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

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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

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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

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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).

The presence of these two teams contributed to produce a lot of essential new data to reconstruct the evolution of the landscape of this important city-port from the Roman period.

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However, the two teams propose different interpretations of the deposits. On the basis of geomorphological, sedimentological, geochemical, geophysical and microfossil analyses, Hadler et al., (2015, 2020), Wunderlich et al. (2018) and Vött et al. (2020) hypothesize the existence of seven palaeotsunami deposits (High Energy Event 1 to 7 spelled thereafter HEE-1 to 7) attributed to five to seven different events (Table 1). Amongst these tsunami events, three to four would have hit the active port-city of Ostia during the Roman period. In contrast, none of these deposits were interpreted such as tsunami by the other team (Goiran et al., 2012, 2014, 2017; Sadori et al., 2016; Pepe et al., 2016; Salomon et al., 2016, 2017, 2018; Delile et al., 2017, 2018).

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

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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 ; Röbke 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

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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 north-west 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

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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 at 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 at 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

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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 ; Röbke 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

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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 palaochannel 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).

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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

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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.

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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 barleeanum, 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/specie observed in all depositional contexts, and are characteristic of estuarine environments (Wang,

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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 though/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., Valvuleria 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 mediterraneaum"* 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

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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

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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; Röbke 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; Röbke and Vött, 2017).

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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

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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

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(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.

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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

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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 palaepollution 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 palaepollution 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.

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During the process of this review, we identified inconsistences 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 ^{14}C-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).

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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.

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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 habour 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

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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

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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

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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.

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

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

Similarly, the presence of Roman villas along the coast at the south of Ostia is supposed to attest to "a generally minor vulnerability of the Latium coastal area to storms" in Hadler et al., (2015 and similar argument in 2020). It should be noticed many research conducted about

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risks, its perceptions, and the level of acceptance of risks by populations (Arnaud-Fassetta et al., 2010; Bradford et al., 2012). It should be more a research question than a statement.

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.

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Additionally, based on the study of the Mediterranean's Medicanes (from *Medi*terranean hurri*canes*, 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 ; Röbke and Vött, 2017) (Fig. 9).

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

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

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

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

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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.

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(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

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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.

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Figures captions

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

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

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

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

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

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

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

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

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

General data			**Depositional context when the HEE are happening**							**HEE – Sedimen** **from Hadler et al. 2015**		
High-Energy Events (HEE)	**Depth of the HEE**	**Main studied cores**	**Facies/Unit of the depositional context in Hadler et al. and Vött et al.**	**Sedimentological context**	**Foraminifers context (Hadler et al. 2015, 2020; Vött et al., 2020)**	**Depositional context interpretation**	**Quality of the trap for identifying single HEE deposits (flood, storm, tsunami)**	**Distance to the coast during the HEE (semi-quantitative)**	**Connectivity with the river**	**HEE samples or facies**	**Grain-size of the HEE**	**Clear change in the facies**
HEE 1 between the 8th and	***6.36-5.61 m b.s.l.***	**OST-3 (+2.29m)**	***Facies I and III***	**Sand to laminated silt and sand**[1]	**Marine to estuarine species**[2]	**Sandy shoreface (close to a river mouth?)**[3]	**Poor** (strong coastal reworking)	**On the coast**	**Medium**	***Facies II***	**Medium to coarse-grained sand**[4]	**Yes**[5]

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[1] **OST-3 / HEE 1** – **Sedimentological context =** Facies I = "fine grained and partly laminated sands" (Hadler et al. 2015, p82); Facies III = "On top of the high-energy deposit, laminated silt and sand document the (re-) establishment of medium-energetic conditions" (Hadler et al. 2015, p84);

[2] **Foraminifera of the context** = Facies I = "contains well preserved foraminiferal species like *Ammonia beccarii* or *Gyroidinoides sp., Cassidulina sp., Cibicides sp., Melonis sp., Nonion sp., Bulimina sp.* and *Brizalina sp*. reflecting the local autochthonous marine to shallow marine environment" (Hadler et al. 2015, p82);
Facies III = The foraminiferal assemblage reaches a maximum in species diversity. Although *Ammonia tepida* and *Triloculina sp.* are dominant, numerous foraminifera associated with 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 marine environment subsequent to the event (Hadler et al. 2015, p84);

[3] **Depositional context interpretation** = "marine to shallow marine environment" (facies I, p84) and "(re-) establishment of a shallow marine environment" (facies III, p84) (Hadler et al. 2015);

[4] **Grain-size of the HEE** = "medium to coarse-grained sand" (Hadler et al. 2015, p. 82);

[5] **Change of facies, basal unconformity, rip-up clasts, normal grading, mud cap** = Facies II demonstrate "sudden environmental change", "subsequent to an erosive contact" with "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);

[6] **Foraminiferae diversity and quantity = "**Recent marine foraminifera are abruptly reduced in both diversity and abundance" (Hadler et al. 2015, p82);

[7] **Foraminiferae - State of preservation =** « strongly abraded and weathered planktonic foraminifera of the family *Globigerinoidae* most likely derives from the local bedrock within the hinterland of the Tiber (Bellotti et al., 2007) » (Hadler et al. 2015, p82) > No data about the other foraminifers;

[8] **Foraminiferae assemblage** = "As many species are generally capable to adapt to gradual ecological changes, the sudden break within the assemblage particularly emphasizes a 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 attest sediment deposition under marine influence, though" (Hadler et al. 2015, p84). > No clear assemblage can be observed. Diversity and quantity are low. Additionally, only *Planorbulina* 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 foraminifera like *Orbulina* sp. and marine groups like *Ammonia* sp. or *Cassidulina* sp. clearly attest sediment deposition under marine influence »;

[9] **Geochemical signature** = "The strongly enriched content of Sr, Ba and Ag in correlation with highest magnetic susceptibility values and an abundant incorporation of volcanic minerals 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., 2007) » (Hadler et al. 2015, p82);

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5th c. BC.	***8.65-7.90 m b.s.***											
HEE 2 during the 4th c. BC.	***3.28-3.05 m b.s.l*** ***5.57-5.34 m b.s.***	**OST-3 (+2.29m)**	***Facies IV***	**Mud**[11]	**Few to very common marine / estuarine species**[12]	**Harbour mud**[13]	**Good**	**Close (ca. 200m)**	**High**	***Facies V***	**Sand**[14]	**Yes**[15]
HEE 3 during the first half of the 1st c. AD	***1.45-0.12 m b.s.l*** ***3.74-2.41 m b.s.***	**OST-3 (+2.29m)**	***Facies IV***	**Mud**	**Few to very common marine species**	**Harbour mud**	**Good**	**Close (ca. 200m)**	**High**	***Facies VI***	**Badly sorted grey sand**	**Yes**
HEE 7 at or	***0.65-0.15 m***	**OST-7A (+2.06m)**	***Facies V-VI***	**Medium sand**	**Few to common marine /**	**River mouth sands**[21]	**Medium** (fluvio-coastal reworking)	**Close (ca. 200m)**	**High**	***Facies VII and***	**Fine sand**[22]	**Yes**

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[10] **HEE event interpretation** = "The facies most likely represents fluvial sediments dislocated by a high energy event within a near-shore deltaic marine environment" (Hadler et al. 2015, p84);

[11] **OST-3 / HEE 2 and 3 = Sedimentological context** = Facies IV = **"**grey lagoonal mud with some thin sandy intercalations" (Hadler et al. 2015, p84);

[12] **Foraminifera of the context** = "While *Ostracodae* occur in increasing numbers, marine foraminifera rapidly decline in both diversity and abundance (facies IVa). The low diversity 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 lagoonal systems and of enclosed lagoonal harbours. To the top of the lagoonal sequence (facies IVb), marine foraminifera slightly increase while also freshwater-associated Characeae occur, probably related to variations in freshwater and seawater inflow" (Hadler et al. 2015, p84);

[13] **Depositional context interpretation** = "A piece of rope found at the base of the unit attests to anthropogenic activity and correlates the lagoonal facies with the ancient harbour basin (Hadler et al. 2015, p84);

[14] **Grain-size of the HEE** = Facies V (HEE 2) = "The harbour facies is intersected by a layer of sand" (Hadler et al. 2015, p84) / Facies VI (HEE 3) = "A massive layer of badly sorted grey sand that incorporates cultural debris like ceramic fragments and a lead sheet";

[15] **Change of facies, basal unconformity, rip up clasts, normal grading, mud cap** = Facies V = "sharp upper and lower contacts" (Hadler et al. 2015, p84) – No grading and no mud cap described;
Favies VI = "A basal erosive contact and a high silt content in the lower part of the unit prove intense reworking of underlying sediments". "Comparable to cores OST 3 and OST 6, 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 described (Hadler et al. 2015, p84);

[16] **Foraminiferae diversity and quantity =** Facies V = "This sand revealed different species of abundant recent marine foraminifera" **/** Facies VI **= "**We found well preserved marine foraminifera with increasing abundances within the high-energy deposit while *Ostracodae* completely disappeared" (Hadler et al. 2015, p84);

[17] **Foraminiferae assemblage** = Facies V = The assemblage is not clearly identified: « This sand revealed different species of abundant recent marine foraminifera such as *A. beccarii*, *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 current river mouth context of the Tiber River would be interesting in such a context with mixed fluvial and sea influences. Statistical treatments should also be proposed. Additionally, 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;
Facies VI = The assemblage is not clearly identified: « Species like *A. beccarii* or *Elphidium* sp. derive from near-shore environments, while *Gyroidinoides* sp., *Melonis* sp. or *Cibicidoides* 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 mouth context of the Tiber River would be interesting in such a context with mixed fluvial and sea influences. Statistical treatments should also be proposed. HEE 3 includes *Quinqueloculina* sp. and *Nodosaria* sp. not observed in the lagoonal harbour but in very low density. Otherwise, all species are observed in the harbour sediments;

[18] **Foraminiferae - State of preservation =** State of the foraminiferae not described for facies V; Facies VI = "We found well preserved marine foraminifera" (Hadler et al. 2015, p84);

[19] **Geochemical signature** = "high contents of Sr, Ba and Ag as well as increased magnetic susceptibility values" (Hadler et al. 2015, p84);

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shortly after AD 355–363	***b.s.l*** ***2.2-2.7 m b.s.***				**estuarine species**[20]					***VIII***		
HEE 4 before the 2nd c. BC (*associated with HEE2 after Hadler et al. 2020*)	-	**TEV-4A (+2.28m)**	***Subunit F2***	**Muddy sand**[31]	**Very to most common marine / estuarine species**[32]	**Fluvial channel close to riverbank / point bar (close to river mouth)** [33]	**Poor** (strong fluvial reworking)	**Far (river path for tsunami?)**	**Very high**	***Sample TEV4A /11***	**Similar to the context**[34]	**No**

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[21] **Depositional context interpretation** = "determined as fluvio-deltaic (lower part of section II) to predominantly fluvial (upper part of unit II, units III to VI) with considerable human impact. The latter seems clearly associated with the use of the site as river harbour." (Vött et al. 2020, p17 of 26);

[22] **Grain size of the HEE = Facies VII and VIII = "**Units VII and VIII are strongly dominated by fine sands" (Vött et al. 2020, p13 of 26);

[23] **Change of facies, basal unconformity, rip up clasts, normal grading, mud cap** = "Also, the clear shift from predominant medium sand in units II to VI (Fig. 8b, e) to fine sand in 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;

[24] **Foraminiferae diversity and quantity** = "It is striking that both abundance and diversity show clearly defined maxima for sediments of units VII and VIII. The number of species 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 this single core abundance and diversity are the highest of the core, but the core has only a thickness of 2 meters;

[25] **Foraminiferae - State of preservation =** not described for facies VII and VIII;

[26] **Foraminiferae assemblage** = "Moreover, species and taxa of Ammonia beccarii, Neoconorbina sp., Nodosaria sp., Nonion sp., Rosalina sp., Valvuleria sp. were exclusively found in units VII and VIII" (Vött et al., 2020, p. 15 of 26). > A comparison with other cores analysed by the same research team would have been interesting. Assemblages should be defined in regard to the other cores drilled in the channel of the Tiber River and the other cores drilled in the harbour;

[27] **Macrofauna** = devoid *Gastropoda* content (not discussed in the original paper; only observed in Figure 7 of Vött et al., 2020);

[28] **Ostracods =** devoid *Ostracoda* content (not discussed in the original paper; only observed in Figure 7 of Vött et al., 2020);

[29] **Geochemical signature** = "Fig. 7 shows a clear dilution effect – magnetic susceptibility as well as concentrations of Ti and Pb are strongly decreased (unit VII) or almost nil (unit VIII)";

[30] **Interpretation** = "southwest of ancient Ostia. Overall, we finally interpret units VII and VIII as related to a possibly two-pulsed extreme wave impact to Ostia's harbour from the seaside" (Vött et al. 2020, p17 of 26);

[20] **OST-7A / HEE 7= Foraminifera of the context** = "The strong marine signature related to units VII and VIII is more than obvious: *Cassidulina sp.* […] show very clear maxima in abundance in units VII and VIII" (Vött et al. 2020, p14 and 15 of 26);

[31] **TEV-4A / HEE 4 and 5** – **Sedimentological context =** Subunit F2 = "Two thick layers of greyish (light) brown muddy sand rest conformably on subunits F1 and F3, respectively." (Hadler et al. 2020, p. 16);
Subunit F3 = "Three sequences of thin and frequently alternating, (light) brown to (light) grey silty sand and mud laminae (<1 cm) conformably overlie subunit F2 and C2 deposits, respectively. Colour and bedding characteristics suggest sedimentation in a (badly-)aerated low-energy but still flow-influenced environment." (Hadler et al. 2020, p. 17);

[32] **Foraminifera of the context** = (a) Subunit F2 = "Foraminifera are significantly increased in both diversity and abundance. Dominant species are *A. beccarii* (23.7 to 37.5%) and *C. pseudoungerinus* (10.2 to 23.8%), accompanied by *Cassidulina spp.* (3.5 to 6.8%), *Bulimina marginata* (up to 5.8%), *E. crispum* (1.7 to 8.2%), *G. soldanii* (0.7 to 5.4%), *Hyalinea baltica* (1.0 to 6.6%), *M. barleanum* (up to 5.1%), *O. universa* (up to 10.2%), *P. bulloides* (1.9 to 6.8%), *Quinqueloculina seminula* (0.5 to 4.9%) and Triloculina sp. (up to 6.1%). Individuals appear fresh and show nearly no signs of reworking and/or weathering. Thus, the assemblage is considered predominantly autochthonous and points to an increased marine influence on the environment" (Hadler et al. 2020, p. 17);
(b) Subunit F3 = "Comparable to subunit F2, sediments show a high diversity and abundance of foraminifera. Dominant species vary between samples, but mainly comprise *A. beccarii* (2.0 to 23.7%), *Cassidulina spp*. (12.7 to 18.4%) and *C. pseudoungerinus* (2.0 to 15.9%), accompanied by *Brizalina spp*. (2.6 to 14.6%), *G. soldanii* (1.5 to 10.2%), *N. fabum* (1.9 to 10.2%) and *O. universa* (2.0 to 8.8%)" (Hadler et al. 2020, p. 17);

[33] **Depositional context interpretation** = (a) Subunit F2 = "Sediments reflect mid-energy fluvial conditions and sedimentation close to the river banks, likely in a point bar position. The slight marine influence indicates the proximity of the river mouth." (Hadler et al. 2020, p. 17);
(b) Subunit F3 = "Sediments reflect mid-energy to low energy fluvial conditions and sedimentation close to the river banks, likely in a point bar position or levee. The slight marine influence again indicates the proximity of the river mouth. (Hadler et al. 2020, p. 17);

[34] **Grain-size of the HEE** = the specificity of the grain-size in HEE 4 and 5 is not described precisely; it seems based only on the foraminiferae (Hadler et al. 2020, p. 17);

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HEE 5 during the 1st c. AD (*associated with HEE3 after Hadler et al. 2020*)	-	**TEV-4A (+2.28m)**	***Subunit F3***	**Silty sand and mud laminae**[31]	**Very to most common marine / estuarine species**[32]	**Fluvial channel close to riverbank / point bar (close to river mouth)**[33]	**Poor** (strong fluvial reworking)	**Far (river path for tsunami?)**	**Very high**	***Sample TEV4A /4***	**Similar to the context**[34]	**No**
HEE 6 after the 17th c. AD	-	**TEV-1A (+1.52m)**	**Unit D**	**Silty mud and sandy mud**[43]	**Few to common quantity of marine / estuarine species**[44]	**Floodplain / palaeo-channel**[45]	**Good** (low fluvial reworking)	**Far (river path for tsunami?)**	**Very high**	***Sample TEV1/ 9***	**Sand**[46]	**No**

Table 1. – Synthesis of the evidences attesting or not the existence of palaeotsunami deposits at the mouth of the Tiber River. Colors correspond to the evidences that are supporting or not

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[35] **Foraminiferae diversity =** Not described in the text for HEE 4 [or TEV4A/11] and HEE 5 [or TEV4A/4] (Hadler et al. 2020, p. 17);

[36] **Foraminiferae quantity =** Common to HEE 4 [or TEV4A/11] and HEE 5 [or TEV4A/4] = "Within these samples, species **abundance** significantly increases by more than 50%" (Hadler et al. 2020, p. 17);

[37] **Foraminiferae - State of preservation =** Common to HEE 4 [or TEV4A/11] and HEE 5 [or TEV4A/4] = "Within these samples (…), individuals are in the best observed **state of preservation**" (Hadler et al. 2020, p. 17);

[38] **Foraminiferae assemblage** = (a) Common to HEE 4 [or TEV4A/11] and HEE 5 [or TEV4A/4] = "Both samples [HEE4 or TEV4A/11 and HEE5 or TEV4A/4] are dominated by *A. beccarii* (37.5% and 23.7%) and *C. pseudoungerinus* (10.2% and 15.9%)"; and "both samples also include some otherwise non-existent individuals of *Cancris auriculus*, *Massilina sp.*, *Siphonaperta aspera*, *Uvigerina sp.* or *Valvulineria complanata*" (Hadler et al. 2020, p. 17);
(b) Specific to HEE 4 = "*B. marginata* (4.3%), *P. bulloides* (4.1%), *Cassidulina spp.* (12.7%) and the planktonic *O. universa* (8.8%) are the most frequently accompanying species in sample TEV 4A/4." (Hadler et al. 2020, p. 17);
(c) Specific to HEE 5 = "Sample TEV 4A/11 shows relatively increased abundances of *M. barleanum* (8.1%), *Q. seminula* (4.9%), *Sphaeroidina bulloides* (2.3%) and *Triloculina sp.* (6.1%)" (Hadler et al. 2020, p. 17);

[39] **Macrofauna** for HEE 4 [or TEV4A/11] = "Sample TEV 4A/11 is also comprised of some juvenile articulated specimens of the marine bivalve *Lentidium mediterraneaum*, associated with shallow water and frequently occurring in sandy estuarine environments (Poppe & Goto, 1993)"; "The sample further comprises some (undetermined) gastropods, scaphopod fragments (*Dentalium* sp.) (…)" (Hadler et al. 2020, p. 17);

[40] **Macrofauna – State of preservation** for HEE 4 [or TEV 4A/11] = "Their articulated state as well as their fragile shells speak clearly against long-term transport or reworking, so sediments neither seem to originate from fluvial reworking of old marine or beach (ridge) deposits nor recent littoral deposits" (Hadler et al. 2020, p. 17);

[41] **Additional data** = HEE 4 [or TEV4A/11] and/or HEE 5 [or TEV4A/4] = "Sediments also incorporate abundant small minerals of vivianite (hydrated iron phosphate)"; HEE 4 [or TEV4A/11] = "The sample further comprises (…) (articulated) brackish ostracods and oospores" (Hadler et al. 2020, p. 17);

[42] **Interpretation** = "Yet, sediments also reflect two distinct short-term interference of the fluvial system from the marine side" (Hadler et al. 2020, p. 17);

[43] **<u>TEV-1A / HEE 6</u>** – **Sedimentological context** (Unit D) = "Alternating layers (>15 cm) of (light) brown, silt-dominated mud and sandy mud gradually follow on top of unit C. In the lower part, sediments show hydromorphic features such as iron patches. In the central section, sediments show some lamination (<1 cm) in terms of colour and grain size, while the uppermost section appears quite homogenous and compact." (Hadler et al. 2020, p. 6-9);

[44] **Foraminiferal assemblage of the context** = "The foraminiferal assemblage generally resembles unit B" (Hadler et al. 2020, p. 6) > In Unit B = Foraminifera comprise few individuals of marine species such as *Ammonia beccarii, Cibicidoides pseudoungerinus* or *Elphidium crispum* (Murray, 2006), but high-energy flow dynamics must be considered as a disturbing factor in terms of autochthonous species assemblages (Murray, 2006)" (Hadler et al. 2020, p. 6) > No data about the preservation of the foraminifers;

[45] **Depositional context interpretation** = "The unit is interpreted as a floodplain environment, associated with overbank deposits, secondary shallow river channel formation and/or crevasse splay dynamics, but also reflects a short-term interference from the marine side" (Hadler et al. 2020, p. 9);

[46] **Grain-size** = "one sandy layer (sample TEV 1/9) (…)" (Hadler et al. 2020, p. 9);

[47] **Foraminiferae diversity =** Not commented in the text (Hadler et al. 2020, p. 9);

[48] **Foraminiferae quantity =** Sample TEV 1/9 "shows a distinct increase in species abundance" (Hadler et al. 2020, p. 9);

[49] **Foraminiferae - State of preservation =** "All individuals are well-preserved and show no signs of reworking or weathering" (Hadler et al. 2020, p. 9);

[50] **Foraminiferae assemblage** = "Species include *A. beccarii, Cassidulina spp., Globigerinoides spp*. and C. *pseudoungerinus*, accompanied by *Brizalina spp., Bulimina spp., Cibicides refulgens* and *Haynesina depressula*, typical of the local marine environment (Bellotti et al., 1994; Hadler et al., 2015)" (Hadler et al. 2020, p. 9).

Journal Pre-proof

the hypothesis of palaeotsunami (green=data supporting the tsunami hypothesis; red = data not supporting the tsunamdeposit hypothesis; yellow=data not conclusive). It should be recalled that evidence supporting tsnumani hypothesis are ***not exclusive***.

Table 1. – Reviews of the evidences available for the seven high energy events identified in

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

Journal Pre-proof

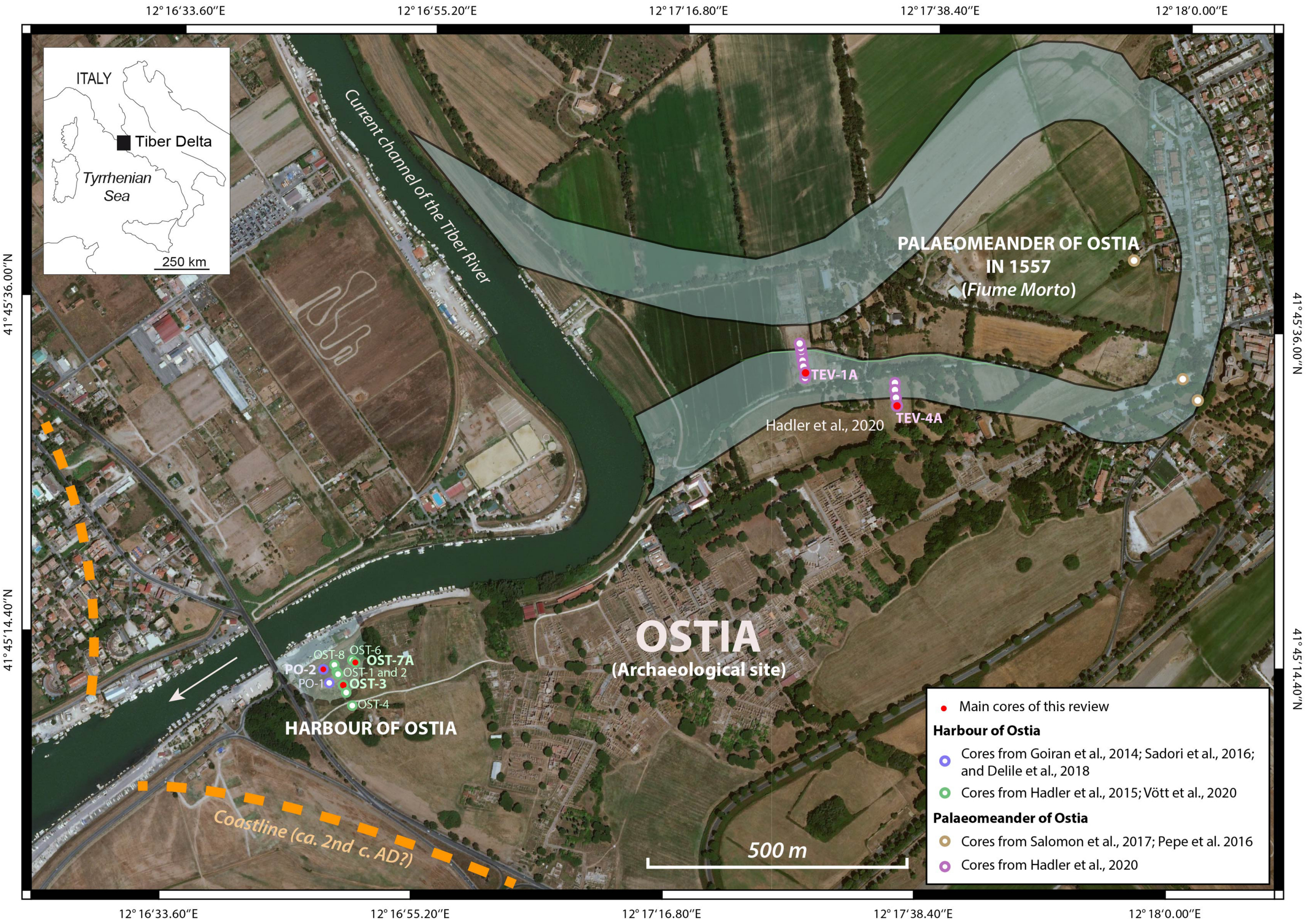

12° 16′33.60″E
12° 16′55.20″E
12° 17′16.80″E
12° 17′38.40″E
12° 18′0.00″E
41° 45′36.00″N
41° 45′14.40″N
ITALY
Tiber Delta
Tyrrhenian Sea
250 km
Current channel of the Tiber River
PALAEOMEANDER OF OSTIA IN 1557 (Fiume Morto)
TEV-1A
TEV-4A
Hadler et al., 2020
OSTIA
(Archaeological site)
HARBOUR OF OSTIA
PO-2
PO-1
OST-8
OST-6
OST-7A
OST-1 and 2
OST-3
OST-4
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

Figure 1

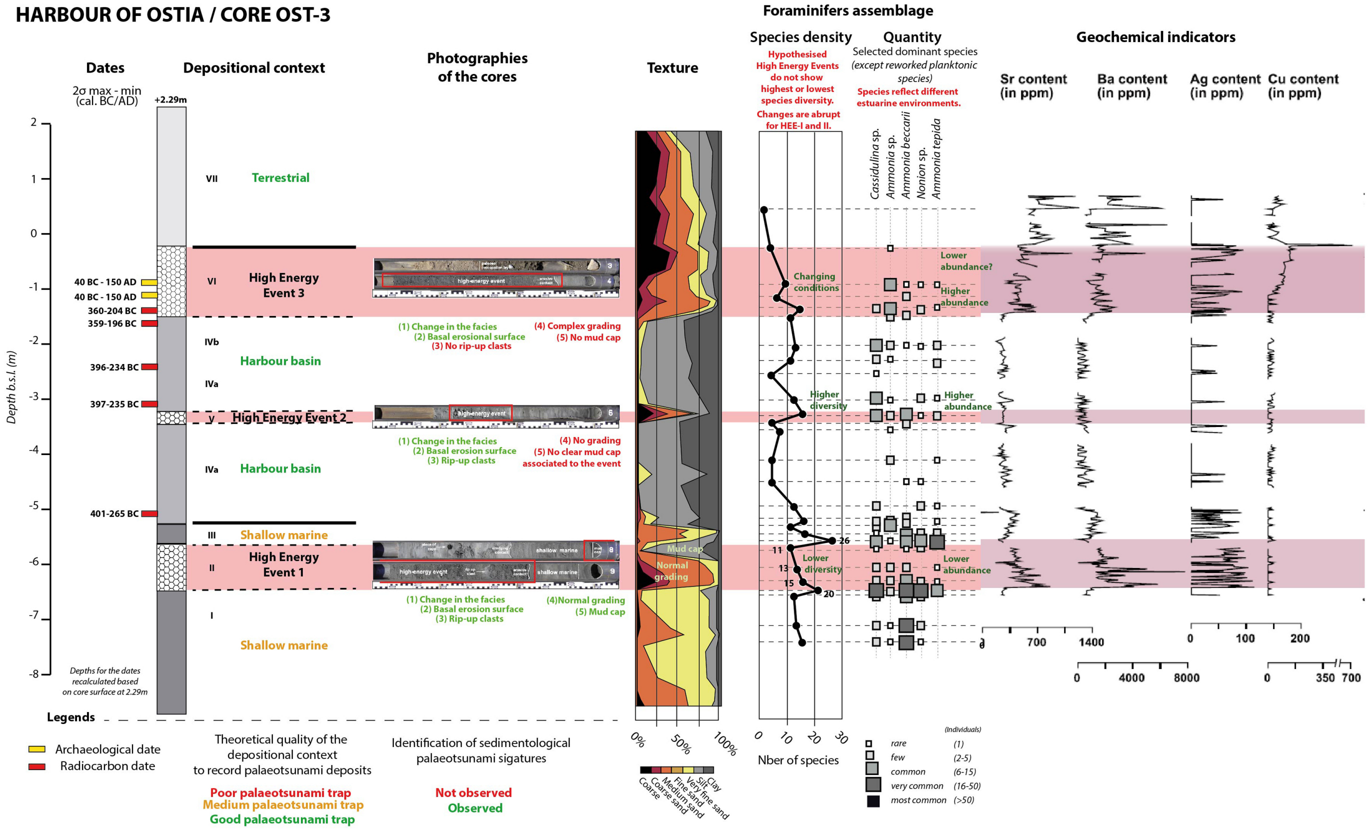

HARBOUR OF OSTIA / CORE OST-3
Dates
2σ max - min (cal. BC/AD)
+2.29m
Depositional context
Photographies of the cores
Texture
Foraminifers assemblage
Species density
Hypothesised High Energy Events do not show highest or lowest species diversity.
Changes are abrupt for HEE-I and II.
Quantity
Selected dominant species (except reworked planktonic species)
Species reflect different estuarine environments.
Cassidulina sp.
Ammonia sp.
Ammonia beccarii
Nonion sp.
Ammonia tepida
Geochemical indicators
Sr content (in ppm)
Ba content (in ppm)
Ag content (in ppm)
Cu content (in ppm)
Depth b.s.l. (m)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
40 BC - 150 AD
40 BC - 150 AD
360-204 BC
359-196 BC
396-234 BC
397-235 BC
401-265 BC
VII
Terrestrial
VI
High Energy Event 3
IVb
Harbour basin
IVa
V
High Energy Event 2
IVa
Harbour basin
III
Shallow marine
II
High Energy Event 1
I
Shallow marine
paleosol (occupation layer)
high-energy event
erosive contact
3
4
(1) Change in the facies
(2) Basal erosional surface
(3) No rip-up clasts
(4) Complex grading
(5) No mud cap
high-energy event
6
(1) Change in the facies
(2) Basal erosion surface
(3) Rip-up clasts
(4) No grading
(5) No clear mud cap associated to the event
piece of rope
dredging contact
shallow marine
mud cap
8
high-energy event
rip up clast
erosive contact
shallow marine
9
(1) Change in the facies
(2) Basal erosion surface
(3) Rip-up clasts
(4)Normal grading
(5) Mud cap
Mud cap
Normal grading
Changing conditions
Higher diversity
26
11
13
15
20
Lower diversity
Lower abundance?
Higher abundance
Higher abundance
Lower abundance
Depths for the dates recalculated based on core surface at 2.29m
0%
50%
100%
Coarse
Coarse sand
Medium sand
Fine sand
Very fine sand
Silt
Clay
0
10
20
30
Nber of species
(Individuals)
rare (1)
few (2-5)
common (6-15)
very common (16-50)
most common (>50)
0
700
1400
0
4000
8000
0
100
200
0
350
700
Legends
Archaeological date
Radiocarbon date
Theoretical quality of the depositional context to record palaeotsunami deposits
Poor palaeotsunami trap
Medium palaeotsunami trap
Good palaeotsunami trap
Identification of sedimentological palaeotsunami sigatures
Not observed
Observed

Figure 2

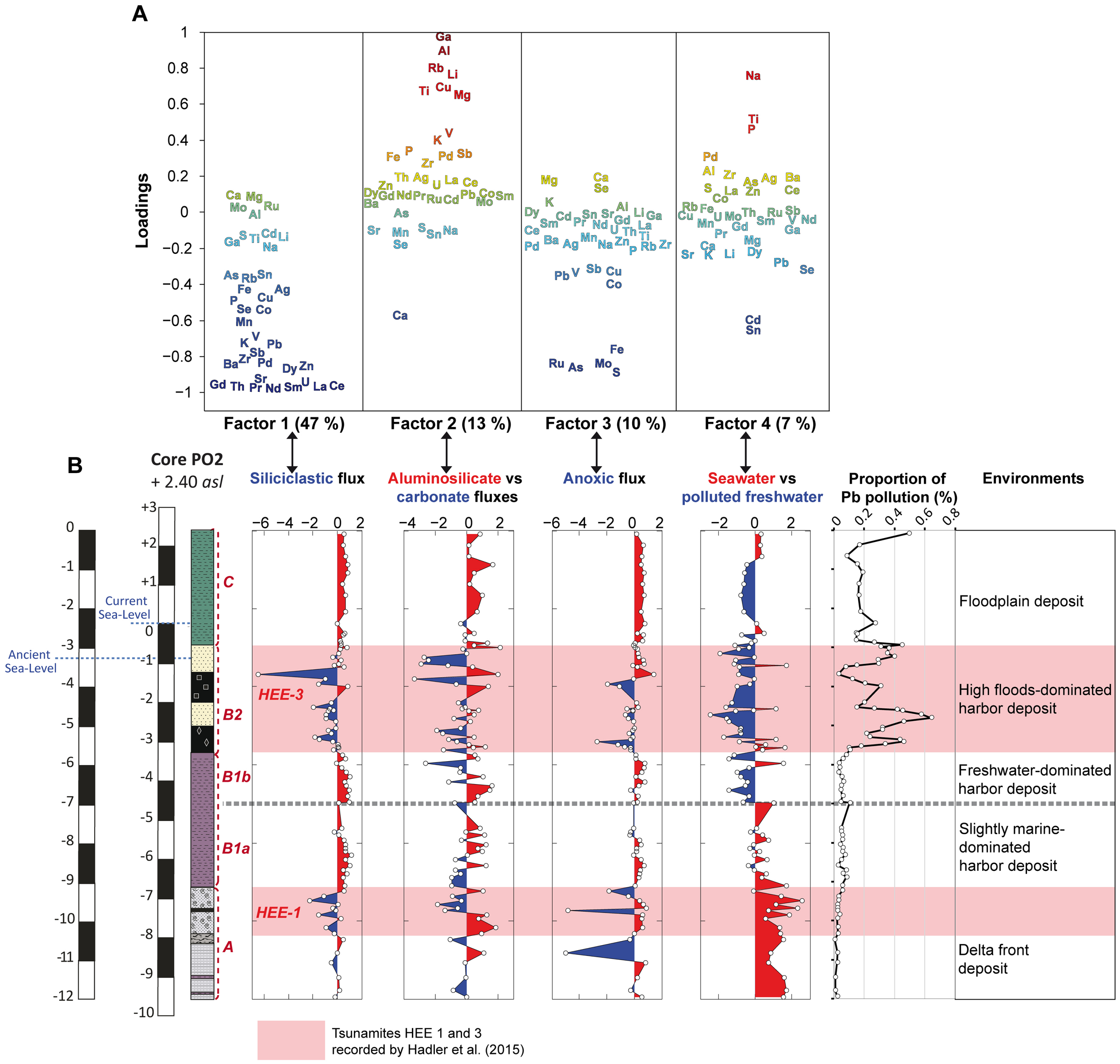

A
Loadings
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
Factor 1 (47 %)
Factor 2 (13 %)
Factor 3 (10 %)
Factor 4 (7 %)
Ga Al Rb Li Ti Cu Mg
K V
Fe P Zr Pd Sb
Na
Ti P
B
Core PO2
+ 2.40 asl
Current Sea-Level
Ancient Sea-Level
C
B2
B1b
B1a
A
HEE-3
HEE-1
Siliciclastic flux
Aluminosilicate vs carbonate fluxes
Anoxic flux
Seawater vs polluted freshwater
Proportion of Pb pollution (%)
Environments
Floodplain deposit
High floods-dominated harbor deposit
Freshwater-dominated harbor deposit
Slightly marine-dominated harbor deposit
Delta front deposit
Tsunamites HEE 1 and 3 recorded by Hadler et al. (2015)

Figure 3

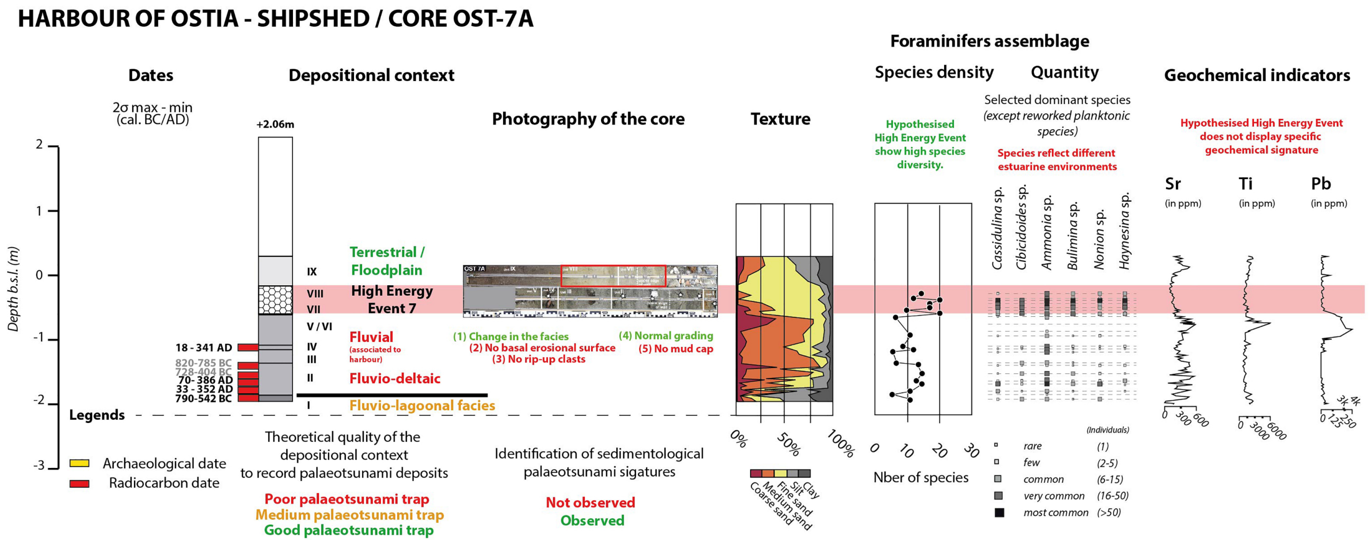

HARBOUR OF OSTIA - SHIPSHED / CORE OST-7A
Dates
2σ max - min
(cal. BC/AD)
Depositional context
+2.06m
Photography of the core
Texture
Foraminifers assemblage
Species density
Quantity
Geochemical indicators
Depth b.s.l. (m)
2
1
0
-1
-2
-3
18 - 341 AD
820-785 BC
728-404 BC
70 - 386 AD
33 - 352 AD
790-542 BC
IX
VIII
VII
V / VI
IV
III
II
I
Terrestrial / Floodplain
High Energy Event 7
Fluvial
(associated to harbour)
Fluvio-deltaic
Fluvio-lagoonal facies
OST 7A
(1) Change in the facies
(2) No basal erosional surface
(3) No rip-up clasts
(4) Normal grading
(5) No mud cap
Hypothesised High Energy Event show high species diversity.
Selected dominant species (except reworked planktonic species)
Species reflect different estuarine environments
Cassidulina sp.
Cibicidoides sp.
Ammonia sp.
Bulimina sp.
Nonion sp.
Haynesina sp.
Hypothesised High Energy Event does not display specific geochemical signature
Sr
(in ppm)
Ti
(in ppm)
Pb
(in ppm)
0 300 600
0 3000 6000
0 125 250 3k 4k
0% 50% 100%
0 10 20 30
Nber of species
Coarse sand
Medium sand
Fine sand
Silt
Clay
(Individuals)
rare (1)
few (2-5)
common (6-15)
very common (16-50)
most common (>50)
Legends
Archaeological date
Radiocarbon date
Theoretical quality of the depositional context to record palaeotsunami deposits
Poor palaeotsunami trap
Medium palaeotsunami trap
Good palaeotsunami trap
Identification of sedimentological palaeotsunami sigatures
Not observed
Observed

Figure 4

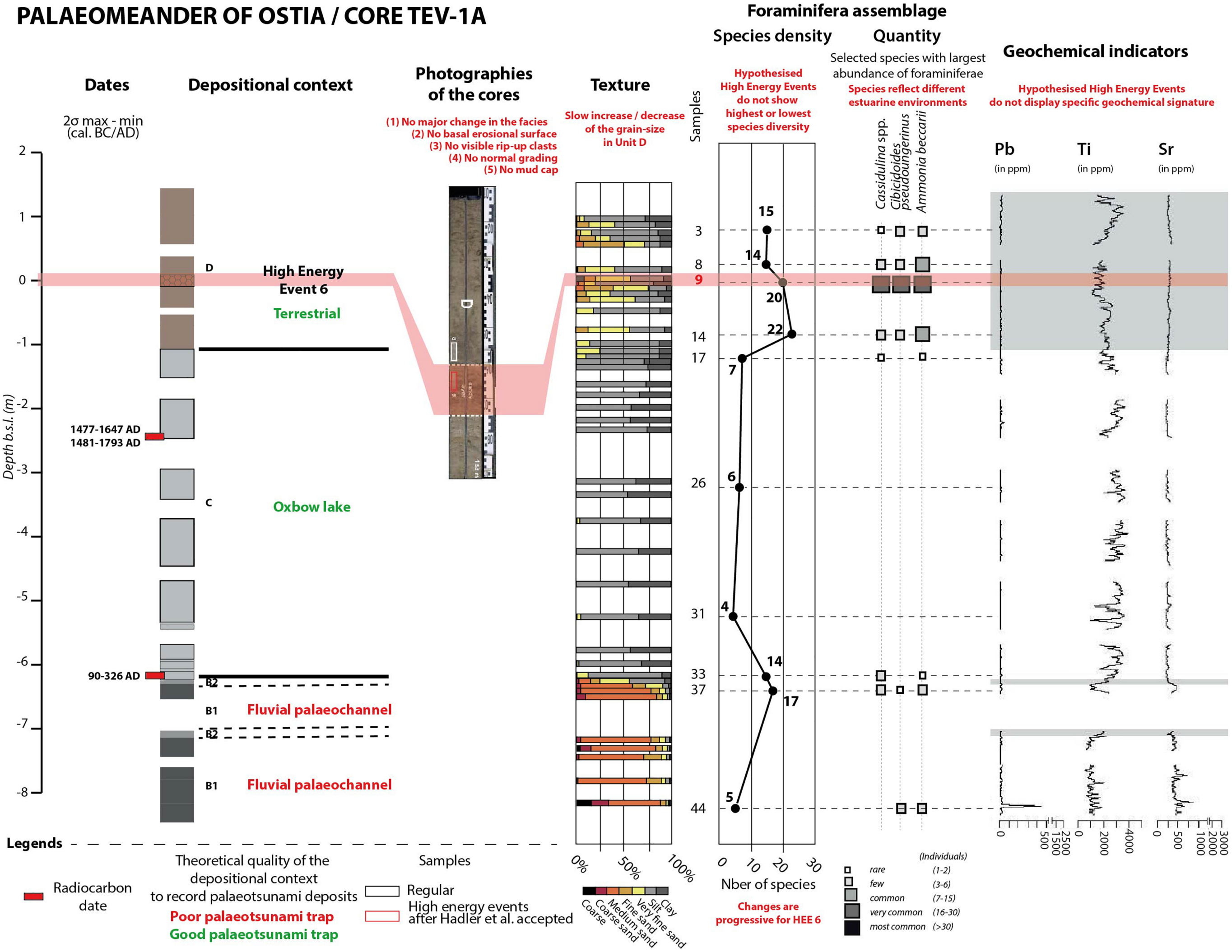

PALAEOMEANDER OF OSTIA / CORE TEV-1A
Dates
2σ max - min (cal. BC/AD)
Depositional context
Photographies of the cores
(1) No major change in the facies
(2) No basal erosional surface
(3) No visible rip-up clasts
(4) No normal grading
(5) No mud cap
Texture
Slow increase / decrease of the grain-size in Unit D
Samples
Foraminifera assemblage
Species density
Hypothesised High Energy Events do not show highest or lowest species diversity
Quantity
Selected species with largest abundance of foraminiferae
Species reflect different estuarine environments
Cassidulina spp.
Cibicidoides pseudoungerinus
Ammonia beccarii
Geochemical indicators
Hypothesised High Energy Events do not display specific geochemical signature
Pb (in ppm)
Ti (in ppm)
Sr (in ppm)
Depth b.s.l. (m)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
1477-1647 AD
1481-1793 AD
90-326 AD
D
High Energy Event 6
Terrestrial
C
Oxbow lake
B2
B1
Fluvial palaeochannel
B2
B1
Fluvial palaeochannel
3
8
9
14
17
26
31
33
37
44
15
14
20
22
7
6
4
14
17
5
0%
50%
100%
0
10
20
30
Nber of species
Changes are progressive for HEE 6
0
500
1500
2500
0
2000
4000
0
500
1000
2000
3000
Legends
Radiocarbon date
Theoretical quality of the depositional context to record palaeotsunami deposits
Poor palaeotsunami trap
Good palaeotsunami trap
Samples
Regular
High energy events after Hadler et al. accepted
Coarse
Coarse sand
Medium sand
Fine sand
Very fine sand
Silt
Clay
(Individuals)
rare (1-2)
few (3-6)
common (7-15)
very common (16-30)
most common (>30)

Figure 5

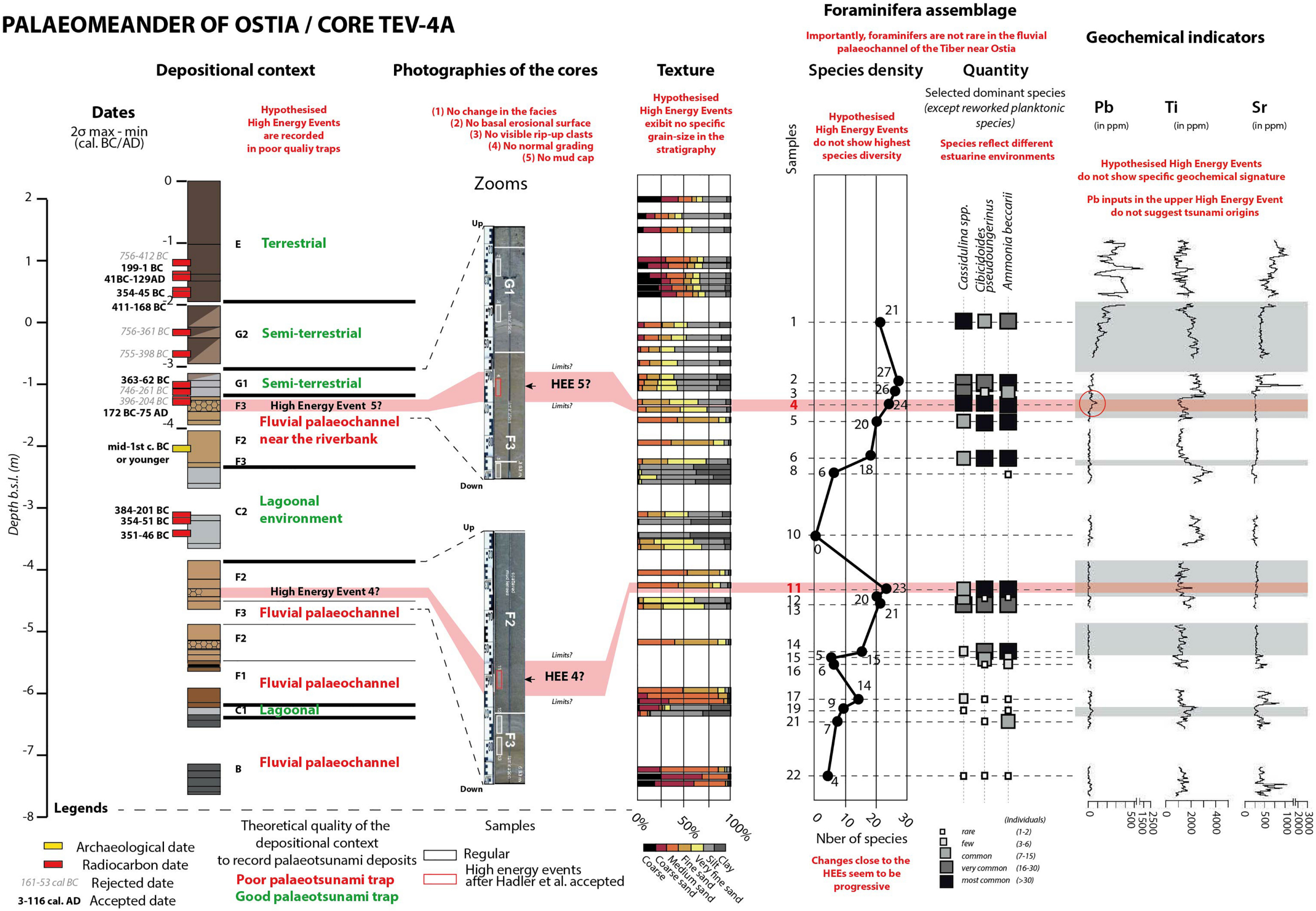

PALAEOMEANDER OF OSTIA / CORE TEV-4A
Depositional context
Photographies of the cores
Texture
Foraminifera assemblage
Importantly, foraminifers are not rare in the fluvial palaeochannel of the Tiber near Ostia
Species density
Quantity
Geochemical indicators
Dates
2σ max - min (cal. BC/AD)
Hypothesised High Energy Events are recorded in poor qualiy traps
(1) No change in the facies
(2) No basal erosional surface
(3) No visible rip-up clasts
(4) No normal grading
(5) No mud cap
Hypothesised High Energy Events exibit no specific grain-size in the stratigraphy
Samples
Hypothesised High Energy Events do not show highest species diversity
Selected dominant species (except reworked planktonic species)
Species reflect different estuarine environments
Pb (in ppm)
Ti (in ppm)
Sr (in ppm)
Hypothesised High Energy Events do not show specific geochemical signature
Pb inputs in the upper High Energy Event do not suggest tsunami origins
Zooms
Depth b.s.l. (m)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0
-1
-2
-3
-4
756-412 BC
199-1 BC
41BC-129AD
354-45 BC
411-168 BC
756-361 BC
755-398 BC
363-62 BC
746-261 BC
396-204 BC
172 BC-75 AD
mid-1st c. BC or younger
384-201 BC
354-51 BC
351-46 BC
E
Terrestrial
G2
Semi-terrestrial
G1
Semi-terrestrial
F3
High Energy Event 5?
Fluvial palaeochannel near the riverbank
F2
F3
C2
Lagoonal environment
F2
High Energy Event 4?
F3
Fluvial palaeochannel
F2
F1
Fluvial palaeochannel
C1
Lagoonal
B
Fluvial palaeochannel
Up
Down
G1
F3
F2
Limits?
HEE 5?
HEE 4?
Cassidulina spp.
Cibicidoides pseudoungerinus
Ammonia beccarii
1
2
3
4
5
6
8
10
11
12
13
14
15
16
17
19
21
22
21
27
26
24
20
18
6
0
23
20
21
5
15
6
14
9
7
4
Legends
Archaeological date
Radiocarbon date
161-53 cal BC Rejected date
3-116 cal. AD Accepted date
Theoretical quality of the depositional context to record palaeotsunami deposits
Poor palaeotsunami trap
Good palaeotsunami trap
Samples
Regular
High energy events after Hadler et al. accepted
0%
50%
100%
Coarse
Coarse sand
Medium sand
Fine sand
Very fine sand
Silt
Clay
0
10
20
30
Nber of species
Changes close to the HEEs seem to be progressive
(Individuals)
rare (1-2)
few (3-6)
common (7-15)
very common (16-30)
most common (>30)
0
500
1500
2500
0
2000
4000
0
500
1000
2000
3000

Figure 6

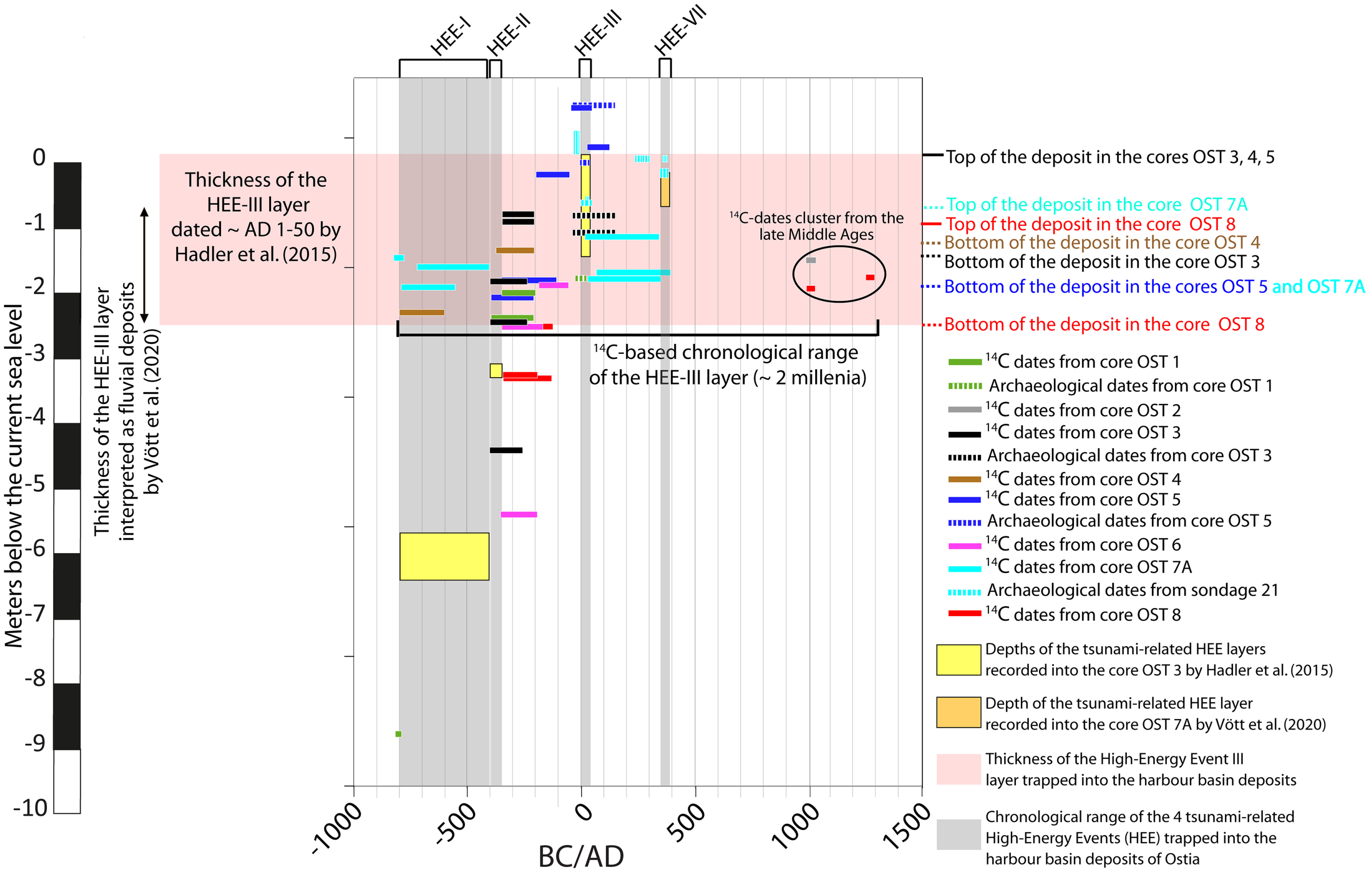

HEE-I
HEE-II
HEE-III
HEE-VII
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Meters below the current sea level
Thickness of the HEE-III layer interpreted as fluvial deposits by Vött et al. (2020)
Thickness of the HEE-III layer dated ~ AD 1-50 by Hadler et al. (2015)
^{14}C-dates cluster from the late Middle Ages
^{14}C-based chronological range of the HEE-III layer (~ 2 millenia)
-1000
-500
0
500
1000
1500
BC/AD
Top of the deposit in the cores OST 3, 4, 5
Top of the deposit in the core OST 7A
Top of the deposit in the core OST 8
Bottom of the deposit in the core OST 4
Bottom of the deposit in the core OST 3
Bottom of the deposit in the cores OST 5 and OST 7A
Bottom of the deposit in the core OST 8
^{14}C dates from core OST 1
Archaeological dates from core OST 1
^{14}C dates from core OST 2
^{14}C dates from core OST 3
Archaeological dates from core OST 3
^{14}C dates from core OST 4
^{14}C dates from core OST 5
Archaeological dates from core OST 5
^{14}C dates from core OST 6
^{14}C dates from core OST 7A
Archaeological dates from sondage 21
^{14}C dates from core OST 8
Depths of the tsunami-related HEE layers recorded into the core OST 3 by Hadler et al. (2015)
Depth of the tsunami-related HEE layer recorded into the core OST 7A by Vött et al. (2020)
Thickness of the High-Energy Event III layer trapped into the harbour basin deposits
Chronological range of the 4 tsunami-related High-Energy Events (HEE) trapped into the harbour basin deposits of Ostia

Figure 7

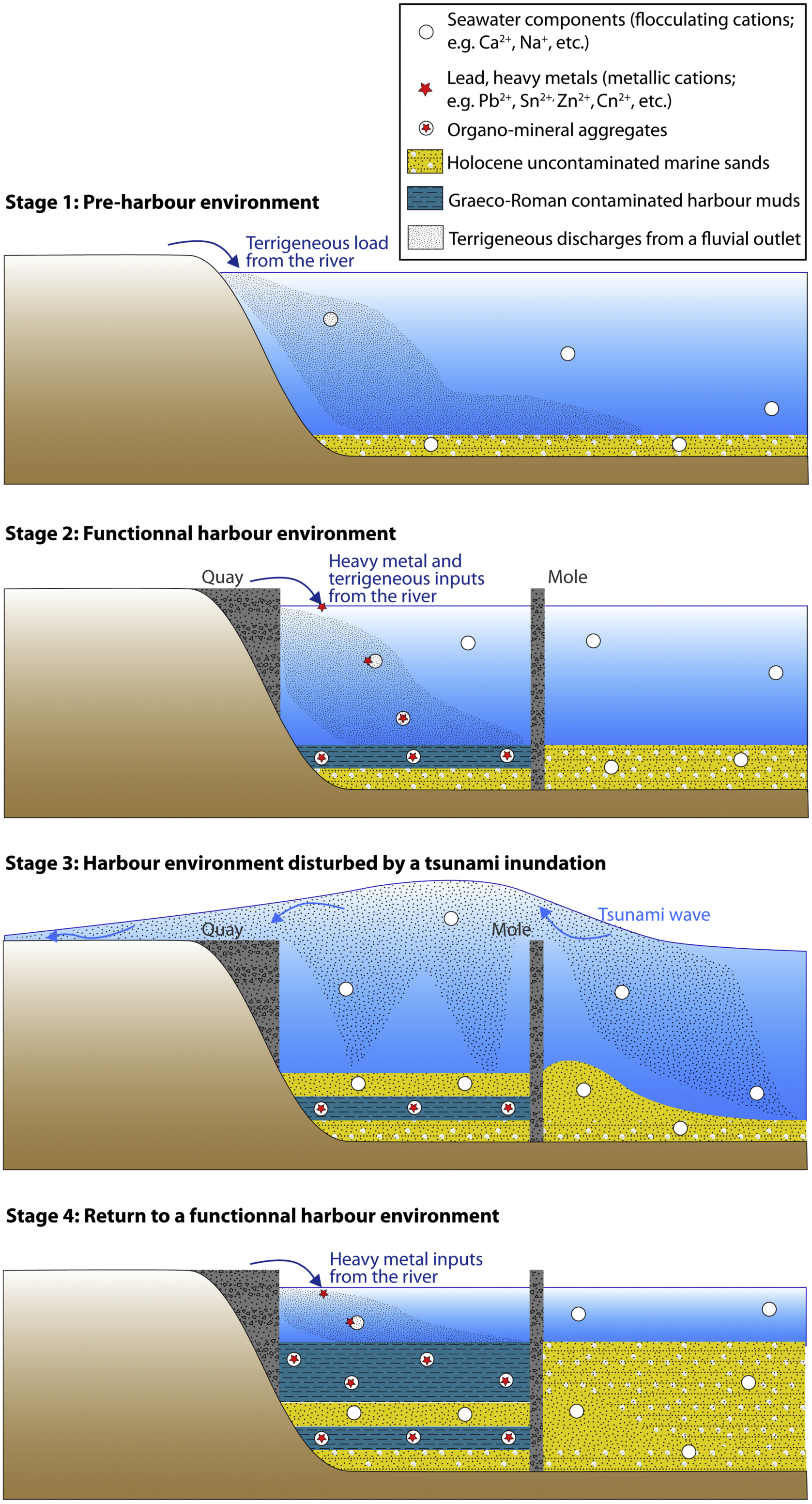
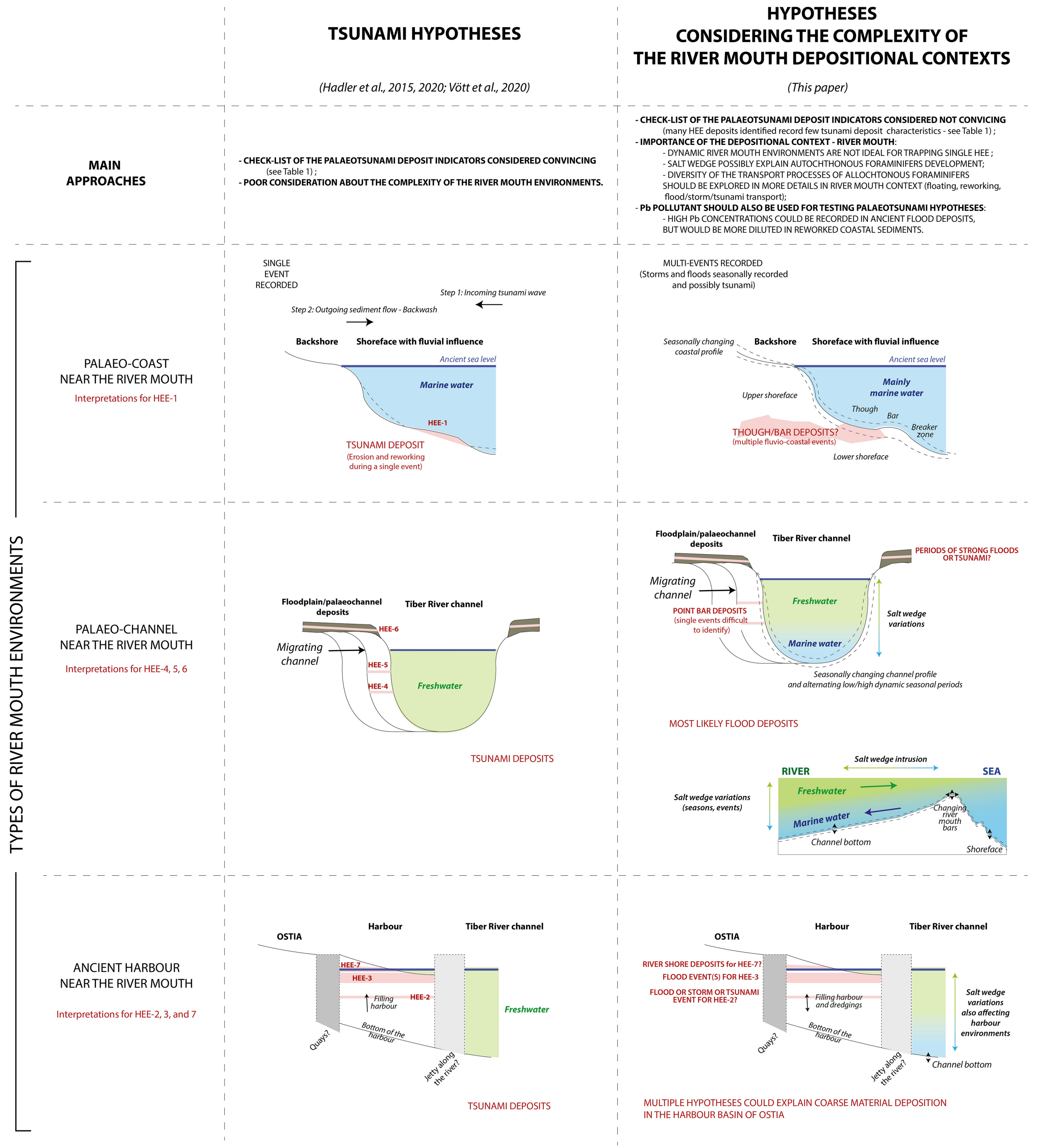

Seawater components (flocculating cations; e.g. Ca2+, Na+, etc.)
Lead, heavy metals (metallic cations; e.g. Pb2+, Sn2+, Zn2+, Cn2+, etc.)
Organo-mineral aggregates
Holocene uncontaminated marine sands
Graeco-Roman contaminated harbour muds
Terrigeneous discharges from a fluvial outlet
Stage 1: Pre-harbour environment
Terrigeneous load from the river
Stage 2: Functionnal harbour environment
Quay
Heavy metal and terrigeneous inputs from the river
Mole
Stage 3: Harbour environment disturbed by a tsunami inundation
Quay
Mole
Tsunami wave
Stage 4: Return to a functionnal harbour environment
Heavy metal inputs from the river

Figure 8



TSUNAMI HYPOTHESES

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

HYPOTHESES CONSIDERING THE COMPLEXITY OF THE RIVER MOUTH DEPOSITIONAL CONTEXTS

(This paper)

MAIN APPROACHES

Tsunami hypotheses:

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

This paper:

- **CHECK-LIST OF THE PALAEOTSUNAMI DEPOSIT INDICATORS CONSIDERED NOT CONVICING** (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 ALLOCHTONOUS 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.

Figure 9