ; Mamo et al., 2009 ; Engel and Brückner, 2011 ; Goiran, 2012; Ishizawa et al., 2020). Strong tsunami deposits are likely to incorporate older organic material dated back to several millennia due to their remobilization induced by erosion of deeper offshore deposits during storm/tsunami events. Figure 7 is a graphical representation of all dates used by Hadler et al. (2015) and Vött et al. (2020) in 2-sigma calibration demonstrating the chronology of the palaeotsunamis history at Ostia. No major inversion can be observed, which does not support the hypothesis of a strong tsunami recorded in the harbour.

During the process of this review, we identified inconsistencies in Hadler et al. (2015), between data from their Tables 1 and 2 and the stratigraphies provided in their Figure 7. The dates OST 8/15 PR at -1.74 a.s.l. and OST 8/16 PR at -1.92 a.s.l. comprised between the 10th and 13th c. AD are located in the HEE-3 layer (Fig. 7) reported in Figure 7 from Hadler et al. (2015). However, they are interpreted as a “fluvial deposit” in the interpretative Table 1 from Hadler et al. (2015). Similar errors could also have affected the date OST 2/14 PR 3.34 at -1.49 a.s.l. Despite the absence of a stratigraphic log for the core OST-2 in Hadler et al. (2015), its location halfway between the cores OST-8 (+1.81 m a.s.l.) and OST-3 (+2.29 m a.s.l.)

(only 45 meters between these two cores) suggests that the topographic level of the Core OST-2 is ~ +2 m a.s.l. This estimate of the topographic level of the Core OST-2 is confirmed by the difference between the depths of the date OST 2/14 PR expressed in meter a.s.l. (- 1.49 meter above present sea level) and m.b.s. (3.34 meter below ground surface), which is + 1.85 m a.s.l. Once these precautions are stated, we note that the date OST 2/14 PR (located at a depth of -1.49 m a.s.l.) between the 10th and 13th c. AD is also located into the center part of the HEE-3 layer (Fig. 7) rather than in the assumed upper fluvial deposits (located between +0.25 and -0.5 m a.s.l. into the core OST-8). The mere presence of these too recent dates in the suspected HEE-3 layer suggest that lateral erosion of the Tiber affected the abandoned Roman harbour of Ostia during the Medieval period (Salomon et al., 2016). On the basis of the Figure 7 we can easily read that the real ¹⁴C-based chronological range of the HEE-3 facies is ~ 2 millennia (linked to different periods of fluvial activity).

Errors are also observed between the photography of Core OST-8 in Figure 3 and its stratigraphy reported in Figure 7 from Hadler et al. (2015). The river harbour and fluvial deposits of Figure 7 should be lower according to the photography of OST-8, and it would replace half of the tsunamigenic deposit hypothesized in Figure 7 from Hadler et al. (2015). Even with this error, the two radiocarbon dates between the 10th and 13th c. AD still date part of the HEE-3 facies in OST-8 (Fig. 7) according to Table 2 in Hadler et al. (2015).

Such errors in OST-8 in the stratigraphy and the position of the radiocarbon dates bring confusion to the interpretations. Based on the photography of OST-8 from Figure 3 and Table 2 in Hadler et al. (2015), and the review of the palaeoenvironmental data available, we could hypothesise a lateral mobility of the Tiber between 10th and 13th c. AD (possibly part of HEE-3 facies) followed by fine deposition. However, lateral erosion of the Tiber River seems to not have affected cores PO-2 and PO-1 located more south (Goiran et al., 2014).

To conclude, we should also point out that the accurate date provided by Vött et al. (2020) of the tsunami-related HEE-7 deposit (“at or shortly after AD 355-363”) is based on an archaeological date (“Mf 21-2”) that were not obtained directly from the Core OST-7A but from an archaeological section (“sondage 21”) located 18 m far from the Core OST-7A. The chronostratigraphic correlation between the Core OST-7A and the archaeological section should be considered carefully especially if we interpret the HEE-7 such as a sandy riverbank deposit (see Fig. 12 in Vött et al., 2020).

7. Discussion: flood, storm or tsunami?

Based on palaeoenvironmental data, the previous parts of this paper demonstrate that there is no clear evidence of palaeotsunami deposits at the ancient mouth of the Tiber River. Multi-proxy analyses are the most important evidence to support any interpretation.

This section reviews the arguments developed in the discussions proposed by Hadler et al. (2015, 2020) and Vött et al. (2020) about flood, storm or tsunami origin of the HEE layers. We classified elements in their discussion linked to the hypotheses of flood, storm, and tsunami to interpret the high-energy events. We identified four topics of discussion: (1) frequency of events during the Roman period; (2) examples of events during the Roman period; (3) archaeological exposure and possible adjustment; and (4) modern period hazards. The potential factors controlling an eventual tsunami are developed in Hadler et al. (2015, 2020) and Vött et al. (2020). Hadler et al. (2015, 2020) refer to the study of Lorito et al. (2008) using tsunami-wave simulations to assign the Southern Tyrrhenian thrust belt, the Tell-Atlas thrust belt, and the western Hellenic arc as the potential source zones of earthquakes triggering long-distance tsunami waves (i.e., teletsunamis). Vött et al. (2020) suggest that the tsunami-induced HEE-7 event was possibly triggered by the AD 365 Crete earthquake. The second cause of tsunamis that authors referred is the volcanic activity in the surrounding area.

For instance, based on simulations of volcanic mass failures in the Bay of Naples (Ischia island), the tsunami-induced HEE-1 event could have been triggered by the eruption of the volcanic island of Ischia (Bay of Naples) prior to the 4th c. BC. One of the most famous example of volcano-induced tsunamis in this area concerns the extreme wave event originated from the 79 AD Vesuvius eruption that struck the Roman harbour of Naples (Delile et al., 2016), and was well described in the second letter of Pliny the Younger addressed to Tacitus (Pliny the Younger, VI, 20). Other processes could have triggered tsunami including aerial-subaqueous landslides. However, the Latium holds a low potential for tsunami generation in Italy (Tinti, 1991). As a result, the Latium coastline records a low number of tsunami events yet referenced (Alberico et al., 2018).

7.1. Frequency of flood, storm, and tsunami and sedimentary time series

Floods and storms are two very frequent hazards affecting the mouth of the Tiber River (Bellotti et al., 2007, 2018; Goiran et al., 2014; Delile et al., 2018; Salomon et al., 2018; Hadler et al., 2015, 2019). Tsunami events affect the shores of the Latium with much lower frequency (Tinti et al., 2004). One strong argument developed by Hadler et al. (2020) concerns the number of HEE identified. The authors consider that since storm events are very frequent and only 4 to 7 single HEE were observed in the palaeochannel and the harbour of Ostia over the last 3000 years, it implies that tsunamis with low frequency are best-fit statistics for these HEE (Hadler et al., 2020). However, we insist that the sediment traps considered at the mouth of the Tiber cannot provide a good *time series* for storms and tsunamis, and even flood events. During each flood, sediments in active channels are reworked by the river (environment of HEE-4 and 5). Similarly, waves and storms continuously transport sediment along the shore (environment of HEE-1). Regarding the harbour of Ostia, the stratigraphy records only a few centuries and dredging could have

affected the regular record of floods and storms (environment HEE-2 and 3) (Salomon et al., 2016; Goiran et al., 2017; Delile et al., 2018). Additionally, the large uncertainty ranges of radiocarbon dates during the second part of 1st millennium BC (Fig. 7) probably do not allow us to identify all dredging activities using hiatuses or inverted dates in the chronology. From such a perspective, the cut-off channel would be better to record a time series of floods and tsunamis (environment of HEE-6). However, in the 16th c. or later, the palaeochannel of Ostia (*Fiume Morto*) would have been too far from the coast to record any storm event.

Consequently, we suggest a discussion on HEE frequencies different to Hadler et al., 2020. Considering that the active channel and the shoreface close to the river mouth, there are not reliable sedimentary traps to provide a time series of HEE due to reworking. Additionally, the deposits in the active channel and the shoreface are mainly related to fluvial and coastal processes where single events are difficult to track. In sheltered harbours, single events are easier to identify. However, the quality of the time series of events depends on the recurrence if the dredgings.

Roman HEE-3 facies reinterpreted here such as a fluvial deposit occurred during a period known as a major hydro-sedimentary crisis, which increased the frequency of floods in several places of the Western Mediterranean between the 1st c. BC to the 2nd c. AD (Berger and Bravard, 2012), and especially in the Tiber River (Le Gall, 1953; Bersani and Bencivenga, 2001; Salomon, 2013 ; Delile et al., 2014a, 2018; Goiran et al., 2014). HEE-6 could express increasing flood frequencies during the Little Ice Age and especially from the end of the 17th c., end of the 18th c. or middle of the 19th c. documented for the Tiber River (Bersani and Bencivenga, 2001; Salomon, 2013).

7.2. Events occurring during the Roman period at the mouth of the Tiber River

Single events described by ancient authors are discussed in Hadler et al., 2015, regarding the harbour basins at the mouth of the Tiber River (Ostia and *Portus*). Two ancient texts are quoted, one related to the fluvial harbour of Ostia (Strabo, 5.3.5), the other to the marine Claudian harbour of *Portus* (Tacitus, 15.18.3).

One of the most significant quotation is the one of Strabo regarding Ostia, which fortunately matches the place (the harbour of Ostia) and the period (late 1st c. BC / beginning of the 1st c. AD) of the palaeoenvironmental evidence. Several scholars have translated his quote as follows: “[*Ostia*] is harbour less on account of the silting up which is caused by the Tiber” (Strabo 5.3.5 after Jones, 1923) or “*Ostia had the inability to maintain or consider a convenient sheltered harbour due to the amount of Tiber sediments transported down to the seashore*” (Strabo, 5.3.5 after P. Arnaud, in Goiran et al., 2014) or “*This city has no port, owing to the accumulation of the alluvial deposit brought down by the Tiber, which is swelled by numerous rivers*” (Strabo, 5.3.5 after Hamilton and Falconer, 1903). In our opinion, the reference to this text corroborates the quick sedimentation of silts in the harbour (Goiran et al., 2014; Hadler et al., 2015), but especially to the deposition of the fluvial bedload-derived deposit on top (HEE-3 - Figs. 2 and 3) (Goiran et al., 2014; Delile et al., 2018).

Although the quotation of Strabo (5.3.5) is more appropriate in discussing the interpretation of the sedimentary drilling of the harbour of Ostia, the storm described by Tacitus is widely discussed by Hadler et al., 2015 (“*some two hundred vessels [...] had been destroyed by a raging tempest*” in 62 AD - Tacitus, 15.18.3 after Jackson, 1937). This quotation does not match in space (Claudian harbour) and time (after the abandonment of the Ostia harbour) any of the HEEs identified in the harbour of Ostia. Additionally, the possibility of this AD 62 event was a tsunami is for now, only hypothetical. Finally, no evidence of the AD 62 deposit was found on top of HEE-3 in the area of the harbour of Ostia (OST-3) or in any other core.

719

720 **7.3. Risk exposure in the Tiber River delta during the Roman period**

721 Arguments based on archaeological data are used in Hadler et al. (2015 and 2020) to
722 discredit hypotheses of floods and storms for the HEE-2 and 3. For the authors, the presence
723 of warehouses called *horrea* along the Tiber River in Ostia suggests that, “Tiber floods were
724 seen as well-manageable natural events rather than as an unscalable hazard” (Hadler et al.,
725 2015 and similar argument in 2020). Floods of the Tiber were a major concern during the
726 Roman period and many solutions were considered or applied to reduce this risk (Le Gall,
727 1953; Aldrete, 2007; Cappelletti, 2009). However, there is no such thing as zero risk in the
728 past, as well as the present time. Even though engineered solutions were probably developed
729 during the Roman period to reduce flood and fluvial depositions in the harbour of Ostia,
730 floods could still have been deposited, and fluvial inundation could have affected the
731 structures. Consequences of floods could have been “seen as well-manageable natural events”
732 by Romans (Hadler et al., 2015), but it did not prevent all kind of HEE to happen. Accelerated
733 siltation of numerous harbour basins are observed along the shores of the Mediterranean Sea,
734 such as that of the Roman harbour of Narbonne in the 1st c. (Rescanières, 2002), and those of
735 Frejus (Excoffon et al., 2010), Ephesus (Stock et al., 2016 ; Delile et al., 2015), Naples (Delile
736 et al., 2016), Pisa (Benvenuti et al., 2006; Mariotti Lippi et al., 2007), as well as that *Portus*
737 (Pepe et al., 2013; Delile et al., 2014a).

738 Similarly, the presence of Roman villas along the coast at the south of Ostia is supposed
739 to attest to “a generally minor vulnerability of the Latium coastal area to storms” in Hadler et
740 al., (2015 and similar argument in 2020). It should be noticed many research conducted about
741 risks, its perceptions, and the level of acceptance of risks by populations (Arnaud-Fassetta et
742 al., 2010; Bradford et al., 2012). It should be more a research question than a statement.

743

7.4. Modern evidence on extreme floods, storms and tsunamis that affected the Lower Tiber floodplain and the Latium coast

While modern occurrences and frequencies of extreme storms and tsunamis are largely discussed in Hadler et al. (2015, 2020), less is developed about extreme floods. We interpret HEE-3, 7, 4, 5 and 6 as mainly driven by fluvial processes, and are willing to also demonstrate the strength of extreme Tiber River floods. However, we are not denying the violence of extreme storms (Noli et al., 1996; Cavichia et al., 2014) and tsunamis (Tinti et al., 2004) that could affect the coasts of the Latium.

Among the floods of the Tiber River, summer floods can be extremely powerful and transport large amounts of sediments – e.g. in 1530, 1557, 1868 and 1965 (Bersani et al., 2004). During the summer flood of 1557, the palaeomeander of Ostia was cut-off and the *Ponte Rotto* in Rome was damaged. More recently in 1965, a summer flood led to the collapse of bridges in the Tiber River watershed, and flooded a large area of Maccarese (Bersani et al., 2004). However, the majority of Tiber River floods occurs in winter. Tiber River winter floods can be exceptional and particularly damaging, carrying large amounts of sediment. The strongest historical flood ever recorded occurred the 24th of September 1598 reaching 19.56 m at Ripetta, and was particularly damaging to Rome (Bersani and Bencivenga, 2001). Flood series based on historical records are available for Rome in Le Gall (1953) and Bersani & Bencivenga (2001).

7.5. Big storm or small tsunami?

Hadler et al. (2015, 2020) promote a sea-born origin of most of the HEE identified in Ostia that raises the issue of the identification of the marine-born processes triggering these HEEs, i.e., storm and tsunamis. Hadler et al. (2020) also develop the hypothesis of minor tsunamis inundating the coastal area: “Although ancient Ostia is not prone to exceptionally

strong tsunami events, the mouth of the Tiber River could provide a potential pathway where even minor tsunami inundation would be capable of leaving a signal in the sedimentary record” (Hadler et al., 2020). It results in even more difficulties to identify clear evidence between small tsunamis and strong storms.

We are not denying these minor tsunamis occur along the coast of the Latium. In fact, modern texts describe some of these small events (Tinti et al., 2004). However, because major tsunami deposits are already difficult to identify in river mouth environments, evidence of minor tsunami deposits should be even harder to track. The river mouth of the Tiber is definitely not the right area to look for palaeoenvironmental evidence of these kinds of natural hazards.

One of the main arguments in excluding a storm origin of the coarsest deposits recorded in the Ostia’s harbour basin is that storm waves could not reach the site of the harbour basin, because today no storm would be able “to inundate far beyond the present coastline” (Hadler et al., 2015) (Fig. 1). We must recall that the coastline was located around 150 m and 500 m away from the ancient harbour basin during the 4th c. BC and the 2nd / 3rd c. AD, respectively (Goiran et al., 2014, Salomon et al., 2018) (Fig. 1). On the other hand, in their database compiling criteria for distinguishing tsunami from storm deposits, Morton et al. (2007) report that storm deposits are restricted to a few hundred meters zone from the shore. For their part, Morton and Sallenger (2003) note that only the most powerful storms, i.e. those contained into the third quartile (25% of the most powerful storms), can transport sand more than 300 m inland, depending on the morphology of the coastline. As a result, these statements argue that storm deposits have easily reached the harbour basin of Ostia during ancient times given the distance separating it from the coastline at these periods. In this regard, the storm hypotheses should still be considered.

Additionally, based on the study of the Mediterranean's *Medicanes* (from *Mediterranean hurricanes*, i.e. tropical-like Mediterranean storm) done by Cavicchia et al. (2014), Hadler et al. (2015) consider it unlikely that the coastal area of Latium experienced “major storm surges” in the past. Actually, one medicane was registered in the last 60 years off the coast of the Latium. This study also demonstrates that medicanes form preferentially in the Western Mediterranean, and the percentage of days on which favorable environmental conditions are found along the Latium coast is comprised of between 0.3 and 0.4. It does not exceed 1% because medicanes are rare storms (Cavicchia et al., 2014). Moreover, no details are provided in this study on the distribution of land falling sites of medicanes, while once formed they can travel hundreds of kilometers offshore before land falling. Finally, this meteo-marine phenomenon of medicanes is only one of the type of storms that may occur in the Mediterranean basin among other more common types (Lionello et al., 2016).

8. Conclusions

This study has aimed to review all of the proxies currently documenting the sedimentary archives of different environments at the mouth of the Tiber River to test the recent hypothesis made by Hadler et al. (2015, 2020), Wunderlich et al. (2018) and Vött et al. (2020) of the occurrence of several tsunamis, which struck Ostia between the 8^e c. BC and the 17th c. AD or later. Based on all of the indicators available (sedimentological, geomorphological, geochemical, chronological, microfaunistic, archaeological and historical data), we consider that there is no clear evidence of tsunami inundations at the mouth of the Tiber River (shoreface / river mouth, harbour or the palaeochannel of Ostia). Fluvio-coastal environments are complex environments where finding clear evidence of palaeotsunami deposits is challenging (Mamo et al., 2009 ; Engel and Brückner, 2011 ; Chagué-Goff et al. 2017 ; Marriner et al., 2017 ; Röbbke and Vött, 2017) (Fig. 9).

817 In our opinion, the formation of HEE-1 is formed from a specific geomorphological
818 feature (river mouth bar-through) and mixed fluvio-coastal processes where no single
819 flood/storm/tsunami can be identified. Several research groups identified this layer in coastal
820 areas near the palaeoriver mouth of the Tiber River (Giraudi et al., 2009; Salomon, 2013;
821 Milli et al., 2013; Goiran et al., 2014; Delile et al., 2018).

822 HEE-2 is trapped in the harbour of Ostia. It is a single event but no evidence allows us
823 to determine its origin (flood/storm/tsunami). This interpretation is based only on a
824 reinterpretation of the data from Hadler et al. (2015). However, it is surprising that among the
825 ten cores taken in the ancient harbour basin of Ostia (about 2.5 ha) (Fig. 1), only Cores OST-3
826 and PO-1 recorded the HEE-2 layer. Additionally, the existence of estuarine assemblages of
827 autochthonous foraminifers developing in the lower reach of the Tiber River should be
828 considered. It would probably contribute to better understand the complexity of the river
829 mouth environments and improve the interpretation of all the cores reviewed here.

830 HEE-3 sealed the harbour of Ostia. It is definitely from fluvial origin based on
831 palaeoenvironmental data from Hadler et al. (2015), Goiran et al. (2014), Sadori et al. (2016),
832 Vött et al. (2020), and geochemical data from Delile et al. (2017, 2018). The processes
833 involved and leading to the presence of foraminifers in flood deposits should be explored
834 (e.g., floating foraminifers, autochthonous foraminifers developing between flood events).

835 HEE-7 would be most likely a semi-protected sandy riverbank developing in a chamber
836 of the shipshed of Ostia. This layer was deposited at the level of the ancient sea level (Goiran
837 et al., 2009; Heinzemann et al., 2020). In this context, the high quantity of foraminifers
838 identified by Vött et al., 2020, could be related to their floating and/or swashing on the
839 riverbank. Clearly, this hypothesis should be confirmed by studying current sandy riverbank
840 near the mouth of the Tiber River.

HEE-4 and 5 are located in the ancient active channel of the Tiber River. In this context, fluvial high-energy events are reworked by other fluvial high-energy events. Most of the sedimentation is controlled by fluvial dynamics, but affected seasonally by salt wedge intrusions. It results in a complex stratigraphy where identifying specific events of floods or any other natural hazards (storm/tsunami) is almost impossible. In our opinion, none of the sedimentological, or palaeoenvironmental data for now available from Hadler et al. (2020) or Salomon et al. (2017) can provide clear evidence of palaeotsunami deposits.

Finally, HEE-6 located in the floodplain and at the last infill stage of the palaeomeander of Ostia demonstrates an event bracketed within a slow increase and decrease of the grain size with all similar estuarine assemblage of foraminifers. We would interpret this change in Unit D in Core TEV-1A as flood deposits settled during a period of major inundations of the Tiber River during the last centuries of the Little Ice Age. More data would be required to support the tsunami hypothesis.

We acknowledge that the tsunami hypothesis should be considered more often among other more common processes when interpreting palaeoenvironmental data, especially in the Mediterranean. However, when looking for tsunamis, the depositional context is crucial (Shanmugam, 2012). Palaeotsunamis may have affected the mouth of the Tiber, but geomorphological and palaeoenvironmental evidence should be identified in other areas along the coast of the Latium. Lagoons and harbour basins far from river mouth environments would provide more reliable data. Additionally, the identification of geomorphological and palaeoenvironmental evidence of tsunamis from the same period separated by several kilometers would reinforce the tsunami hypothesis.

Even if each pluridisciplinary evidence has to be considered as a complementary source of information to identify palaeotsunami deposits, we believe that some of them are particularly useful, and therefore, require special attention in this type of study.

(i) The *chronology* of palaeotsunami events trapped in sedimentary archives should be supported by dates directly obtained from the high-energy deposits, or at least as close as possible to them. Moreover, it is imperative that all of the dates conducted are readable directly on the stratigraphic logs.

(ii) Some *geomorphological features* may be relevant to the identification of processes involved in high-energy deposits. First, the spatial continuity of the tsunami layers in the harbour basins should be observed. In practical terms, this means that tsunamites should be identified in a large majority of cores taken in the area, which is presumed to have experienced past tsunami events. The distinction between a storm and a tsunamigenic origin requires, among other factors/variables, knowing the evolution of the palaeoshoreline positions over time, including the coastal evolution in palaeotsunamis research (Garrett et al., 2016).

(iii) *Micropalaeontology*, and more specifically *foraminiferal assemblages*, are known to be powerful tools in identifying high-energy marine events. The best foraminiferal evidence for tsunami sediments contain deep water assemblages and/or, to a lesser extent, sudden displaced assemblages, and a higher species diversity (Dawson et al., 1995; Hindson and Andrade, 1999; Hindson et al., 1996, 1998; Hawkes et al., 2007; Mamo et al., 2009).

(iv) *Elemental geochemistry* has also become an essential tool to the study of palaeotsunamis because it can identify both sedimentary sources and the fluvial or marine transport vector (Chagué-Goff et al., 2017). At Ostia, this approach has shown a gradual and continuous regression of seawater influence within Core PO-2 stratigraphy due to the freshwater inputs (Delile et al., 2018).

(v) *Heavy metal palaeopollutions* might easily help to identify palaeotsunamites based on their presence or absence. The palaeotsunami sediments anterior to the Late Modern Period (post AD 1750) are known to be devoid of any traces of Pb palaeopollutions (Hadler et al., 2013; Finkler et al., 2018a,b; Kolaiti et al., 2017). At Ostia, the presence of anthropogenic Pb excesses fluctuating over times consistently with robust peaks and troughs in the coarsest sediments (Delile et al., 2017) invalidate the youngest tsunami event.

If clear evidence suggests palaeotsunami events in Ostia or on the coast of Lazio, this would be of major importance. However, based on the dataset reviewed, none of the HEE layers identified around Ostia suggest a clear palaeotsunami origin. Even if we consider the importance of the geomorphological and sedimentological impacts of high-energy events, we would like to point out the extreme geomorphological variability of coastal environments, in particular river mouth environments. Such a highly mobile deposit environment appears to be not suitable in the reconnaissance of palaeotsunamis deposits, and therefore requires all the more caution for multi-proxy interpretations. We still consider the palaeotsunami hypothesis seriously, and it should be examined carefully in balance with other fluvial and coastal processes.

Acknowledgments

We thank the *Soprintendenza Speciale per i Beni Archeologici di Roma - Sede di Ostia* for the permission to drill core PO-2 in the ancient harbour basin of Ostia. We further acknowledge the ARTEMIS-SHS program and radiocarbon laboratory of Lyon for conducting the radiocarbon dating. The Young Scientist Program of the Agence Nationale de la Recherche (CNRS) (ANR 2011 JSH3 002 01), the Roman Mediterranean Ports program (ERC grant agreement n° 339123), and the Ecole Française de Rome provided financial and logistic support. Finally, we are grateful to Jean-Philippe Goiran, Cécile Vittori for our useful

discussions on this issue of palaeotsunami deposits at the Tiber River mouth and their insightful advices. Finally, we would like to thanks the two anonymous reviewers for their valuable remarks and comments, which significantly contributed to the quality of the paper.

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1199

1200 **Figures captions**

1201 **Figure 1.** Location map of the ancient harbour basin of Ostia and the palaeochannel of the
1202 Tiber (called *Fiume Morto*), and the sediment cores reviewed in this work.

1203 **Figure 2.** Synthesis of the palaeoenvironmental data from Core OST-3 redraw from Hadler et
1204 al. (2015).

1205 **Figure 3. (A)** Factor analysis of elemental concentrations in the Core PO-2. The number of
1206 factors is limited to four: (1) silicate detrital fraction (47%), (2) aluminosilicate detrital
1207 fraction vs carbonate fraction (13%), (3) anoxic conditions (10%), (4) seawater influence vs
1208 polluted freshwater (7%). **(B)** Distribution of factors with depth in the column able to identify
1209 the palaeoenvironments. The red shadings show the sedimentary deposits interpreted as
1210 tsunamis-related HEE-1 and 3 by Hadler et al. (2015). The highest Pb level palaeopollutions
1211 (see Delile et al., 2017 for details) recorded in the B2 unit strongly reject the assumption of a
1212 tsunami deposit for the HEE-3 (modified from Delile et al., 2018).

1213 **Figure 4.** Synthesis of the palaeoenvironmental data from Core OST-7A redraw from Vött et
1214 al. (2020).

1215 **Figure 5.** Synthesis of the palaeoenvironmental data from Core TEV-1A redraw from Hadler
1216 et al. (2020).

1217 **Figure 6.** Synthesis of the palaeoenvironmental data from Core TEV-4A redraw from Hadler
1218 et al. (2020).

1219 **Figure 7.** Plot of radiocarbon (2σ confidence range) and archaeological dates used by Hadler
1220 et al. (2015) and Vött et al. (2020) to define the tsunamis chronology of the ancient harbour
1221 basin of Ostia. To test this chronology, dates are compared with the depths of the four HEE
1222 layers (yellow boxes) and their chronological range (grey shadings) according to the current
1223 sea level. The red shading shows the depth of the only coarse layer (HEE-3) recorded in all
1224 the cores, and for which the bottom and upper limits are reported.

1225 **Figure 8.** Conceptual model of the recording of heavy metal palaeopollutions in the ancient
1226 harbour basins before, during, and after a palaeotsunami event.

1227 **Figure 9.** Main discussion points regarding the interpretation of the HEE units (See Table 1
1228 for more detailed discussion of the different indicators).

1229 **Table 1.** – Reviews of the evidences available for the seven high energy events identified in
1230 Hadler et al. (2015, 2020) and Vött et al. (2020).

12° 16' 33.60"E

12° 16' 55.20"E

12° 17' 16.80"E

12° 17' 38.40"E

12° 18' 0.00"E



Current channel of the Tiber River

PALAEOMEANDER OF OSTIA
IN 1557
(Fiume Morto)

TEV-1A

Hadler et al., 2020

TEV-4A

OSTIA
(Archaeological site)

OST-8
PO-2
OST-7A
OST-1 and 2
PO-1
OST-3
OST-4

HARBOUR OF OSTIA

Coastline (ca. 2nd c. AD?)

500 m

• Main cores of this review

Harbour of Ostia

• Cores from Goiran et al., 2014; Sadori et al., 2016; and Delile et al., 2018

• Cores from Hadler et al., 2015; Vött et al., 2020

Palaeomeander of Ostia

• Cores from Salomon et al., 2017; Pepe et al. 2016

• Cores from Hadler et al., 2020

41° 45' 36.00"N

41° 45' 14.40"N

12° 16' 33.60"E

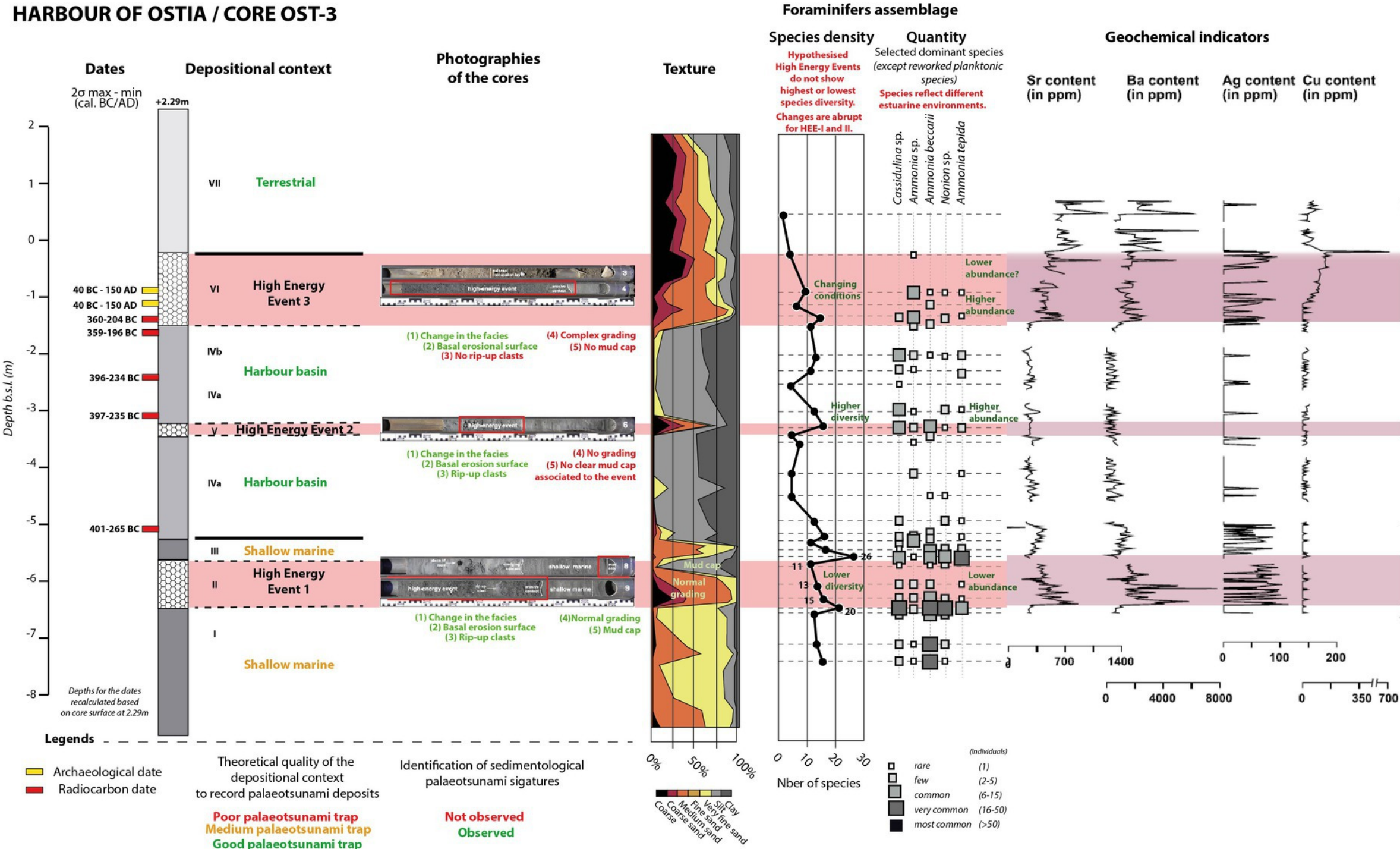
12° 16' 55.20"E

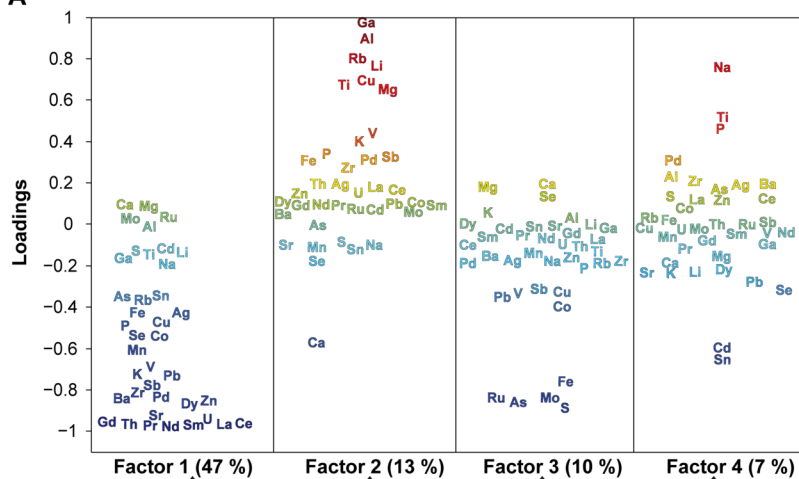
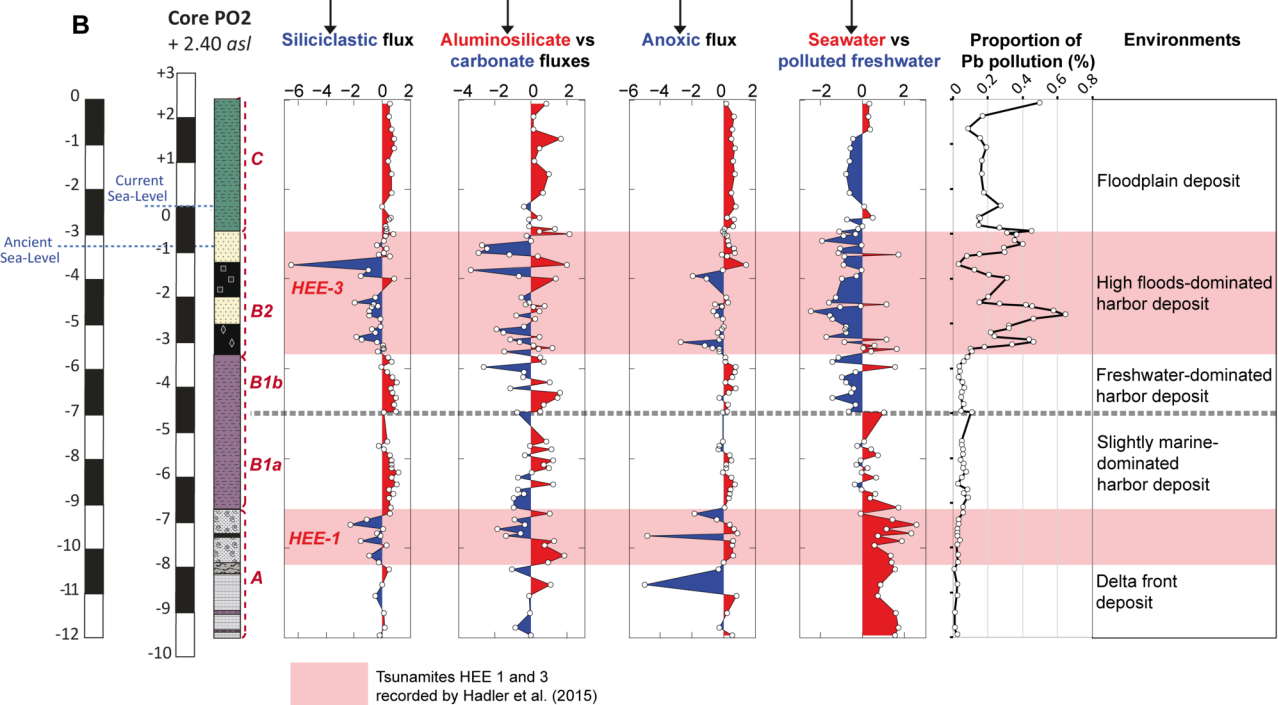
12° 17' 16.80"E

12° 17' 38.40"E

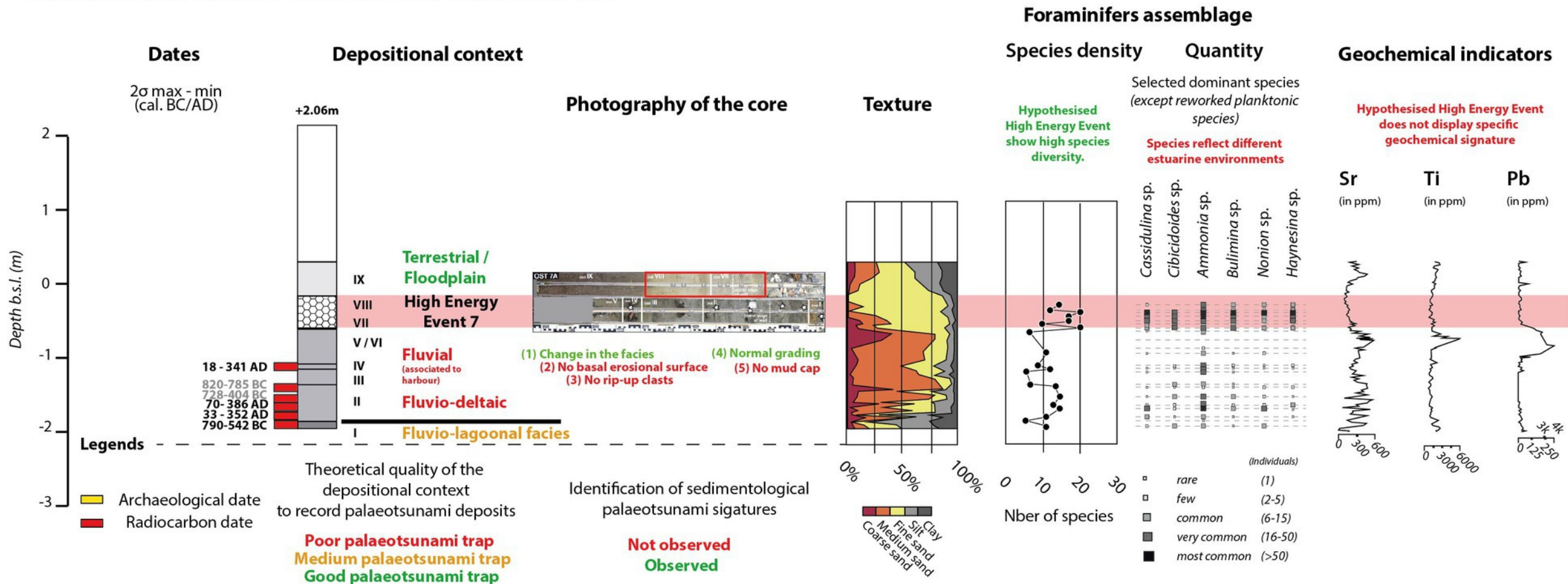
12° 18' 0.00"E

HARBOUR OF OSTIA / CORE OST-3

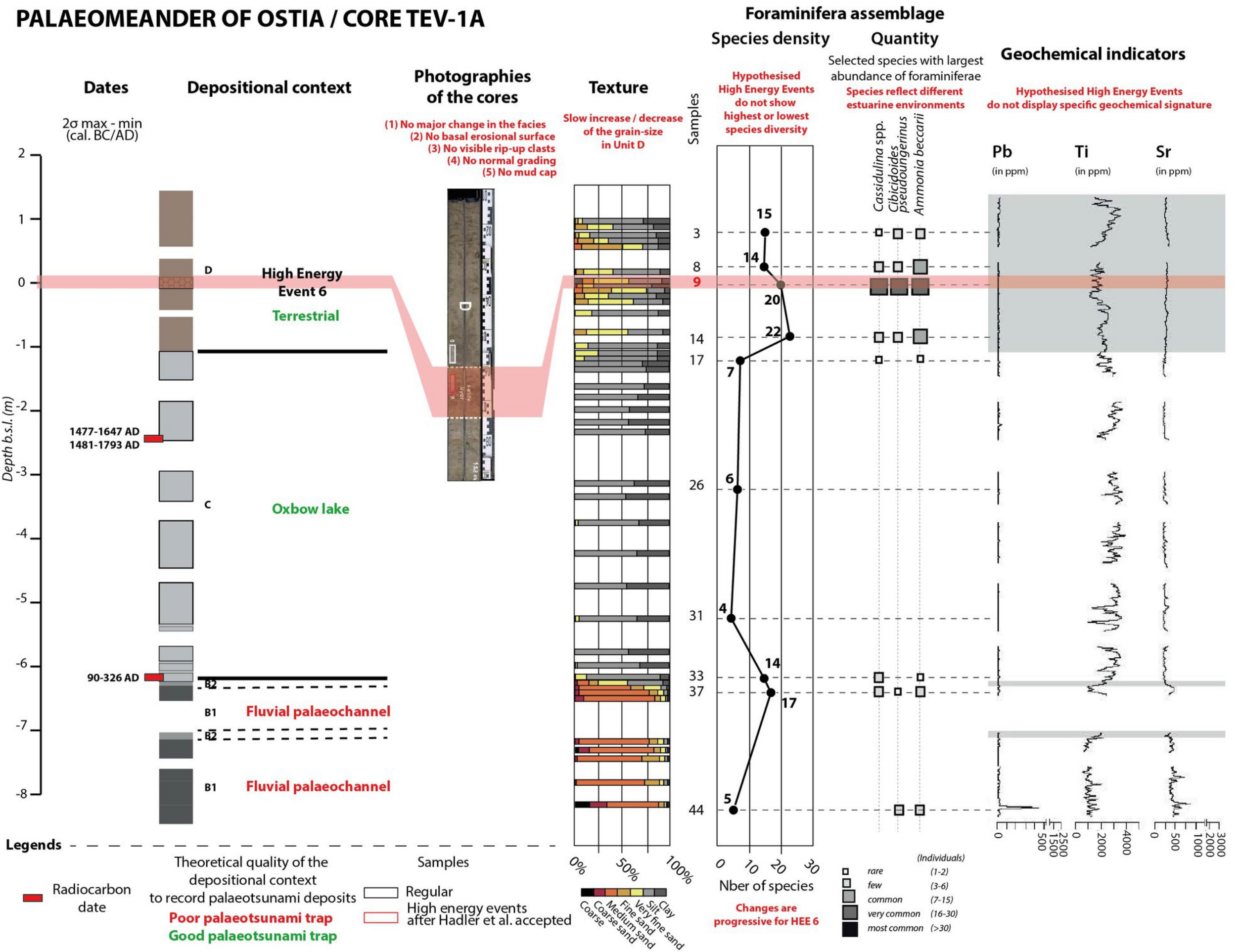


A**B**

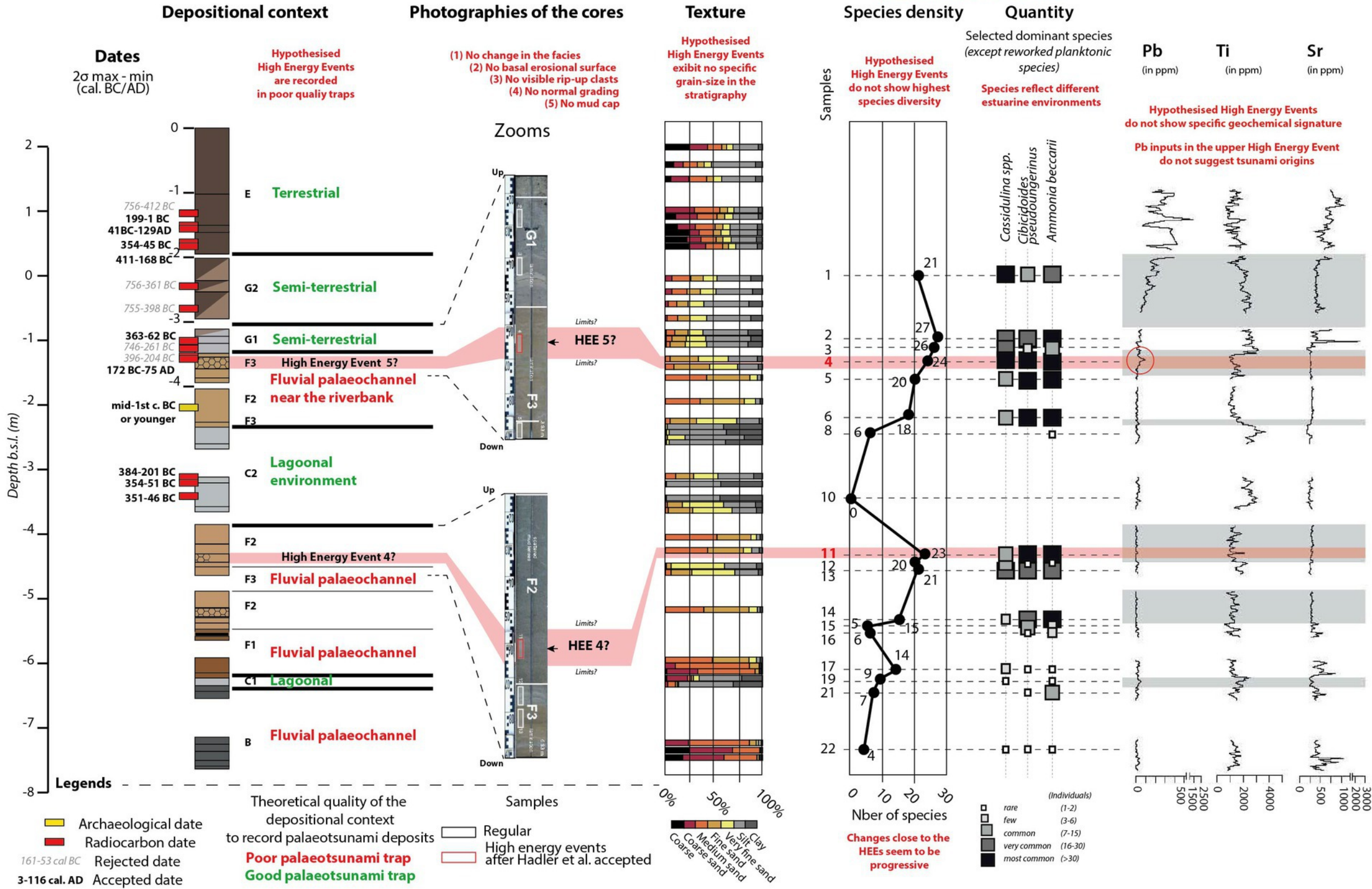
HARBOUR OF OSTIA - SHIPSHED / CORE OST-7A



PALAEOMEANDER OF OSTIA / CORE TEV-1A



PALAEOMEANDER OF OSTIA / CORE TEV-4A



Depositional context

Dates
2σ max - min
(cal. BC/AD)

Hypothesised High Energy Events are recorded in poor quality traps

Photographies of the cores

Texture

Foraminifera assemblage

Geochemical indicators

Species density

Quantity

Selected dominant species (except reworked planktonic species)

Pb (in ppm)

Ti (in ppm)

Sr (in ppm)

Zooms

HEE 5?

HEE 4?

HEE 5?

HEE 4?

Legends

Theoretical quality of the depositional context to record palaeotsunami deposits

Archaeological date

Radiocarbon date

Rejected date

Accepted date

Regular

High energy events after Hadler et al. accepted

Poor palaeotsunami trap

Good palaeotsunami trap

Coarse sand

Medium sand

Fine sand

Silt

Clay

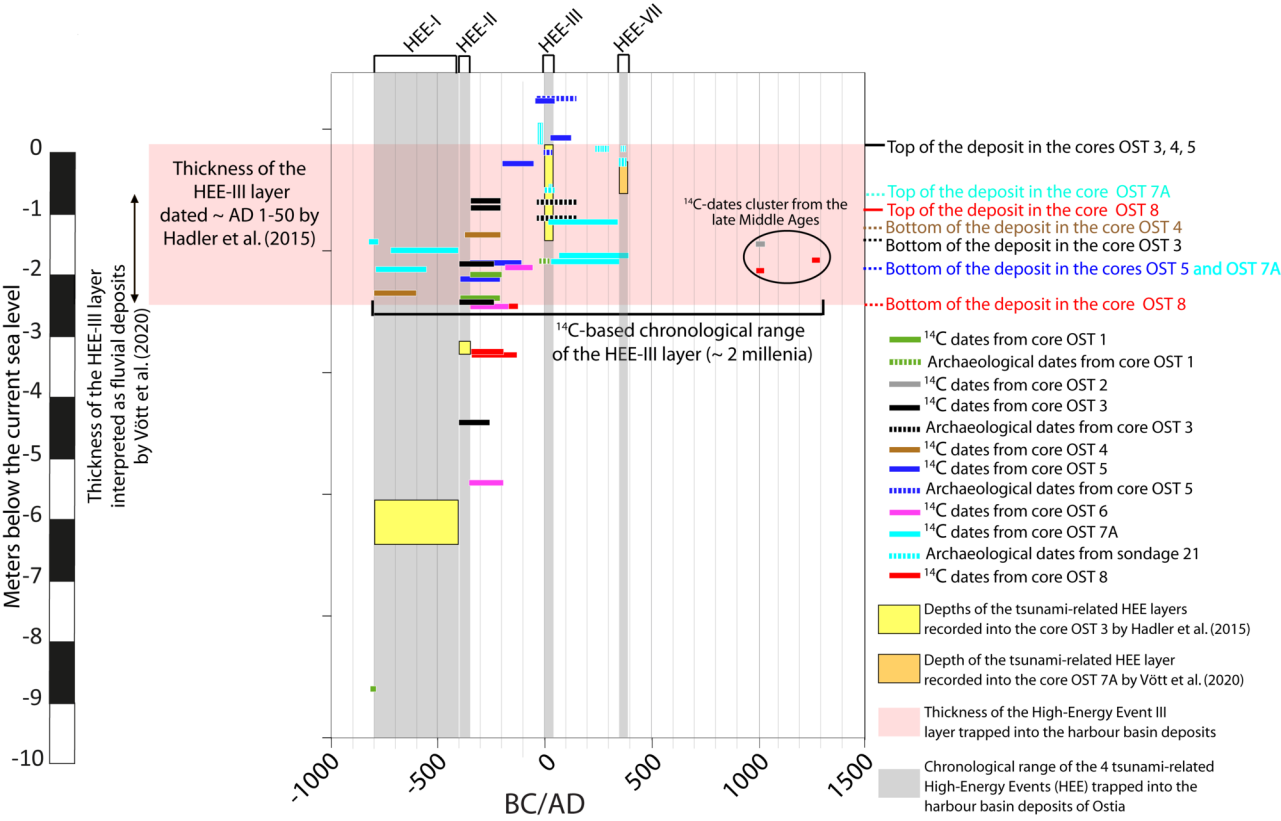
Changes close to the HEEs seem to be progressive

Hypothesised High Energy Events do not show highest species diversity

Species reflect different estuarine environments

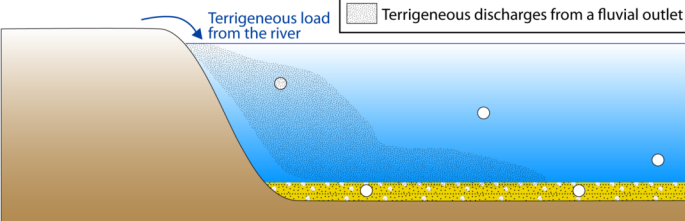
Hypothesised High Energy Events do not show specific geochemical signature

Pb inputs in the upper High Energy Event do not suggest tsunami origins

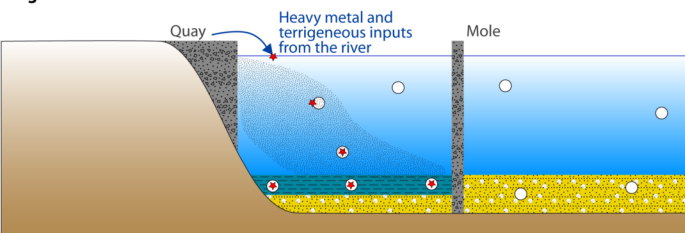


- Seawater components (flocculating cations; e.g. Ca^{2+} , Na^{+} , etc.)
- ★ Lead, heavy metals (metallic cations; e.g. Pb^{2+} , Sn^{2+} , Zn^{2+} , Cu^{2+} , etc.)
- ⊙ Organo-mineral aggregates
- Holocene uncontaminated marine sands
- Graeco-Roman contaminated harbour muds
- Terrigenous discharges from a fluvial outlet

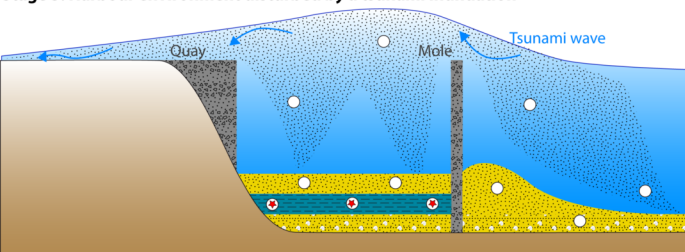
Stage 1: Pre-harbour environment



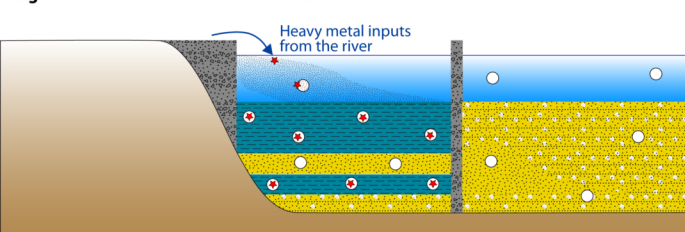
Stage 2: Functionnal harbour environment



Stage 3: Harbour environment disturbed by a tsunami inundation



Stage 4: Return to a functionnal harbour environment



TSUNAMI HYPOTHESES

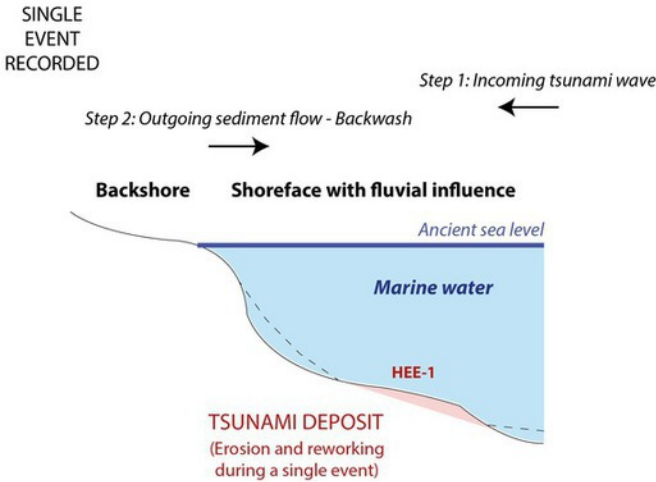
(Hadler et al., 2015, 2020; Vött et al., 2020)

MAIN APPROACHES

- CHECK-LIST OF THE PALAEOTSUNAMI DEPOSIT INDICATORS CONSIDERED CONVINCING (see Table 1) ;
- POOR CONSIDERATION ABOUT THE COMPLEXITY OF THE RIVER MOUTH ENVIRONMENTS.

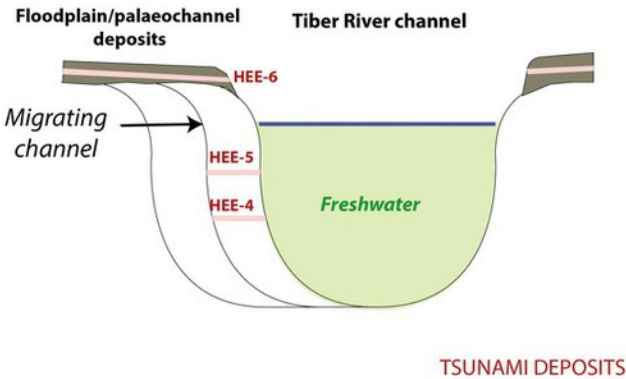
PALAEO-COAST NEAR THE RIVER MOUTH

Interpretations for HEE-1



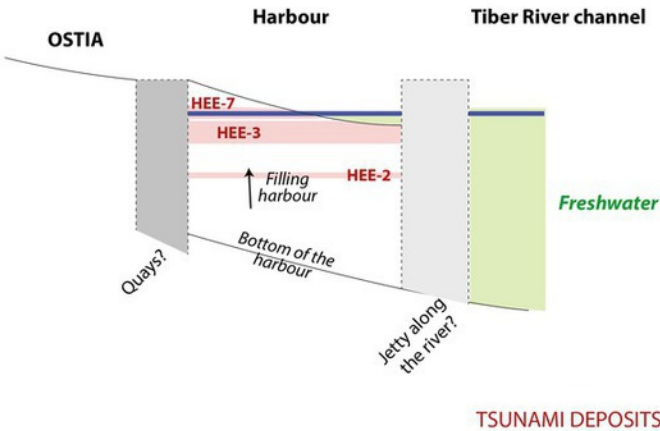
PALAEO-CHANNEL NEAR THE RIVER MOUTH

Interpretations for HEE-4, 5, 6



ANCIENT HARBOUR NEAR THE RIVER MOUTH

Interpretations for HEE-2, 3, and 7

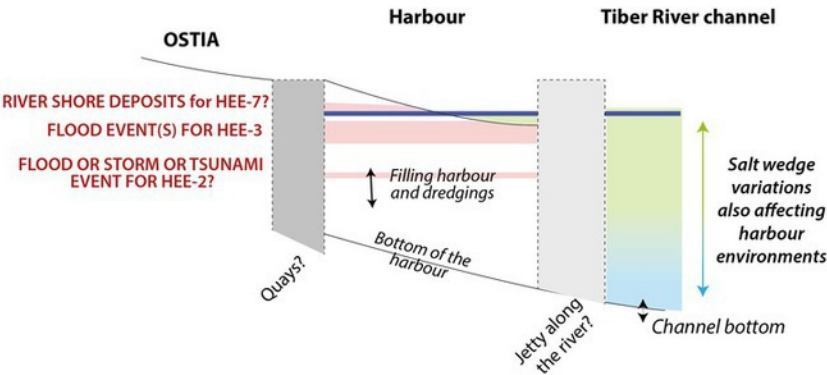
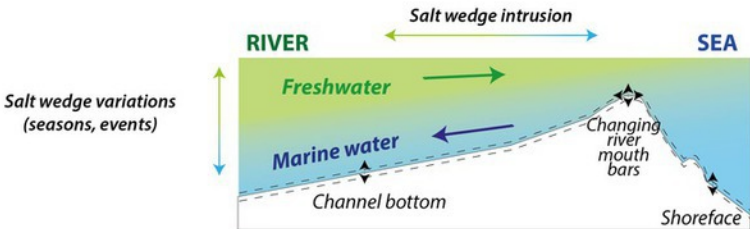
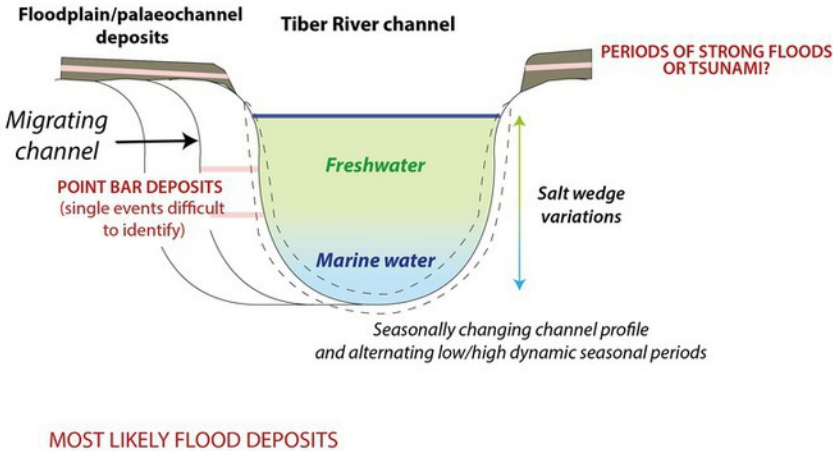
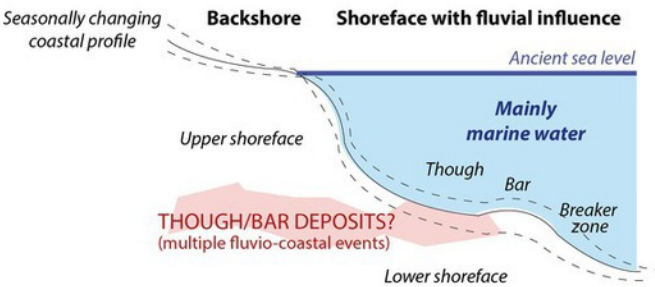


HYPOTHESES CONSIDERING THE COMPLEXITY OF THE RIVER MOUTH DEPOSITIONAL CONTEXTS

(This paper)

- CHECK-LIST OF THE PALAEOTSUNAMI DEPOSIT INDICATORS CONSIDERED NOT CONVINCING (many HEE deposits identified record few tsunami deposit characteristics - see Table 1) ;
- IMPORTANCE OF THE DEPOSITIONAL CONTEXT - RIVER MOUTH:
 - DYNAMIC RIVER MOUTH ENVIRONMENTS ARE NOT IDEAL FOR TRAPPING SINGLE HEE ;
 - SALT WEDGE POSSIBLY EXPLAIN AUTOCHTHONOUS FORAMINIFERS DEVELOPMENT;
 - DIVERSITY OF THE TRANSPORT PROCESSES OF ALLOCHTHONOUS FORAMINIFERS SHOULD BE EXPLORED IN MORE DETAILS IN RIVER MOUTH CONTEXT (floating, reworking, flood/storm/tsunami transport);
- Pb POLLUTANT SHOULD ALSO BE USED FOR TESTING PALAEOTSUNAMI HYPOTHESES:
 - HIGH Pb CONCENTRATIONS COULD BE RECORDED IN ANCIENT FLOOD DEPOSITS, BUT WOULD BE MORE DILUTED IN REWORKED COASTAL SEDIMENTS.

MULTI-EVENTS RECORDED
(Storms and floods seasonally recorded and possibly tsunami)



MULTIPLE HYPOTHESES COULD EXPLAIN COARSE MATERIAL DEPOSITION IN THE HARBOUR BASIN OF OSTIA

Higher	Higher ²⁴	– ²⁵	No clear specific assemblage ²⁶	No Gastropoda ²⁷	-	No ostracods ²⁸	Low Sr, Ti, MS ²⁹	Low	-	-	-	Possibly triggered by the AD 365 Crete earthquake (?)	Beach/riverbank close to the river mouth
Nothing specific in the context ³⁵	Higher ³⁶	Good ³⁷	No clear specific assemblage ³⁸	Shallow marine and estuarine specie ³⁹	Articulate d state ⁴⁰	Articulated brackish ostracods ⁴¹	Nothing specific in the context	No	-	-	-	Tsunamigenic deposit ⁴²	Point bar fluvial deposit in estuarine environment

minated silt and sand document the (re-) establishment of medium-energetic conditions“ (Hadler et al. 2015, p84);

sp., *Bulimina sp.* and *Brizalina sp.* reflecting the local autochthonous marine to shallow marine environment” (Hadler et al. 2015, p82);

ch facies I re-occur in high abundance. Additional groups like *Rosalina sp.*, *Miliolinella sp.* or *Planorbulina sp.* And the increased content of *Posidonia* document the (re-) establishment of a shallow

er et al. 2015);

n “incorporated rip-up clasts”. “A fining upward sequence with a mud cap attests initially strong but subsequently decreasing flow dynamics” (Hadler et al. 2015, p82);

n the hinterland of the Tiber (Bellotti et al., 2007) » (Hadler et al. 2015, p82) > No data about the other foraminifers;

major environmental interruption associated with the high-energy deposit” (p82); “Recent planktonic foraminifera like *Orbulina sp.* and marine groups like *Ammonia sp.* or *Cassidulina sp.* clearly *Orbulina sp.* *Hyalinea sp.* differs from shallow coastal environments below and above the HEE 1, but present in very small quantities. After Hadler et al. 2015 concerning HEE 1: « Recent planktonic

nerals also seem to reflect the fingerprint of the Tiber river catchment that is dominated by volcanic rocks and Plio-/Pleistocene calcareous marine deposits (Bozzano et al., 2000; Bellotti et al.,

. 2015, p84);

ty and the occurrence of groups like *Ammonia sp.* and *Haynesina sp.*, tolerant to ecological stress, correspond well to unfavourable, brackish to freshwater environmental conditions typical of eae occur, probably related to variations in freshwater and seawater inflow” (Hadler et al. 2015, p84);

r basin” (Hadler et al. 2015, p84);

rey sand that incorporates cultural debris like ceramic fragments and a lead sheet”;

ud cap described;

deposits of the lagoonal harbour [in OST 6] are also overlain by a massive layer of sand including rip-up clasts and ceramic fragments.” (Hadler et al. 2015, p84) – No grading and no mud cap

the foraminifera with increasing abundances within the high-energy deposit while *Ostracodae* completely disappeared” (Hadler et al. 2015, p84);

ii, *Cassidulina sp.*, *Elphidium sp.* or *Orbulina sp.* attesting the short-term input of sea-borne allochthonous sediments into the lagoonal harbour » (Hadler et al. 2015, p84).. > Additional work on the

ally, no specific species were found for this HEE 2 comparing to the species commonly found in the lagoonal harbour of Ostia, below and above this unit;

es sp. may originate Gyroidinoides sp., Melonis sp. or Cibicidoides sp. may originate from slightly deeper marine environments» (Hadler et al. 2015, p84).. > Additional work on the current river

eloculina sp. and *Nodosaria sp.* not observed in the lagoonal harbour but in very low density. Otherwise, all species are observed in the harbour sediments;

4);

in abundance in units VII and VIII” (Vött et al. 2020, p14 and 15 of 26);

man impact. The latter seems clearly associated with the use of the site as river harbour.” (Vött et al. 2020, p17 of 26);

n units VII and VIII (Fig. 8f, g) can be clearly seen.” (Vött et al. 2020, p13 of 26) ; No basal unconformity and rip up clasts evidences are reported;

s found here is up to double as high as in the sediments below” (Vött et al. 2020, p14 of 26) > A comparison with other cores analysed by the same research team would have been interesting. For

