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## **Reconstruction of the Tiber Deltaic stratigraphic successions near Ostia using the PADM chart and tracking of the bedload-derived facies (Rome, Italy)**

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1 Reconstruction of the Tiber Deltaic stratigraphic successions near Ostia using  
2 the PADM chart and tracking of the bedload-derived facies (Rome, Italy)

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24 **Keywords:** chronostratigraphy; palaeoenvironments; PADM chart; Tiber delta.

25 **Highlights**

- 26 • Reconstruction of coastal transgression and progradation at the transition between the inner  
27 and outer delta plain near the archaeological site of Ostia;
- 28 • High sedimentation rates and deepening facies coeval to sea level jumps from the 9-8 k cal.  
29 BP;
- 30 • Strong progradational phases are recorded around 4 k cal. BP, and from 2.8 to 2.6 k cal. BP;
- 31 • Identification of the Tiber River influence below and near the area of the archaeological site  
32 of Ostia: 4.2 to 4 k, 2.9 to 2.5 k, 2.5 to 1.7 k cal. BP;
- 33 • Synthesis of chronostratigraphic data and delineation of the envelope of the fluvial lateral  
34 mobility of the Tiber River since 6 k cal. BP (channel belt);
- 35 • PADM chart demonstrates great efficiency in interpreting stratigraphic successions in a river  
36 delta, in identifying evidence of coastline-trajectories and should help in constraining  
37 decompaction methods for deltaic sequences.

38 **Abstract**

39 Located between the deltaic plain and the subaqueous delta, base level is one of the most  
40 important factors that affect depositional systems and the sedimentary architecture of river deltas.  
41 In this respect, its changes are essential to reconstruct delta evolution during the Holocene. In this  
42 paper, we study three cores drilled in the Tiber delta (Italy). Palaeoenvironmental analyses were  
43 performed and included new sedimentological data (laser grain size, loss-on-ignition, magnetic  
44 susceptibility), new data from bioindicators (ostracods and macrofauna), and 11 new radiocarbon  
45 dates. The three cores were analysed and replaced in a cross section between the Inner and Outer

46 Tiber delta, i.e., in the palaeolagoon and in the progradational delta plain. First, we have mapped the  
47 Holocene transgression and progradation of the Ostia area using palaeoenvironmental age-depth  
48 modelling techniques (PADMs). PADM charts help to interpret a stratigraphic succession in a river  
49 delta. They contribute to the understanding of the links between depositional environments,  
50 sedimentation rate, and sea level rise and to reconstruct coastline trajectories. More precisely, they  
51 contribute to the interpretation of the consequences of the sea level jumps dated to the 9000-8000  
52 cal. BP period on coastal environments and help to identify progradational phases (around 4 k, and  
53 from 2.8 to 2.6 k cal. BP). Second, we identify indirect (freshwater bioindicators) and direct (bedload-  
54 derived facies) evidence of fluvial activity in the studied cross section. The studied deep cores  
55 indicate that at least one palaeochannel of the Tiber River was already flowing in the  
56 middle/southern part of the delta from 4 k cal. BP. Finally, a first map of the lateral mobility of the  
57 palaeochannels of the Tiber River is proposed for the last 6 k cal. BP using the new data and a  
58 synthesis of all the data available at the scale of the delta.

## 59 **INTRODUCTION**

60 Geomorphologically, river deltas are composed of a subaerial plain and a subaqueous part  
61 separated by the sea level or base level (Wright and Coleman, 1973; Wright, 1977, 1985; Coleman,  
62 1982; Stanley and Warne, 1994; Hori and Saito, 2007; Anthony et al., 2014). The existence of deltas  
63 depends primarily on the sediment load transported by the rivers to the sea and on the coastal and  
64 marine conditions. River channels are essential to route sediment to the coastlines and contribute to  
65 shape the deltas. In parallel, the sedimentary architecture of river deltas is mainly controlled by the  
66 base level that changes over time. It is a key factor that affects the characteristics and the location of  
67 fluvial, coastal, and marine facies. The reconstruction of the formation of river deltas during the  
68 Holocene depends on an integrated approach, taking into account a large range of data such as  
69 sediment facies, facies distribution, unconformities, relative sea level change, and accommodation  
70 space. In this regard, methods, notions, concepts, and visualisation tools developed in sequence

71 stratigraphy are essential (Posamentier and James, 1993; Catuneanu, 2006; Catuneanu et al., 2009;  
72 Embry et al., 2007). The time-stratigraphic context is also crucial to interpret sediment deposits in  
73 sequence stratigraphy. We suggest testing the Palaeoenvironmental-Age Depth Model (PADM chart)  
74 to visualise and interpret links between sedimentary facies, the relative sea level change rate, and  
75 the sedimentation rate (Salomon et al., 2016a). It corresponds to a classic age-depth model, but  
76 instead attempts to integrate a wide range of relevant data to interpret deltaic sediment deposits by  
77 using concepts developed in sequence stratigraphy.

78         In this study, we not only consider coastal and marine sediments and their relation to the  
79 Holocene base level, but also consider river deposits even though they follow different trends. It is  
80 very easy to spot the current channels, but multiple channels have existed throughout the Holocene  
81 that are less easy to identify. The palaeogeographical reconstruction of river mobility in deltas  
82 through the Holocene is a challenge. During the Early Holocene transgressive phase, the  
83 identification of river mouth palaeochannels is based on sedimentary cores. Their locations are  
84 mostly because of chance or a large chronostratigraphic database with many cores,  
85 palaeoenvironmental analyses and dates. In this case, palaeogeographical reconstruction of the  
86 Holocene transgression of the river mouth area of the Rhine is remarkable (Hijma and Cohen, 2011).  
87 The locations of the deltaic river courses or the river mouths are easier for younger stages of delta  
88 formation: when base level rise stalls, a high stand is established and the delta system becomes  
89 progradational. The progradational phase started around 6500 cal. BP in the Mediterranean area  
90 because of sea level rising more slowly (Nile delta: Stanley and Warne, 1993, 1994; Po delta: Amorosi  
91 et al., 2017; Stefani and Vincenzi, 2005; Rhone delta: Vella and Provansal, 2000; Vella et al., 2005;  
92 Ebro delta: Sornoza et al., 1998; Cearreta et al., 2016). From these youngest millennia, some  
93 morphological changes are noticeable on the ground surface. Palaeochannels, beach ridges, and  
94 palaeolagoons can be traceable through aerial photography, satellite imagery, old maps, or LiDAR  
95 data. Palaeochannels can be characterised by their morphologies (levees, ridges and swales, cut-off  
96 channels) or their location is inferred when they cut pre-existing beach ridges (Pranzini, 2007;

97 Ullmann et al., 2018; Gebremichael et al., 2018). Alternatively, palaeoriver mouths can be located  
98 using beach ridges in cuspidate deltas (Stefani and Vincenzi, 2005; Vella et al., 2005) or by producing  
99 submarine topographic/geophysical profiles of subaqueous lobe deltas (Shaw et al., 2016). However,  
100 through time, floodplain deposits and coastal dynamics, respectively, contribute to cover and rework  
101 morphological evidence.

102 Typically, studies on coastal palaeodynamics are more numerous than studies on fluvial  
103 palaeodynamics of the adjacent delta plain inland. This can be attributed to a better record of coastal  
104 morphologies on aerial photography/satellite imagery (beach-ridges), and also because coastal  
105 dynamics are better expressed vertically in relation to the base level (RSL - Relative Sea Level).  
106 Progradational beach ridges can extend widely along the coast and can be studied using  
107 perpendicular cross sections (dates of the progradational phases and identification of potential  
108 erosional or stability phases) (Bicket et al., 2009 for the Tiber delta). The location of palaeochannels  
109 is more difficult to predict (especially when it involves avulsion processes), and river systems often  
110 rework older alluvial morphologies. In recent years, this discrepancy between coastal and fluvial  
111 studies tends to be filled by an increasing number of sedimentary drillings, as well as the  
112 development of LiDAR data. For example, the recurrent discussion about the identification of Nile  
113 River branches is currently reexamined by LiDAR data from TamDEM-X (Gebremichael et al., 2018;  
114 Ullmann et al., 2018).

115 This paper focuses on cores drilled between 2011 and 2013 down to 25m in the area of the  
116 archaeological site of Ostia (Figs. 1 and 2). The studied cross section includes the turning point  
117 between the last phase of the transgression and the early phases of the progradation (Figs. 2 and 3).  
118 Palaeoenvironmental Age-Depth Models (PADM charts) are made to clarify the interpretation of this  
119 coastal area and display the effect of river erosion on the sedimentary sequences.

## 120 **GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS**

121 The Tiber delta is located in the Tyrrhenian extensional continental margin. This  
122 configuration started during the Miocene and shaped the landscape with northwest/southeast  
123 normal faulting and northeast/southwest transverse systems in the lower Tiber (Funciello, 1995).  
124 The Tiber delta is developing near Upper-Middle Pleistocene volcanoes on the east of the Tyrrhenian  
125 Sea back arc basin (Karner et al., 2001b) and takes part of the Quaternary succession starting in the  
126 Late Pliocene near Rome (Milli, 1997; Karner et al., 2001a). General uplift of the area is related to  
127 volcanic activity and isostasy (De Rita et al., 1994; Ferranti et al., 2006; Mantovani et al., 2009).  
128 Active faults in the Tiber delta during the Holocene are still discussed by different research teams  
129 (Bigi et al., 2014; Ciotoli et al., 2016; Marra et al., 2019) (Fig. 1).

130 The Tiber delta is a wave dominated delta (Bellotti et al., 1994). The Tiber River is 405 km  
131 long with a spring at 524 m a.s.l. The watershed area is 17,375 km<sup>2</sup> (Autorità di Bacino del Fiume  
132 Tevere, 2006). Today, the regime of the Tiber River is pluvio-nival with maximum mean discharge in  
133 winter (February) and minimum mean discharge in summer (August). During the twentieth to  
134 twenty-first centuries the annual water discharge is 213 m<sup>3</sup>/s, with a minimum at 62 m<sup>3</sup>/s (August  
135 1986) and a maximum at 2750 m<sup>3</sup>/s (December 1937) (Bersani and Bencivenga, 2001). The first  
136 palaeogeographical reconstructions date to the 1950s and 1960s with the aerial-photo interpretation  
137 of J. Bradford (1957 – Fig. 23) and a geological map (Segre in Dragone et al., 1967). In the context of  
138 the construction of the International Airport of Rome – Fiumicino, Segre (1986) hypothesized the  
139 presence of many palaeochannels in the Tiber delta. The first palaeogeographical reconstruction,  
140 based on sedimentary cores and radiocarbon dates, was proposed in the 1980s (Belluomini et al.,  
141 1986). Later, reconstructions based on an integrated approach of sedimentary cores,  
142 sedimentological analysis, palaeoenvironmental data, and sequential stratigraphy were coordinated  
143 by Bellotti (Bellotti et al., 1994, 1995, 1989, 2007, 2018), and more recently by Milli (Amorosi and  
144 Milli, 2001; Milli et al., 2013, 2016). These studies contributed in reconstructing the formation of the  
145 prodelta, the delta front, and the deltaic plain during the Holocene. Traditionally, the Tiber delta  
146 plain is divided into two main geomorphological units; the inner delta plain occupied by the

147 palaeolagoon of Ostia and Maccarese, and the outer delta plain corresponding to the prograded  
148 deltaic plain.

149           Similar to other river deltas across the world, two periods characterise the evolution of the  
150 Tiber river mouth since the Last Glacial Maximum. Following the quick sea level rise starting around  
151 16,500 cal. BP (Lambeck et al., 2014), transgression affected the Tiber River mouth and contributed  
152 to the formation of a specific sedimentary sequence: the Transgressive Systems Tract (TST).  
153 Afterwards, since 7000-6000 cal. BP, sea level rise slowed down and the Tiber delta started to form a  
154 large prograded plain (Bellotti et al., 2007). During this second period, sedimentary deposits belong  
155 to the Highstand Systems Tract (HST). More detailed analysis of the phases of progradation and  
156 erosion are proposed by Giraudi (2004) and Bicket et al. (2009). For the last 2000 yr, archaeological  
157 and historical data can be used to reconstruct fluvial and coastal mobility (Le Gall, 1953; Bersani and  
158 Moretti, 2008) and can be combined with sedimentary cores, <sup>14</sup>C and OSL dates (Salomon, 2013).

159           Many hypotheses exist for the location of the river channels or channel belts in the Tiber  
160 delta during the Holocene (Dragone et al., 1967; Segre, 1986; Bellotti et al., 2007; Giraudi et al.,  
161 2009). The topography of the unconformity at the base of the Tiber Depositional Sequence confines  
162 the lateral instability of the river channels in the centre of the Tiber delta during the early stages of  
163 the transgression (13,000 – 9000 cal. BP - Bellotti et al., 2007; Milli et al., 2013). Main phases of  
164 evolution suggest a channel belt of the Tiber in the central axis of the delta during the Early Holocene  
165 (> 9000 cal. BP - Bellotti et al., 2007; Milli et al., 2013, 2016), and a displacement of the channel belt  
166 towards the south until today (< 9000 cal. BP - Bellotti et al., 2007). The identification of  
167 palaeochannels visible in aerial photography, satellite imagery, and old maps makes it possible to  
168 reconstruct the evolution of the lateral mobility of the Tiber during at least the last 2500 yr  
169 (Arnoldus-Huyzendveld and Paroli, 1995; Arnoldus-Huyzendveld and Pellegrino, 1999; Salomon et al.,  
170 2017; 2018). The first detailed description of the bedload-derived facies for the Tiber delta is  
171 proposed for the bottom of the channels of the meander of Ostia dated between the end of the first

172 millennium BCE and 1557 CE (bedload-derived deposits at the bottom of the point bar and at the  
173 bottom of the oxbow - Salomon et al., 2017). Studies based on cores drilled in the coastal area  
174 (Goiran et al., 2010; Salomon, 2013; Goiran et al., 2014), in the palaeolagoon of Ostia (Bellotti et al.,  
175 2011; Vittori et al., 2015) and in palaeochannels of the Tiber River of Ostia (Salomon et al., 2017,  
176 2018), suggest a migration of the last section of the course of the Tiber in its delta towards the south  
177 between 2800 cal. BP and 2300-1700 cal. BP. Most of the evidence is from indirect fluvial influence  
178 suggested by bioindicators (Bellotti et al., 2011; Goiran et al., 2014). Recently, coarse bedload-  
179 derived facies from this period have been dated just north of Ostia (Hadler et al., in press, Core  
180 TEV2A/TEV DP8), and could be product of the initial phase of formation of the palaeomeander of  
181 Ostia (Salomon et al., 2017, 2018). Earlier phases of the fluvial evolution are still to be tracked and  
182 dated with precision.

## 183 **METHODS**

184 This paper includes new chrono-stratigraphical and palaeoenvironmental data from Cores  
185 PO-1 and 2, CAT-3 and MO-2. The upper parts of these cores were previously published and studied  
186 with a geoarchaeological perspective. These upper stratigraphic sequences were interpreted in  
187 regards to the evolution of the Roman city of Ostia (Core MO-2 in Salomon et al., 2017; Cores CAT-2  
188 and CAT-3 in Salomon et al., 2018) and its harbours (PO-1 and 2 in Goiran et al., 2014). Core LOA-1  
189 (Vittori et al., 2015), Core CAT-2 (Salomon et al., 2018) and Core OST-4 (Hadler et al., 2015)  
190 complement the cross section.

191 Cores PO-1 / PO-2, CAT-2 / CAT-3, and MO-2 were drilled between 2010 and 2013.  
192 Stratigraphies record a large range of sedimentary facies and were analysed using  
193 palaeoenvironmental indicators classically used in such context (Figs. 4, 6, and 8). Before any  
194 destructive analysis, the magnetic susceptibility of the core sequences were measured in CGS using a  
195 Bartington MS2E1 (Dearing, 1999). In the Tiber delta, the magnetic susceptibility records content of  
196 clinopyroxenes and magnetites coming from the volcanic areas of the watershed (Belfiore et al.,

197 1987). High magnetic susceptibility is primarily observed in the sand fraction of the fluvial bedload-  
198 derived facies or in coastal sandy placers formed along the coast. Magnetic susceptibility is mainly  
199 used here to support the delineation of stratigraphical units. Palaeohydrodynamic context is  
200 deduced from grain-size analyses. Wet sieving at 63 $\mu$ m and 2mm was systematically applied to the  
201 sediments sampled from the different units of the core stratigraphies. For selected samples  
202 distributed in all stratigraphical units, wet sieving was completed with detailed grain size analysis  
203 conducted on a laser particle analyzer from Malvern Panalytical. Common grain size indicators such  
204 as sorting and median were calculated (Folk and Ward, 1957; Cailleux and Tricart, 1959). Loss-on-  
205 ignition measurements were also conducted on sediments heated at 550°C for four hours (for  
206 organic matter) and 950°C for two hours (for carbonates) following the method proposed by Heiri et  
207 al. (2001).

208 Palaeoecological context is based on the analysis of macrofauna and ostracods. Macrofauna  
209 was extracted from sieved samples >2 mm (Perès and Picard, 1964; Bellan-Santini et al., 1994). In the  
210 sieved sediments (63  $\mu$ m < x < 1 mm), all ostracods (small bivalved crustaceans) were picked and  
211 normalised to 10 g of sediment weight (Carbonel, 1988; Frenzel and Boomer, 2005; Mazzini et al.,  
212 2011; Ruiz et al., 2005; Vittori et al., 2015). Macrofauna and ostracods were identified in order to  
213 deduce, in particular, the freshwater and marine influences and the depositional context (Goiran,  
214 2001; Marriner et al., 2006; Goiran et al., 2011). Ostracods from Core PO-2 presented here were also  
215 published in Sadori et al. (2016).

216 Palaeoenvironmental Age-Depth Models (PADM charts) are used to interpret chronometric  
217 and integrated stratigraphy data (Salomon et al., 2016a) (Figs. 5, 7 and 9). Developed to interpret  
218 ancient coastal harbours and to cross datasets of different types and disciplines, this PADM chart is  
219 related to geohistory diagrams, also called backstrip diagrams (Van Hinte, 1978; Allen and Allen,  
220 2013). The PADM chart is based on a classic age-depth model, with stratigraphical and  
221 palaeoenvironmental context recorded on the y-axis, and palaeogeographical and chronological

222 information transferred to the x-axis. The standardised PADM chart integrates all relevant data to  
223 interpret the stratigraphical sequences. A quick glance at the charts offers an overview of the local  
224 modelled sea level curve, the different apparent sedimentation curves, the results of the  
225 palaeoenvironmental analyses and their interpretations. Most importantly, this chart simplifies the  
226 identification of sediments related to the Transgressive Systems Tract or the Highstand Systems  
227 Tract. Additionally, the systematic combination of the sea level curve with a sedimentation curve  
228 exposes clear correlations to their respective evolutions or the variability of the accommodation  
229 space through time.

230         The sedimentation curve is reconstructed with no vertical adjustments – i.e., without any  
231 decompaction, subsidence or uplift corrections. The calibration of radiocarbon ages has been  
232 performed using the curve proposed by Reimer et al. (2013) with the software OxCal (Ramsey, 1995;  
233 Ramsey and Lee, 2013) (Table 1). No model was used to calibrate and narrow down age ranges (e.g.,  
234 Bayesian model). Interpretative sedimentation curves are proposed based on radiocarbon dates.  
235 Between dates the sedimentation curves can be adjusted depending on the processes hypothesised  
236 (e.g., sediment starvation, condensed section). Only the *apparent sedimentation curve* and the  
237 *apparent accommodation space* are reported here. Interpretations will be proposed consequently.  
238 Many papers suggest decompaction methods taking into account the stratigraphy, porosity, grain  
239 size, organic matter content, deposition rate, and overload weight (water or sediment) (Van Hinte,  
240 1978; van Asselen et al., 2009; Kominz et al., 2011; Allen and Allen, 2013; Johnson et al., 2018). A  
241 decompaction method was also applied to the Tiber delta (Marra et al., 2013). However, the  
242 unconformity at the base of the Tiber Depositional Sequence is not precisely known in the studied  
243 area (only estimations are proposed in Milli et al., 2013, between 30 and 40 m below Ostia) and  
244 stratigraphies of the Late Pleistocene / Early Holocene are not known for the cores presented here. If  
245 the interplay between sedimentation rate, compaction, and tectonics can be discussed, the main  
246 phases of the chronology proposed is not affected by this vertical instability. The sea level curve used  
247 in this paper is an eustatic curve with glacio-hydro-isostatic predictions proposed by Lambeck et al.

248 (2011) for the Tiber delta. In Fig. 3, this local modelled curve is compared to the best estimate of the  
249 ice-volume equivalent global sea level function (Lambeck et al., 2014) and the modelled sea level  
250 curve for the Tiber delta area from Vacchi et al. (2016) (ICE-5G VM2 Model). The age-depth models  
251 (apparent sedimentation rates) and the palaeoenvironments will be interpreted taking into account  
252 their relations to the local sea level curve prediction. The sedimentation curves proposed in this  
253 paper are not taking into account the elevation loss caused by sediment compaction (van Asselen et  
254 al., 2009; Marra et al., 2013). Possible vertical changes (compaction, neotectonic) will be considered  
255 in regards to several parameters: it is suggested that the aspect of the *apparent sedimentation curve*  
256 is constrained by the palaeoenvironmental characteristics of the deposits (e.g., subaerial and  
257 subaqueous bioindicators, shallow or deep water sediment characteristics), the depositional  
258 processes involved, the geometry and the temporal development of the transgressive/progradational  
259 sequences ((Tamura et al., 2003; Tanabe et al., 2006; Milli et al., 2016), and to a certain extent by the  
260 modelled local sea level curve (Lambeck et al., 2011 for the present paper).

## 261 **ANALYSES**

262 Cores **PO-2**, **CAT-3** and **MO-2** are described in detail (Figs. 4 to 9), and observations in the  
263 other cores are used as supporting information. The upper sequences above the bold erosional  
264 boundaries lines in Fig. 10 are already published: PO-2 in Goiran et al. (2014) and Sadori et al. (2016)  
265 (Harbour of Ostia Sequence); CAT-3 in Salomon et al. (2018) (stratigraphy of a palaeochannel of the  
266 Tiber River); and MO-2 in Salomon et al. (2017) (stratigraphy of a palaeochannel of the Tiber River).  
267 In Group 1, Core PO-2 will be completed by cores PO-1 (new data for the lower part of the sequence)  
268 and Core OST-4 (Hadler et al., 2015). In Group 2, Core CAT-3 will be completed by Core CAT-2. Core  
269 MO-2 is the only one forming Group 3, and Core LOA-1 is the only one for Group 4.

270 **Core PO-2** is the deepest reaching core in the Ostia study area (25 m b.s.l.) and the  
271 sedimentation refers to a long period of time between 8000 and 2000 cal. BP (Figs. 4 and 5). Four  
272 main units were observed below the Roman harbour of Ostia, Units A to D. Unit A is composed of

273 bedded grey silty sand. Around 22 m b.s.l., few cm-layers are composed of silts or organic material.  
274 Ostracods mainly reveal a coastal assemblage, mostly brackish lagoonal, but with a large amount of  
275 marine and phytal coastal species. No date is available for this unit. Silty sands are still deposited in  
276 Sub-unit B1 but interbedded with grey silty clay. In Sub-unit B2, the deposits are compact grey silty  
277 clay with no more sandy layers visible (96% of silt and clay). Ostracod assemblage is similar to Unit A.  
278 Organic material was radiocarbon dated at 7677 to 7588 cal. BP (6790±30 BP). Silty sand layers are  
279 observed again in Unit C (30% of sand). This includes small cm-layers in Unit C1 and sandy deposits in  
280 Unit C2 over several decimetres thick. Sub-unit C3 is back to grey silty clay deposits. Interestingly,  
281 freshwater ostracods are identified at the bottom of Unit C, but brackish lagoonal deposit  
282 assemblages increase in this layer. Organic matter was dated to 4520 to 4296 cal. BP (3955 ± 30 BP)  
283 at 14.34 m b.s.l. Bedded grey sand with silty layers are deposited in Unit D with higher value for  
284 magnetic susceptibility. Magnetic susceptibility values rise slowly from 5-10 CGS to 10-20 x10<sup>-6</sup> CGS  
285 but never reached 100 x10<sup>-6</sup> CGS in Units A to C (mean value = 7 CGS). Values rise in Unit D and reach  
286 more than 1000 x10<sup>-6</sup> CGS in Sub-unit D2. Carbonate content is generally rising (up to 30% in Sub-unit  
287 D2) while organic matter content decreases in the sedimentary sequence. Additionally, freshwater  
288 species are more represented in the ostracods identified in Sub-Unit D1 than in the lower units. Unit  
289 D2 contains more *Posidonia*, and some fibers were dated to 2786 to 2686 cal. BP (2955 ± 25 BP). The  
290 harbour of Ostia is composed of compact dark grey silts mainly with freshwater ostracods. The  
291 harbour is finally sealed by coarse fluvial deposits (Unit E) and fine fluvial deposits (Unit F) (see  
292 Goiran et al., 2014 for a detailed description).

293 Fours layers were identified in Core PO-1 below the Roman harbour sequence (Fig. 10), but  
294 the core only reaches 18 m b.s.l. Grey silty clay of Core PO-1/Unit A and Unit C are most probably  
295 similar to deposits of Sub-unit B2 and C3 in Core PO-2. Surprisingly, dark coarse sand and small  
296 gravels were drilled between 15 and 17 m b.s.l. in Core PO-1. Organic matter in the layer was dated  
297 to 2715 to 2363 cal. BP (2455 ± 30 BP), but it is covered by grey silty clay in Unit C, which was dated  
298 to 4151 to 3981 cal. BP (3720 ± 30 BP) on a piece of wood laying at -14.64 m b.s.l. PO-1/Unit D

299 corresponds to laminated grey sand similar to Core PO-1/Unit D. A similar period was obtained for  
300 these two layers with a radiocarbon date on plant material at 8.49 m b.s.l. in Core PO-1/Unit D (2845  
301 to 2748 cal. BP,  $2670 \pm 30$  BP). A similar harbour sequence was obtained in Cores PO-1 and 2.

302 Core OST-4 (Hadler et al., 2015) reveals the upper part of the natural sedimentary sequence  
303 that was truncated by harbour excavation during the Roman Republic period, between 2400 and  
304 2100 cal. BP (Units E in cores PO-1 and 2) (Fig. 10). Medium sands are still observed in Unit A and still  
305 dated between 2800 and 2500 cal. BP at 2.30 m b.s.l. ( $2752$  to  $2547$  cal. BP /  $2562 \pm 19$  BP). Unit B is  
306 a fine deposit of grey silt dated to 2326 to 2157 cal. BP ( $2229 \pm 17$  BP) and covered again by sand in  
307 Unit C.

308 **Core CAT-3** reaches 16 m b.s.l. (Figs. 6 and 7). Laminated silty fine sands are drilled at the  
309 bottom in Unit A. Almost 1 m of grey silt is deposited in Unit B, with low magnetic susceptibility ( $<10$   
310  $\times 10^{-6}$  CGS). Some ostracods were observed in this unit and are associated with brackish environments  
311 (*Cyprideis torosa*) or environments without freshwater (*Palmoconcha turbida*, *Leptocythere* sp.,  
312 *Costa batei*). Charcoals trapped in this protected environment are dated to 6858 to 6677 cal. BP  
313 ( $5985 \pm 30$  BP). From 13.5 to 6.5 m b.s.l., Unit C is composed of laminated silty sand and the upper  
314 part is dated to 3717 to 3573 cal. BP ( $3400 \pm 30$  BP). Magnetic susceptibility rises slowly from the  
315 bottom to the top of this unit. Sands are mainly fine. Comparatively, these laminated sands are more  
316 sorted and finer than in Core PO-2. Ostracods were identified at the bottom of these units and  
317 indicate a coastal environment with freshwater influence (*Palmoconcha turbida*, *Costa batei*,  
318 *Pontocythere turbida*). An important change in the grain size occurs at 6.51 m b.s.l. Unit D is 1 m thick  
319 and composed of 15% to 40% of coarse material. This unit is then covered by almost 3 m of silts (Unit  
320 E). Heterometric anthropic material constitutes the upper unit F.

321 The core sequence of CAT-2 is only reaching 8 m b.s.l. (Salomon et al., 2018), but reveals the  
322 upper sedimentation eroded by fluvial mobility between 2800 and 2200 cal. BP in Core CAT-3. Units B  
323 and C in CAT-2 are finer deposits in between medium sand in Units A, C and E. Four radiocarbon

324 dates are distributed from the bottom to the top of this stratigraphic sequence. In Core CAT-2 / Unit  
325 B two radiocarbon dates (4151 to 3981 cal. BP – 3720 ± 30 on organic matter - and 3333 to 3135 cal.  
326 BP – 3365 ± 30 BP on *Posidonia*) include the time span of the last date obtained in the upper part of  
327 Core CAT-3 / Unit C (3717 to 3573 cal. BP).

328 Finally, between 21.30 and 12 m b.s.l., **Core MO-2** reveals Early Holocene deltaic deposits  
329 settled before the development of the palaeomeander of Ostia between 2400 to 1700 cal. BP (Figs. 8  
330 and 9). The upper 12 m are described in detail in Salomon et al. (2017). The oldest radiocarbon dates  
331 of the area are recorded in Unit B and C and covered the period between 8500 and 7900 cal. BP. Unit  
332 A (21.30-19.39 m b.s.l.) is mainly composed of silt and clay (56%) with high content of sand (43%).  
333 The organic content is only 3% (loss-on-ignition). The macrofauna is particularly interesting. Shells of  
334 *Zonites nitidus* were observed, which usually live along shores of lakes and riverbanks. *Oxychilidae* sp.  
335 were also identified, which live in terrestrial contexts in wet environments, generally near lakes.  
336 Other terrestrial species were observed like *Mediterranea depressa* or other gastropods. No  
337 ostracods were identified. The magnetic susceptibility is low, around  $10 \times 10^{-6}$  CGS on average.  
338 However, magnetic susceptibility rises in Unit B correlatively with the grain size. Unit B is composed  
339 of very well sorted sand with very low organic matter content (1%). A lot of macrofauna fragments  
340 were collected including many bivalves sp., gastropods, and other shells difficult to identify. The  
341 shells identified are mainly characteristic of sandy or rocky environments (*Bittium reticulatum*,  
342 *Cerastoderma edule*, *Rissoa venusta* etc.). *Lentidium mediterraneum* suggests a sandy/clayey bottom  
343 close to a river. A marine shell was dated at 8525-8345 cal. BP at 19 m b.s.l. (7965 ± 40 BP).  
344 Ostracods identified include *Cyprideis torosa* and *Loxoconcha elliptica*, revealing a brackish  
345 environment with high salinity variability, *Loxoconcha rhomboidea*, *Xestoleberis nitida*, *Leptocythere*  
346 sp. and *Propontocypris cf. prifera*, characterising lagoonal-coastal environments (euryhaline) with low  
347 salinity changes (polyhaline), and *Cushmanidea* (or *Pontocythere*) *elongata*, *Urocythereis* possibly  
348 *favosa*, and *Heterocythereis albomaculata*, typical of a dynamic coastal environment, but with  
349 ostracods sometimes hiding in *Posidonia*. Similar to Unit A, deposition in a calm environment is again

350 observed in Unit C, with 95% of silts and clay. Specific diversity reduces in this unit and only some  
351 species of *Rissoa Linoelata* and *Bittium reticulatum* living in algae, *Posidonia*, or rocks were observed.  
352 Some *Posidonia* fibers were observed at the top of this unit, which confirms marine influence in this  
353 unit. Ostracods reveal a brackish environment, indicating some contact with the sea, but not directly  
354 open to the sea (*Loxoconcha rhomboidea*, *Xestoleberis* sp., to infralittoral often with algae,  
355 *Cytheridea*, *Paracytheridea*, *Carinocythereis carinata*). Several dates were performed on this unit,  
356 from the bottom to the top. At 18.25 m b.s.l. a piece wood was dated to  $8070 \pm 40$  BP and calibrated  
357 at 9125-8780 cal. BP. This date is followed at 17.15 m b.s.l. by a date on wood calibrated at 8540-  
358 8390 cal. BP ( $7655 \pm 30$  BP). In the upper part of this unit, *Posidonia* fibers are dated to 8525-7925  
359 cal. BP ( $7545 \pm 35$  BP) and 8155-7965 cal. BP ( $7600 \pm 40$  BP). Lastly, laminated silty sands are  
360 deposited in Unit D. A sand content of 94% was measured at the bottom but with an average of 76%  
361 for all the samples analysed in this unit. Macrofauna exposes species from different environments,  
362 from a sandy bottom (*Cerastoderma edule*, *Macra* sp., *Neverita Josephina*...), or an area near the  
363 river mouth (*Zonites nitidus*). Ostracods reveal lagoonal-brackish (*Cyprideis torosa*) to marine  
364 environments (*Aurila woodwardii*) with coastal species (*Cushmanidea elongata* and *Urocythereis*  
365 *favosa*). The bottom of Unit D reveals many shell fragments. Most of the shell fragments cannot be  
366 identified. A fragment of shell was dated in this unit but should be rejected for the interpretation  
367 ( $9370 \pm 45$  BP at 16m b.s.l. – 10,340-10,130 cal. BP). In Unit E, very coarse pebbles were recorded at  
368 the bottom with black coarse to very coarse sand. These deposits are the coarsest ever recorded in a  
369 Middle/Late Holocene channel of the Tiber in the delta (coarsest pebbles are 2.5 cm (A-axis)  $\times$  2 cm  
370 (B-axis)  $\times$  1 cm (C-axis)). Unit F is an intercalation of sand and grey silty clay deposited in the Roman  
371 period. Finally, unit G is sub-modern deposits of grey silty clay.

## 372 **DISCUSSION**

### 373 **Interpretation of the depositional systems**

374           The study area considered in this paper straddles the inner and the outer delta plain. It  
375 crosses part of the palaeolagoon and the area of the archaeological site of Ostia (Fig. 2). Fig. 10  
376 presents a synthetic cross section interpreting the depositional systems of the studied cores. Core  
377 LOA-1 studied in Vittori et al. (2015) is located in the inner deltaic plain and all other studied cores  
378 are located in the outer deltaic plain. Sandy deposits identified at the bottom of Cores PO-2 (Unit A)  
379 and MO-2 (Unit B) and Unit B in Core LOA-1 are issued from a transgressive sandy coast. Several <sup>14</sup>C  
380 and OSL dates confirm that Unit A / Core LOA-1 goes back from the Pleistocene (Vittori et al. in  
381 prep.). Units D in Cores PO-1 and PO-2, Unit C in Core CAT-3, Units A, B, C, D, E in Core CAT-2, and  
382 Unit D in Core MO-2 are shallowing upward successions related to the progradational delta front.  
383 Fine marine sediments deposited in the prodelta are observed in Core PO-1 / Units A and C, Core PO-  
384 1 / Units B and C, Core CAT-3 / Unit B, and Core MO-2 / Unit C.

385           Transitions between these three depositional systems can also be observed. The location of  
386 Core PO-2 is the most seaward and the core better records changes in its stratigraphy. The fine  
387 interstratification of sand and silty clay in Sub-unit B1 demonstrates change from the transgressive  
388 sandy coast (Unit A) to the prodelta (Sub-unit B2). It demonstrates a normal regression of the  
389 coastline during the TST. The sandy layers within the grey silty clay in Core PO-2/Unit C corresponds  
390 to the transition between the prodelta to the delta front. It is the distal delta front part of the  
391 progradational system during the HST.

392           Based on our data, the switch from TST to HST, called the maximum flooding surface (mfs), is  
393 not always easy to locate precisely. According to the chronostratigraphy, it seems to happen in the  
394 Prodelt in Core PO-2 (Sub-unit B2 - Fig. 4). More analyses would be necessary to identify a slower  
395 rate of deposition and a condensed layer of fauna (condensed section). In Core CAT-3, the mfs could  
396 be on top of Unit B or not reached by the core. A deeper core, bioindicators, and additional dates  
397 would have helped to define it better (e.g., condensed section, sediment starvation, hiatus). The  
398 abrupt deepening facies in Core MO-2 / Unit C (marine grey silty clay) is covered by a small layer

399 characterised by sediment starvation. It is expressed by high macrofaunal density (hiatus) and can be  
400 associated to the mfs (Fig. 8). Finally, the mfs in Core LOA-1 is probably at the limit between Unit B  
401 and C.

402 Late Holocene lateral fluvial mobility removed part of the delta front deposits of the HST in  
403 Cores MO-2 (Sequence 2 – Palaeochannel - Units E, F G) and CAT-1 (Sequence 2 –  
404 Palaeochannel/Harbour – Units D and E). In addition, the excavation of the harbour of Ostia during  
405 the Roman period also removed progradational sands of the HST in Group 1 area (2400-2000 cal. BP  
406 in PO-1 and PO-2 Units E).

407 In the interpreted cross section between groups 1 and 4, there is currently no clear evidence  
408 of fault activity. Deeper cores and complementary dates in the stratigraphies would be necessary to  
409 interpret the sequences to examine this further.

#### 410 **From the TST to the HST: use of the interpretative PADM chart for single core** 411 **interpretations**

412 According to the PADM charts of Cores PO-2 (Fig. 5), Core CAT-3 (Fig. 7) and Core MO-2 (Fig.  
413 9), the stratigraphies overlap the end of the Transgressive phase and the Progradational phases until  
414 2500 cal. BP.

415 Amongst the analysed cores, the transgressive coastal sand is only dated in Core MO-2. The  
416 sedimentation rate in Units B and C seems to roughly follow the rate of the modelled local sea level  
417 curve between 9000 and 8000 cal. BP, which would confirm the validity of the modelled curve of  
418 Lambeck et al. (2011). It should be noticed that these four dates at the bottom of Core MO-2 dates  
419 sediments from periods often lacking in deltaic sequences or displaying a change of the facies (River  
420 deltas worldwide: Stanley and Warne, 1994; Po delta: Amorosi et al., 2017 and Bruno et al., 2017;  
421 Rhine delta: Hijma and Cohen, 2011, 2019; Asian deltas: Hori and Saito, 2007; Mississippi delta: Yu et  
422 al., 2012). The period 9000-8500 cal. BP is characterised by facies changes related to a sea level jump  
423 in Asian deltas (Hori and Saito, 2007). This change is characterised by a shift from coastal/estuarine

424 sand or mud to prodelta mud. A sea level jump would also occur later between 8500 and 8200 cal.  
425 BP, possibly in two phases according to the data from the Rhine delta (Hijma and Cohen, 2019). The  
426 marine silty clay from MO-2 / Unit C could be related to a rapid deepening facies similar to the  
427 observations made by Hory and Saito (2007) for Asian deltas. The modelled curve of Lambeck et al.  
428 (2011) for the Tiber delta is correct, but too smoothed to show these sea level jumps. Core MO-2 /  
429 Unit C offers sedimentation for the period between 9000 and 8000 cal. BP. To support such a  
430 sediment rate in a deeper context, the sediment load transported by the Tiber River was probably  
431 very important. This strong sedimentation (sandy and fine) could be linked to the Sapropel S1  
432 deposits in the Tyrrhenian Sea (9500-6600 cal BP in Emeis et al., 2000; 8900-7300 cal. BP in Zanchetta  
433 et al., 2007; 10,800-6100 cal BP in De Lange et al., 2008). On top of Unit C, sediment starvation  
434 occurs with a hiatus (mfs). The sedimentation rate probably stopped to be consistent with the  
435 relative sea level rise, but the chronology is lacking.

436 At the beginning this sea level jump period, Core MO-2 shows very quickly changing environments  
437 from freshwater and terrestrial context in Unit A to a protected environment with high marine  
438 influence in Unit C, intercalated with two units of coastal sand in Units B and D. Terrestrial,  
439 freshwater, coastal and marine palaeoenvironments seem to be very close, suggesting a high  
440 mobility of the coastline and closely controlled by the rising sea level. Unit A can be associated to a  
441 coastal lake or an estuarine environment.

442 The upper part of Core MO-2 shows a channel-fill sequence (Sequence 2) related to the activity (2400  
443 cal. BP and 1557 CE) and the infill of the palaeomeander of Ostia (1557 CE to the reclamation in the  
444 Late nineteenth/ Early twentieth century CE - Salomon et al., 2017). Cores S6 and S1 in Bellotti et al.  
445 (2011) and Cores E, D and A farther south in Bellotti et al. (2007) demonstrate that sandy deposits  
446 continued to be deposited in the upper sequence of Core MO-2 before their removal by the  
447 palaeomeander.

448           The grey silty clay deposits of Core CAT-3 / Unit B are dated from 6858 to 6677 cal. BP. Unit B  
449 could be just before or contemporary with the transition from the TST to the HST (mfs). A deeper  
450 core and complementary analyses would be necessary to identify the mfs. In Fig. 7, two hypothetical  
451 sedimentation rates are proposed between Unit A and B. Unit A is either related to the transgressive  
452 coast or an instability of the delta front during the TST-HST transition. Unit B is possibly a condensed  
453 prodelta layer with a low sedimentation rate (mfs facies similar to Unit B2 in Core PO-2).

454           The stratigraphic sequence of Core PO-2 records both the transition from the delta front to  
455 the prodelta during the transgression phase, and the transition from the prodelta to the prograded  
456 plain after the sea level rise slows down around 7000 yr ago. The coastal sands identified at the  
457 bottom of Core PO-2 might coincides with dates obtained in the TST deposits inland, pre-dating 7000  
458 cal. BP. No dates are available for Unit A but we estimate that these transgressive coastal sands were  
459 deposited around 10,000 and 9000 cal. BP relying on the local sea level curve proposed by Lambeck  
460 et al. (2011). Sub-unit B1 shows the transition from the delta front (Unit A) to the prodelta (Unit B  
461 and C) while the coastline should be moving towards the east near Core MO-2 (retrogradation). The  
462 water-filled space (accommodation space) expands quickly right after the coastline in Core PO-2 is  
463 transgressed, but tends to reduce when the sea level rise slows down and the progradation occurs.  
464 Even if part of the slow sedimentation observed in Units B and C is because of compaction, such  
465 geometry and temporal evolution are expected in this geomorphological context. The mfs facies  
466 might also occur during this period (Unit B2). Units B to D expose the transition from the prodelta to  
467 the delta front while the Tiber delta plain is prograding. Sub-unit C1 records the first sandy layers  
468 since Sub-unit B1 was deposited in the Early Holocene. Interestingly, freshwater ostracods species  
469 were identified in Sub-unit C1 along with brackish, coastal, and marine species. According to these  
470 palaeoenvironmental data and chronology obtained, a prograding palaeoriver mouth of the Tiber  
471 was most likely not far from Core PO-2 between 4500 and 4200 cal. BP. However, a stronger delta  
472 front influence is recorded just afterwards in Sub-unit C2. The delta front definitely progrades  
473 towards PO-2 between 4000 and 2500 cal. BP according to Unit D. The higher sedimentation rate in

474 the upper level of Unit C and Unit D is probably because of less compaction but also to local factors  
475 linked to the closer coastline and adjustment of the slope of the delta front. This Sub-unit C2 could  
476 be related to the period of drier conditions between 4300-3800 cal. BP with intercalated phases of  
477 increased moisture recorded in lakes from Central Italy (Magny et al., 2007, 2009, 2012; Sadori et al.,  
478 2011). Similar progradational phases are also recorded in the Ombrone River delta (Bellotti et al.,  
479 2004). Anthropogenic factors, especially stronger human impact in the watershed, also most likely  
480 affected this coastal progradation from 4400 cal. BP (Bronze Age - Magri, 1999; Sadori et al., 2011).  
481 More ostracods usually living in freshwater were observed in Unit D suggesting closer river influence  
482 in this coastal area. According to Core OST-4 (Hadler et al., 2015), the area of Core PO-2 definitely  
483 turns into the subaerial deltaic plain between 2.8 k and 2.5 k cal. BP.

#### 484 **Integrated age-depth model and interpretations**

485 Fig. 11 is a synthesis of all of the apparent sedimentation curves from the cores drilled along  
486 the studied cross section from the archaeological site of Ostia to the palaeolagoon. This diagram  
487 integrates all of the PADMs presented above. Subsidence may have affected the sedimentation curve  
488 of the Outer subzone (Group 1) more than the curves of Inner subzone (Group 2 and 3), because of a  
489 deeper Holocene sequence to the west (see the unconformity at the base of the Tiber Depositional  
490 Sequence - Milli et al., 2013) and the thicker fine prodelta deposits recorded in Cores PO-1 and 2.  
491 However, despite the lack of dates at the bottom of each core, this chart confirms the succession of  
492 transgressed coastlines from west to east. The first coastline to be transgressed is in Group 1 (Core  
493 PO-2 – Outer subzone), then Group 2 (Core CAT-3), and finally Group 3 (Core MO-2 – Inner subzone).  
494 Consequently, the apparent accommodation space for the Outer subzone is deeper than for the  
495 Inner subzone between 8000 and 3000 cal. BP. This difference is also partly related to a higher  
496 subsidence in the Outer subzone. The apparent sedimentation rate is very low between 8000 and  
497 4000 cal. BP in the Outer subzone, and accelerates since 4000 cal. BP to the definitive progradation  
498 of the Outer subzone (Group 1) around 2800-2700 cal. BP. This quicker sedimentation rate observed

499 from 4000 cal. BP can be related to the lower compaction of these sandier layers, but also to delta  
500 front progradation in the Outer subzone. Additionally, it can also be a response to the aridification  
501 and stronger erosion happening across the Mediterranean since 4.2 k cal. BP.

502           The apparent sedimentation curves in the upper parts are a combination by groups of cores.  
503 Several radiocarbon dates were rejected to produce coherent sedimentation curves for each group  
504 and are crossed out on the diagram. Deepest and more recent radiocarbon dates were generally  
505 selected to plot the sedimentation curve (especially for Cores CAT-2 and 3). When dates were very  
506 close in date and depth, we combined them within the sedimentation curve (Cores PO-1, PO-2 and  
507 OST-4). However, for the deepest date performed in Core PO-1 / Unit B we adopted a different  
508 strategy because of the possible effect of the river, and two scenarios may be considered for now  
509 (see discussion below). In any case, it results in a meeting of the sedimentation curves of Groups 1  
510 and 2 around 2.8-2.5 k cal. BP. This observation confirms the quick progradation happening at that  
511 period (Salomon et al., 2018). Unfortunately, the HST coastline related to Core MO-2 is not known  
512 because of the erosion of the sediment from the upper part of the core by the palaeomeander of  
513 Ostia.

514           Considering (1) the succession of transgressed coastline from west to east observed in the  
515 integrated age-depth model (retrogradation), (2) the slower sedimentation in the prodelta  
516 comparing to the delta front, and (3) the sandy deposits reaching the modelled sea level curve during  
517 the HST (progradation), the model proposed fits into theoretical trends expected from a Holocene  
518 transgressed/prograded coast (see also Stanley and Warne, 1994; Tamura et al., 2003; Tanabe et al.,  
519 2006). The PADM chart seems relevant to identify evidence to reconstruct coastline-trajectories. The  
520 distinction between the apparent sedimentation curve of Groups 1, 2, and 3 might be amplified by  
521 the effect of compaction, but does not reassess the model proposed. Additionally, no strong chrono-  
522 topographical inversions suggest faulting activity below Ostia. This is confirmed by the fact that the  
523 dates in the lower part of Core MO-2 match the trend of evolution of the modelled local sea level

524 curve. This approach considering geomorphological processes and their effect on sedimentation  
525 could contribute to improve decompaction methods for Late Pleistocene / Holocene deltaic  
526 sequences.

### 527 **Fluvial bedload-derived facies within coastal sand near Ostia**

528 The cross section presented in Fig. 10 shows the presence of facies interpreted such as fluvial  
529 bedload-derived deposit in very different palaeoenvironmental contexts: (1) in the prodelta in Core  
530 PO-1/Unit B; (2) in the progradational delta front in Core MO-2 / Unit E, CAT-3 / Unit D; and (3) in the  
531 Roman harbour in Core PO-1 and 2 - upper part of Units E. The bedload-derived facies of the Tiber  
532 River in its delta results in a distinct facies, composed of medium/coarse black sand with gravels and  
533 pebbles. Similar bedload-derived facies were also found in the Roman *Portus* canals (Salomon et al.,  
534 2014, 2016b) and in Core ISF-1 at the river mouth of the Tiber between 2500 and 2000 cal. BP  
535 (Salomon et al., 2018). Indirect fluvial influence is recorded on the coast and in the palaeolagoon  
536 with bioindicators such as ostracods and macrofauna. For information, the current maximum depth  
537 of the Tiber channel in the delta can reach 12 m (Castellano and Colatosti, 2003).

538 Initially, only coarse fluvial deposits from fluvial bedload-derived facies were assured to be  
539 found in the palaeomeander of Ostia (Core MO-1, 2 and 3). The aerial photography taken in 1911 by  
540 balloon and sixteenth-seventeenth century texts and maps clearly revealed the position of the  
541 palaeomeander cut-off in 1557-1562 CE (Shepherd, 2006; Pannuzi, 2009). Other bedload-derived  
542 deposits were drilled by chance since Core CAT-2 was covered by a thick archaeological layer within  
543 the Roman city of Ostia. The fluvial harbour of Ostia was supposed to reveal only fine harbour muds,  
544 and only fine prodelta deposits were expected in the lower part of Core PO-1.

545 The bedload-derived facies of Unit B from Core PO-1 is related to a strong progradation in  
546 either 4000 cal. BP or around 2800-2700 cal. BP. The date of this fluvial deposit depends on the  
547 acceptance or the rejection of the date of 2715-2365 cal. BP dated on organic matter sampled in this  
548 unit. First, it was quite surprising to identify two meters of coarse fluvial deposits between 15 and 17

549 m b.s.l. between two units of grey silty clay. This seems to be related to a quick and strong fluvial  
550 event. Second, Core PO-2 (located only 20m away from Core PO-1) does not record a similar deposit.  
551 However, in Core PO-2 / Sub-unit C1 around 15 m b.s.l. combined with the sandy layers deposited in  
552 the prodelta, few ostracods characteristic of a freshwater environment were identified. Third, the  
553 date of the bedload influx is similar to the quick progradation of 2800-2700 cal. BP recorded at the  
554 mouth of the Tiber delta (Salomon et al., 2018), but the date just on top could be related to the 4.2 k  
555 BP event (Magny et al., 2007; Sadori et al., 2011). Consequently, if the date is rejected, this bedload-  
556 derived deposit in PO-1 / Unit B could be attributed to 4500-4000 cal. BP and be coeval with PO-2 /  
557 Unit C. Alternatively, if the date of 2715-2363 cal. BP is accepted, this bedload-derived deposit would  
558 be part of the major change happening at the mouth of the Tiber River at 2800-2700 cal. BP.

559           The very coarse material issued from the bedload-derived deposit in the palaeomeander of  
560 Ostia in Core MO-2 / Unit E was supposed to originate from the *Ponte Galeria* formation upstream of  
561 the Tiber delta and brought by a strong flood event (Salomon et al., 2017). The re-interpretation of  
562 the lower part of Core LOA-1 / Unit A suggests that it could also belong to outcrops of Pleistocene  
563 deposits buried a few metres below the palaeolagoon of Ostia (Vittori et al. in prep.). Some pebbles  
564 from the Pleistocene outcrops could have been more locally eroded and trapped in the pool drilled in  
565 MO-2. The bedload-derived deposit found in Core CAT-3 / Unit D is related to the palaeodynamic of  
566 the same palaeomeander of Ostia (Salomon et al., 2018). More surprising are the coarse deposits  
567 settled high over the sediment of the harbour of Ostia (Goiran et al., 2014). Their deposition in such a  
568 position could suggest shoals at the mouth of the Tiber River around 2000 cal. BP.

#### 569           **Tiber river mobility in the Tiber delta during the last 6000 years cal. BP**

570           The last figure is a map of the lateral mobility of the Tiber River during the last 6000 yr in its  
571 delta with data available for now (Fig. 12). This timespan covers most of the period of the HST and  
572 the progradation of the Tiber delta. Several data have been collected to produce this map : (1) beach  
573 ridge and fluvial features observed in satellite imagery, old aerial photography, and geophysical

574 surveys (Keay et al., 2005; Keay and Paroli, 2011); and (2) stratigraphic sequences with coarse fluvial  
575 deposits. Only the upper 30 m of the cores were considered. Beach ridge features are important data  
576 because they express progradation phases not removed by river mobility. The limit of this indicator is  
577 in cases of strong coastal erosion. In this case, stratigraphic sequences can be of great help. This  
578 dataset is completed by the new data published in this paper.

579         Recently, several papers suggested the existence of a palaeochannel of the Tiber below the  
580 Roman harbour of Portus between 3000 and 2400 cal. BP and a strong avulsion towards the south  
581 (Giraudi et al., 2009). However, for now no clear evidence of bedload-derived deposits supports such  
582 a hypothesis. Data from Cores PO-1 and 2 demonstrate that a branch of the Tiber River in the  
583 southern side of the delta existed since 4500-4000 cal. BP. Nevertheless, an area void of surficial  
584 features and sedimentary drilling remains between the southern part of the International airport of  
585 Fiumicino and the north of the harbour of the Roman emperor Trajan (Fig. 1).

586         Most of the coarse fluvial deposits identified in the upper 30 m of the cores were drilled in  
587 the northern part of the Palaeolagoon of Ostia and the current Tiber (Bellotti et al., 2007). Cores  
588 drilled at Ostia, especially Cores CAT-2 and CAT-3, expose a clear southern limit for the fluvial  
589 mobility of the Tiber during the Late Holocene. Less clear is the central and southern part of the  
590 palaeolagoon of Ostia. Finally, a recent magnetic survey conducted in the Isola Sacra revealed fluvial  
591 features in the southern part (Germoni et al., 2018; Keay, Strutt et al. in prep.). A migration of the  
592 Tiber from the middle of the Isola Sacra to Ostia could have occurred in the between 2800 and 1700  
593 cal. BP. During the last 2000 yr, the lateral mobility of the Tiber in the new prograded delta plain was  
594 mainly constrained along the Fiumara. The main change seems to be related to the cut-off of the  
595 Tiber River near Ostia and the construction of the Roman canals, including the Fiumicino.

## 596 **Conclusion**

597         This paper demonstrates that PADM charts (Palaeoenvironmental Age-Depth Models) are  
598 very well adapted to interpret deltaic stratigraphic sequences and to distinguish transgressive and

599 progradational sequences. During the Early Holocene, the transgression of the coastline from east to  
600 west is clearly observed in the studied cross section. Single and combined PADM charts for different  
601 group of cores also expose the different progradation phases affecting the Tiber delta. The  
602 integration of different apparent sedimentation curves in a single age-depth model demonstrates the  
603 effect of the the sedimentation context (e.g., higher sedimentation rates in the delta front comparing  
604 to the prodelta) and clearly expose the succession of transgressed and prograded coastlines during  
605 the Holocene. It gives clear evidence to reconstruct coastline-trajectories. This integrated model  
606 could contribute to adjust decompaction methods for deltaic sequences.

607         Within the PADM chart, fluvial mobility makes the interpretations more complex. River  
608 dynamics erode part of the coastal stratigraphic sequences. Nevertheless, the PADM chart produces  
609 a clear view of the palaeoenvironmental context in which fluvial sediments are deposited  
610 (prodelta/deltafront, incision/deposition). It also exposes the relation between the fluvial deposits  
611 and the modelled sea level curve. Indirect evidence of fluvial activity based on bioindicators  
612 (freshwater influence) recorded in the prodelta or delta front are very informative. They suggest that  
613 the Tiber flowed towards the south of its delta from 4500-4200 cal. BP. Additionally, the Tiber  
614 bedload-derived facies recorded in the prodelta reveals complex depositional processes and  
615 interplays between the river and the delta formation.

616 The reconstruction of the coastal and fluvial mobility in deltaic contexts during the Holocene remains  
617 a difficult task. The reconstruction of the Holocene relative sea level curves remains one of the most  
618 important data in producing reliable interpretations. A more detailed and less smoothed modelled  
619 relative sea level curve is essential and would bring more reliable interpretations. This is particularly  
620 true to study the consequence of the sea level jumps between 9000-8000 cal. BP on coastal  
621 depositional contexts.

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958

960 Figure 1. – Study area location. The map exposes the geomorphology of the Tiber delta and core  
961 locations. Other factors possibly affected the geomorphology of the Tiber delta like the depth of the  
962 unconformity at the base of the Tiber Depositional Sequence available in Milli et al. (2013), or faults  
963 hypothesized in Bigi et al. (2014), Ciotoli et al. (2016), Marra et al. (2019). However, there is no  
964 consensus yet related to the activity of the faults in the Tiber delta during the Holocene.

965 Figure 2. – Location of the studied cores and other boreholes drilled in the area of Ostia.  
966 Archaeological remains of Ostia and neighboring structures (white lines) are reported along with the  
967 main geo-features identified in this area of the Tiber delta (strandlines, fluvial ridges and swales, and  
968 the location of the palaeolagoon of Ostia according to Amenduni, 1884)

969 Figure 3. – Reconstructed relative sea level curves and best estimations at local, regional and global  
970 scales for the Holocene (Lambeck et al., 2011, 2014; Vacchi et al., 2016). The modelled eustatic and  
971 glacio-hydro-isostatic prediction for the Tiber delta will be used (Lambeck et al., 2011).

972 Figure 4. – Sedimentological and palaeoenvironmental analyses of Core PO-2

973 Figure 5. – PADM chart of Core PO-2

974 Figure 6. – Sedimentological and palaeoenvironmental analyses of Core CAT-3

975 Figure 7. – PADM chart of Core CAT-3

976 Figure 8. - Sedimentological and palaeoenvironmental analyses of Core MO-2

977 Figure 9. – PADM chart of Core MO-2

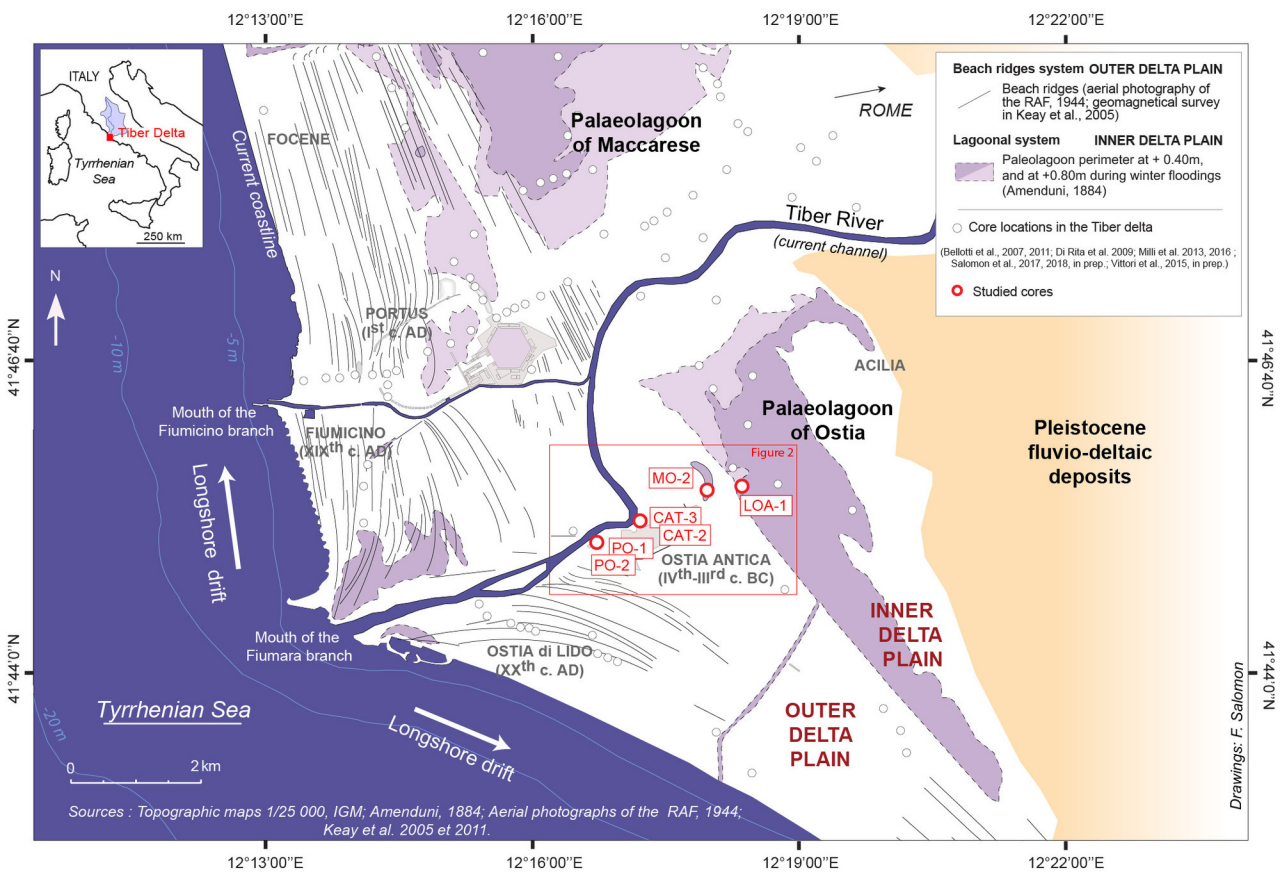
978 Figure 10. – Cross section of sedimentary cores drilled in the neighboring area of Ostia from the  
979 Roman palaeo-river mouth to the palaeolagoon of Ostia (new data and published data from Goiran  
980 et al., 2014; Vittori et al., 2015; Salomon et al., 2017, 2018)

981 Figure 11. – Synthetic PADM chart for the final transgression phase and progradation until the  
982 Roman period. Sedimentation curves were merged into three studied area: Group 1 in green –

983 Roman harbor area (Cores PO-1, PO-2 and OST-4); Group 2 in yellow – Area of the *Castrum* of Ostia  
984 (Cores CAT-2 and 3); and Group 3 – Area of the lobe of the palaeomeander of Ostia (Core MO-2). This  
985 diagram show evidence to reconstruct coastline-trajectories.

986 Figure 12. – Map of the possible channel belt of the Tiber in its delta for the last 6000 yr.

987 Table 1 – Radiocarbon dates - calibrated with the IntCal13 curve - Reimer et al., 2013 (Materials in  
988 blue and with an asterisk are calibrated with the Marine13 curve - Reimer et al., 2013).



12°16'30"E

12°17'00"E

12°17'30"E

12°18'00"E

12°18'30"E

41°46'0"N

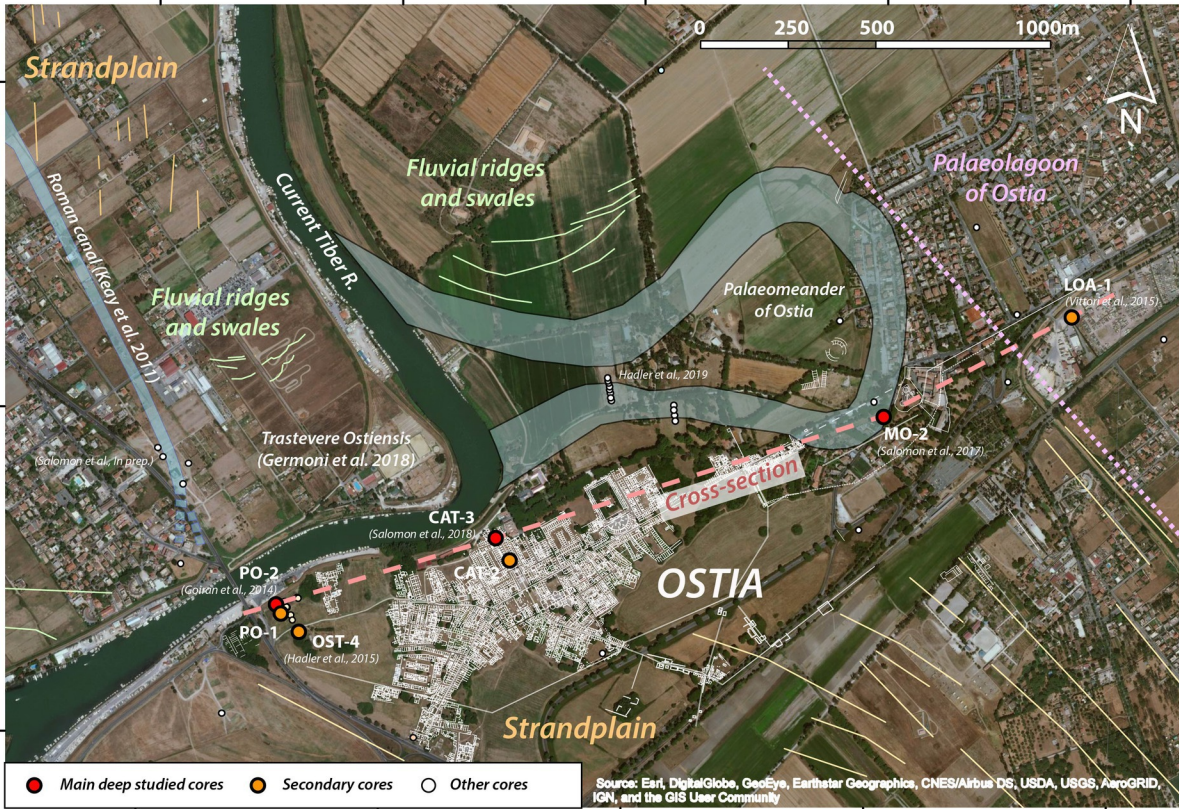
41°45'30"N

41°45'0"N

41°46'0"N

41°45'30"N

41°45'0"N



- Main deep studied cores
- Secondary cores
- Other cores

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

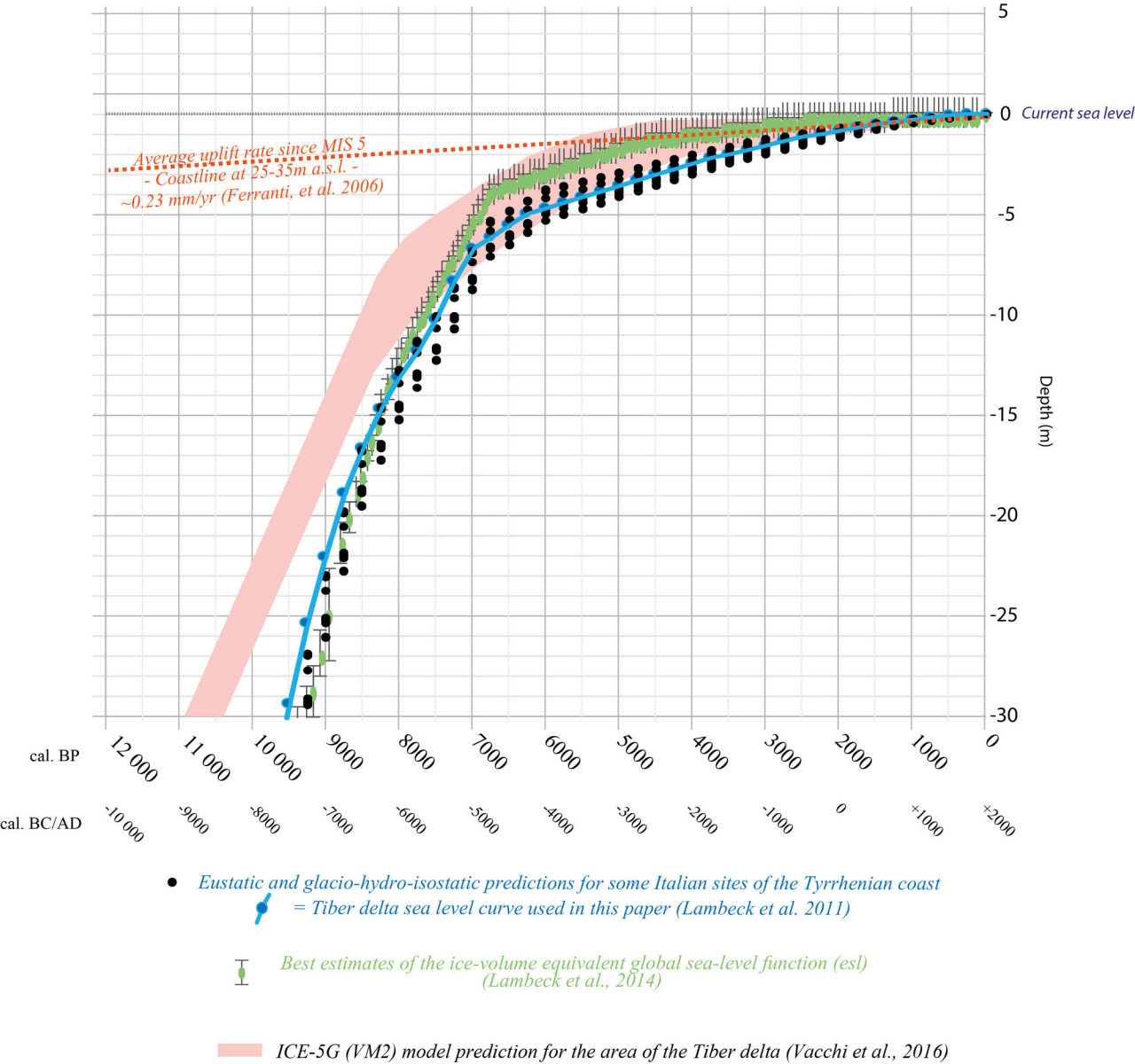
12°16'30"E

12°17'00"E

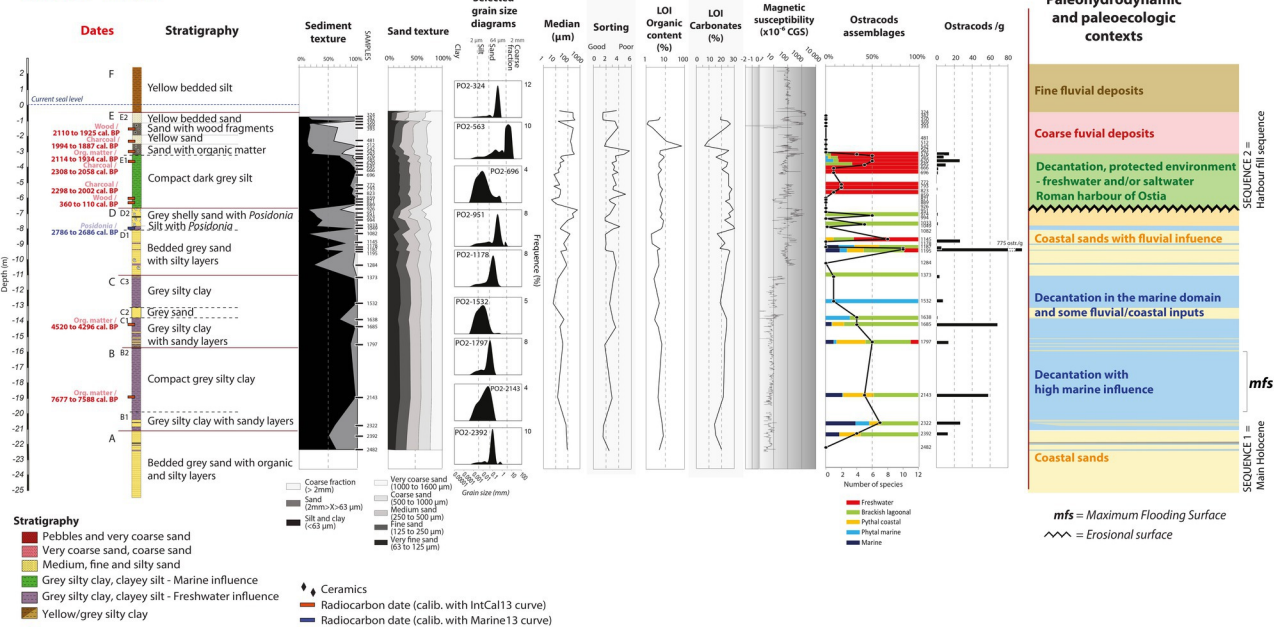
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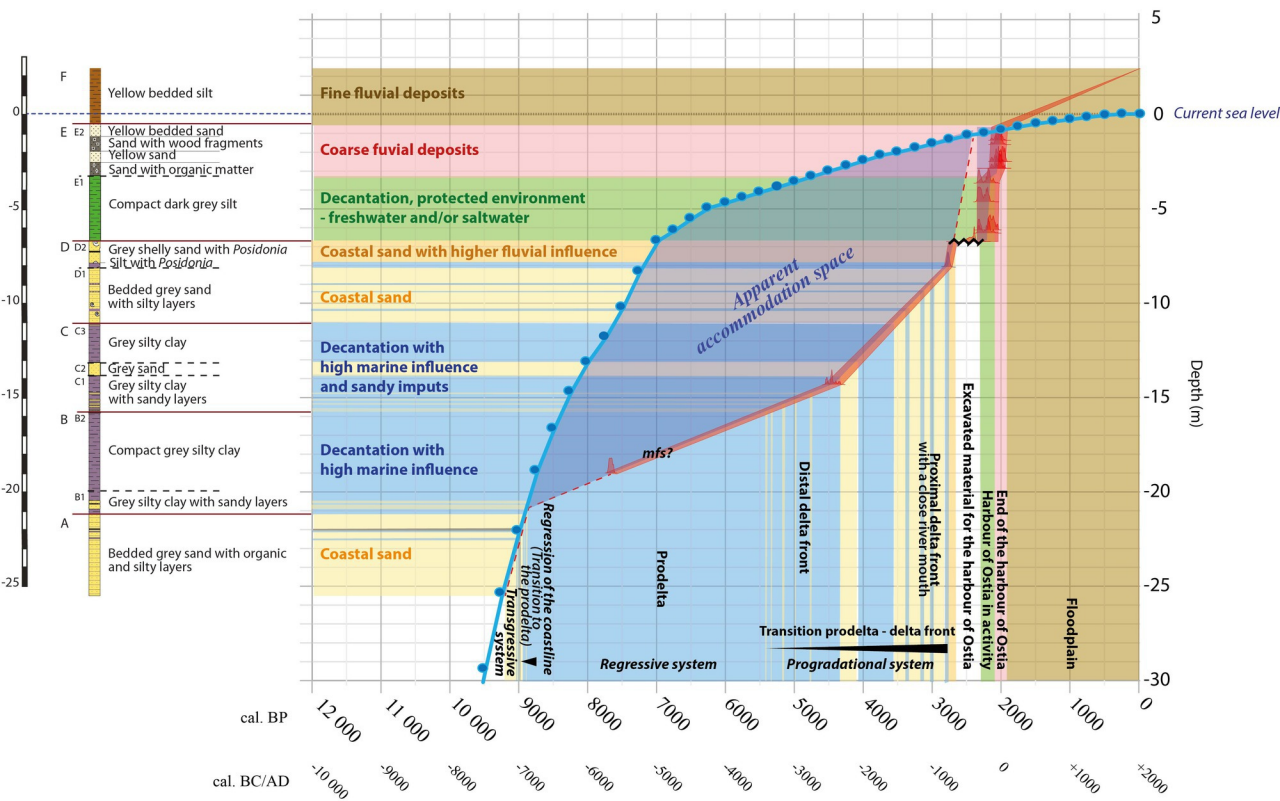
12°18'00"E

12°18'30"E



# Core PO-2 - Analysis



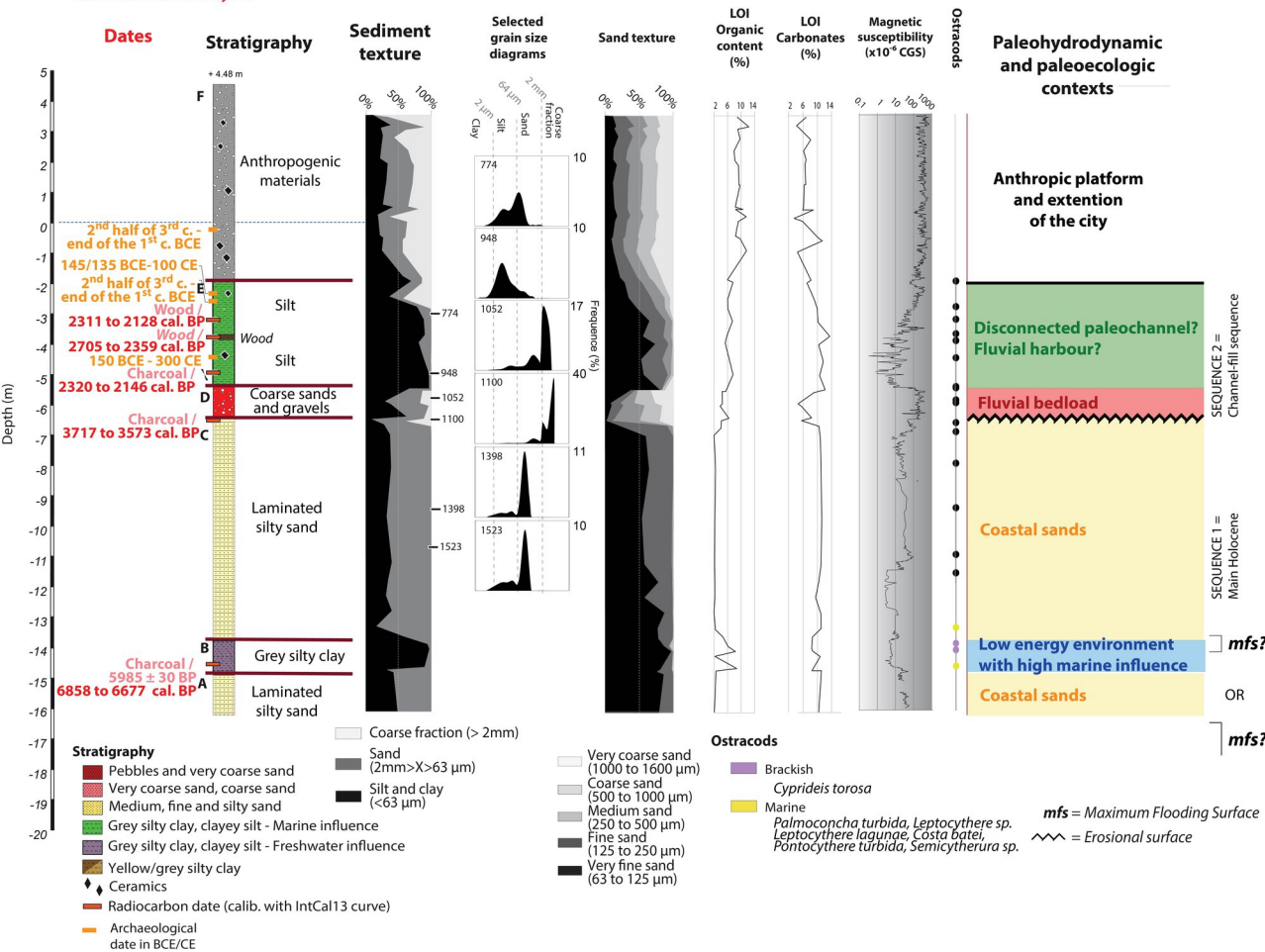


= Eustatic and glacio-hydro-isostatic prediction for the Tiber delta (Lambeck et al. 2011)

Radiocarbon date (calib. with IntCal13 curve)

Radiocarbon date (calib. with Marine13 curve)

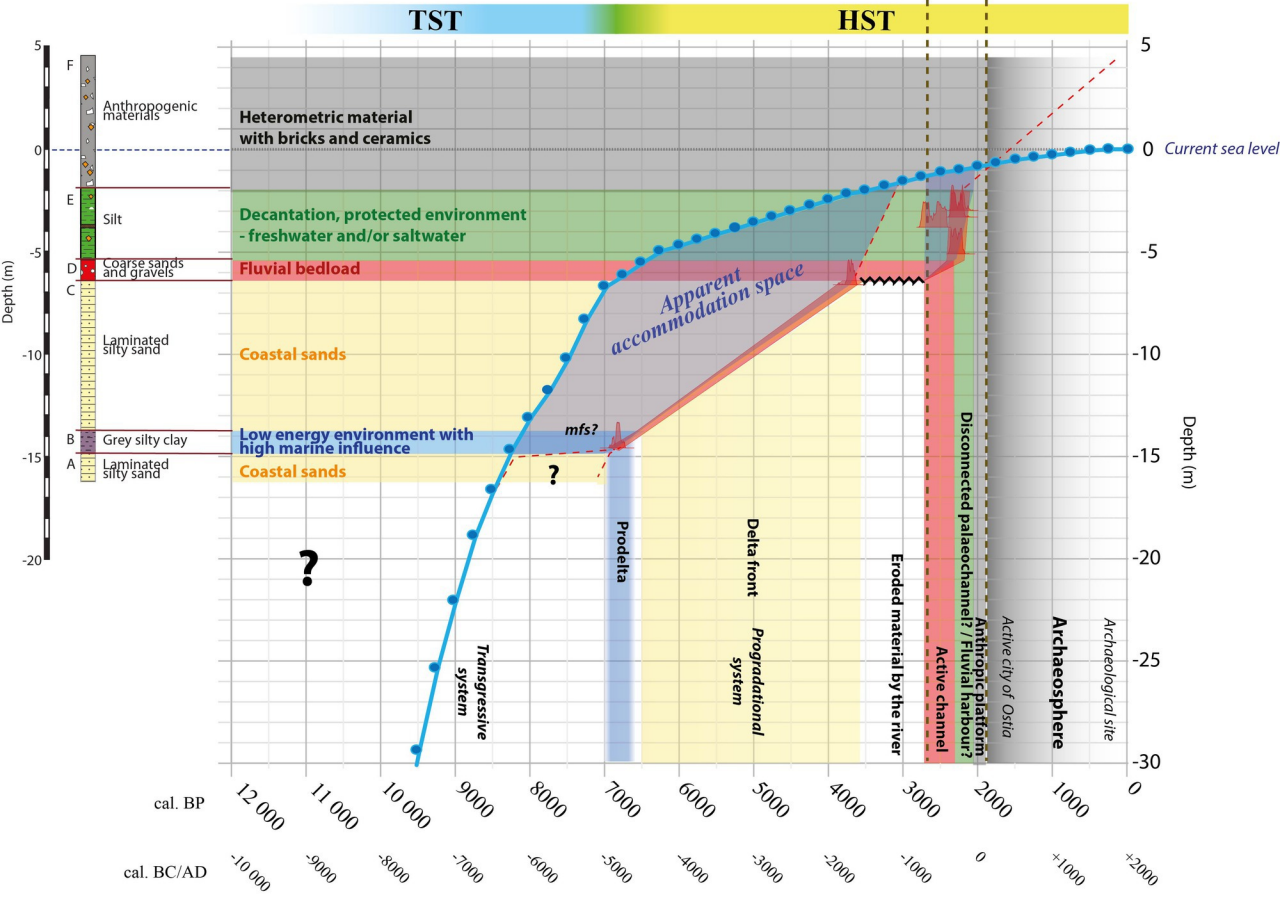
# Core CAT-3 - Analysis



# Core CAT-3

## Stratigraphy

## Palaeoenvironmental Age-Depth Model







WEST

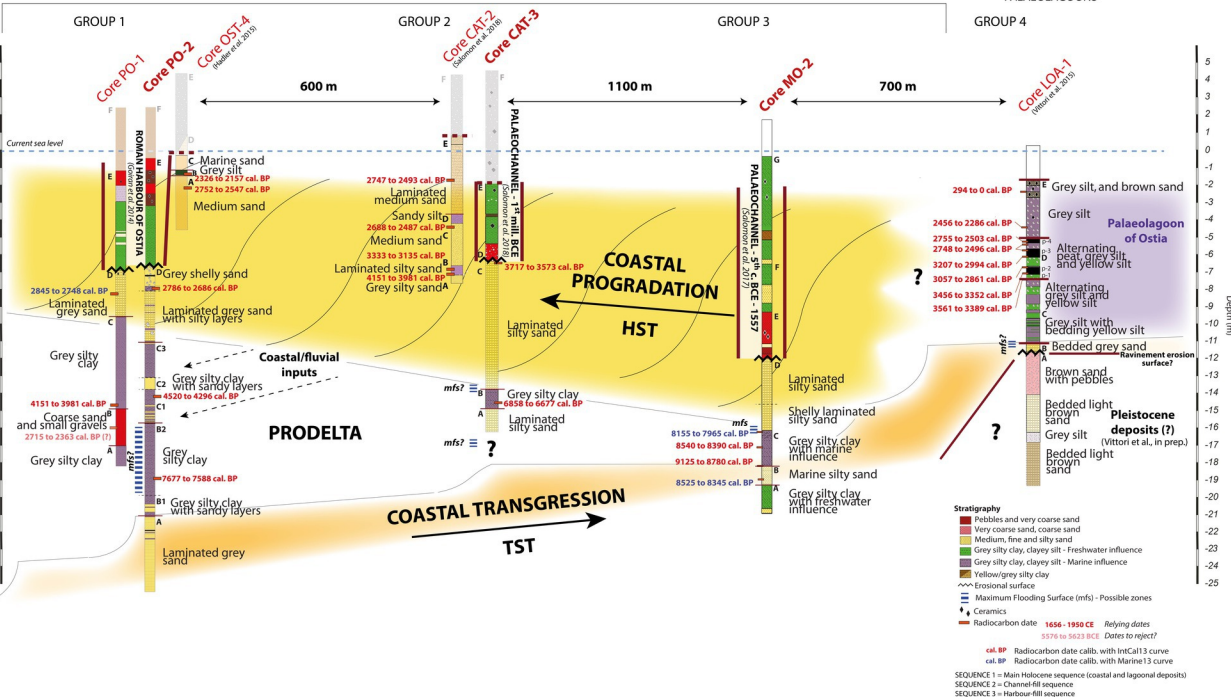
OUTER DELTA PLAIN

PROGRADED PLAIN

INNER DELTA PLAIN

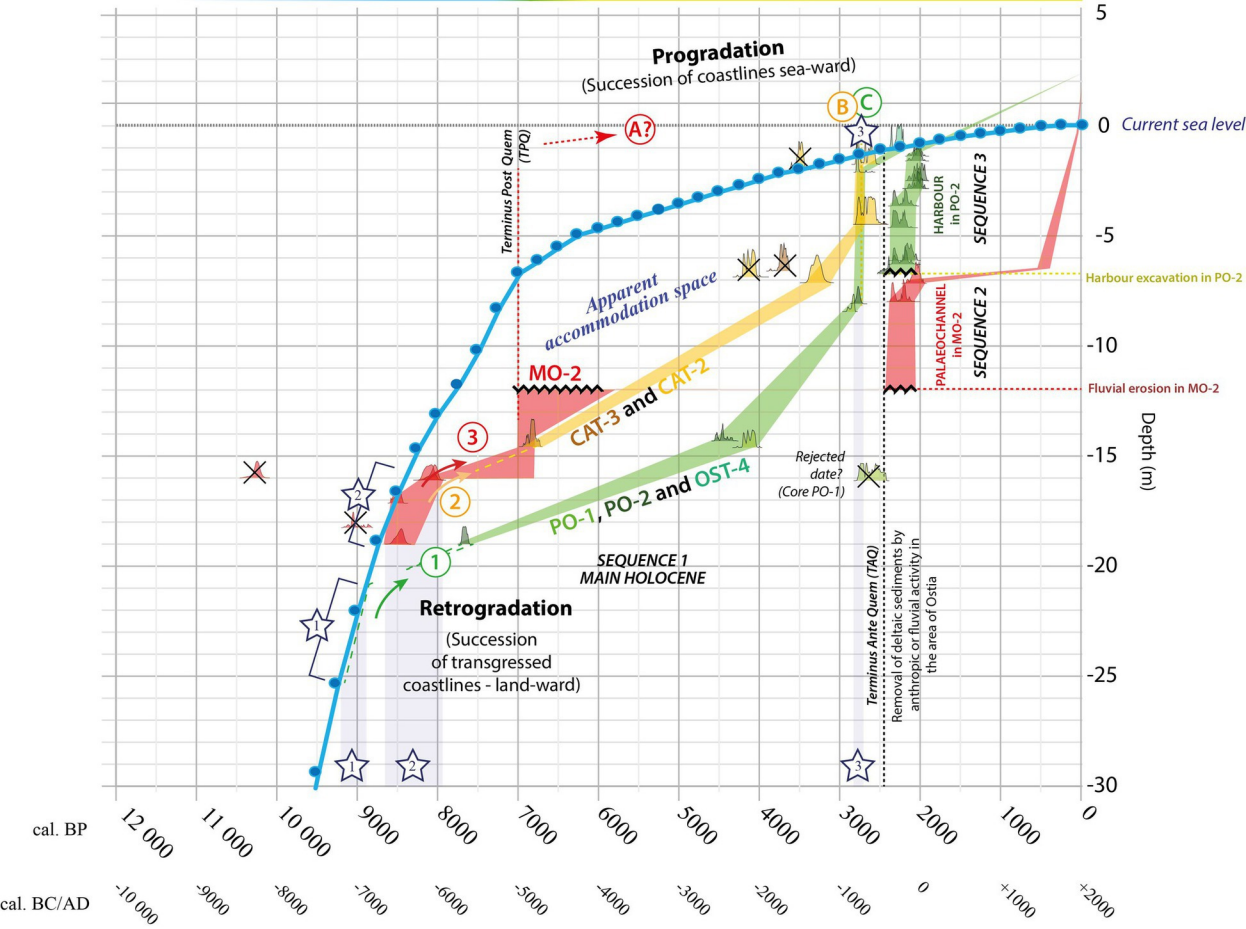
PALAEOLAGOONS

EAST

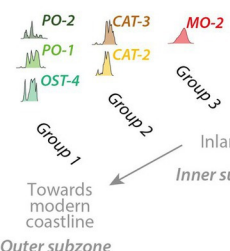


TST

HST



= Eustatic and glacio-hydro-isostatic prediction for the Tiber delta (Lambeck et al. 2011)



Calibrated radiocarbon dates

Rejected dates

Apparent sedimentation curves of the three studied areas

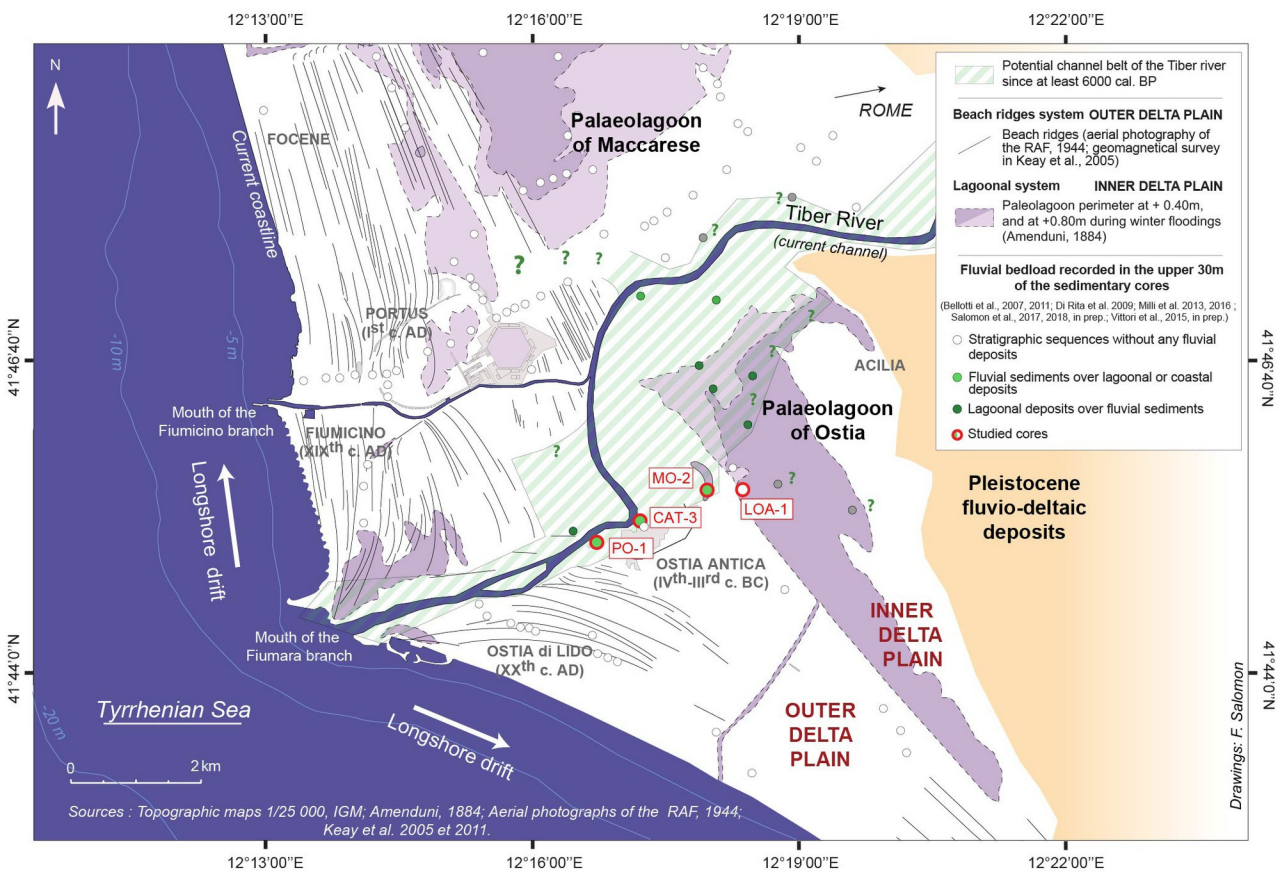
Erosional surfaces

Evidence for reconstructing the coastline-trajectories

1 - Transgressive coastline near Group 1 Outer subzone

2 - Transgressive coastline near Groups 2 and 3 Inner subzone

3 - Coastline near Groups 1 and 2 Outer subzone



Core	Sample	Depth below surface (m)	Depth below sea level (s.l.m - Genoa) (m)	Lab. sample	Dating support	<sup>14</sup> C yr B.P.	±	Age calibrated BCE-CE (Reimer et al., 2013) - 2σ	Age calibrated cal. BP (Reimer et al., 2013) - 2σ	Reference
<b>Area of the palaeolagoon of Ostia</b>										
LOA-1 (+0.45m)	LOA-1 / 1308	13.08	-12.63	Lyon-10104	Plant material	175	30	AD 1656 to 1950	294 to 0	Vittori et al., 2015
LOA-1	LOA-1 / 503	5.03	-4.58	Lyon-10105	Shell*	2660	30	506 to 336 BCE*	2456 to 2286	Vittori et al., 2015
LOA-1	LOA-1 / 584	5.84	-5.39	Lyon-10106	Peat	2560	30	805 to 553 BCE	2755 to 2503	Vittori et al., 2015
LOA-1	LOA-1 / 596	5.96	-5.51	Lyon-10107	Peat	2535	30	798 to 546 BCE	2748 to 2496	Vittori et al., 2015
LOA-1	LOA-1 / 644	6.44	-5.99	Lyon-10108	Peat	2535	30	798 to 546 BCE	2748 to 2496	Vittori et al., 2015
LOA-1	LOA-1 / 677	6.77	-6.32	Lyon-10109	Peat	2940	30	1257 to 1044 BCE	3207 to 2994	Vittori et al., 2015
LOA-1	LOA-1 / 747	7.47	-7.02	Lyon-10110	Peat	2835	30	1107 to 911 BCE	3057 to 2861	Vittori et al., 2015
LOA-1	LOA-1 / 783	7.83	-7.38	Lyon-10097	Peat	3175	30	1506 to 1402 BCE	3456 to 3352	Vittori et al., 2015
LOA-1	LOA-1 / 823	8.23	-7.78	Lyon-10098	Peat	3240	30	1611 to 1439 BCE	3561 to 3389	Vittori et al., 2015
LOA-1	LOA-1 / 1595	15.95	-15.5	Lyon-9323	Organic matter	6800 <i>Rejected</i>	30	5576 to 5623 BCE	7526 to 7573	Vittori et al., 2015
<b>Area of the palaeomeander of Ostia</b>										
MO-1 (+1.79m)	MO-1 / 76	2.55	-0.76	Ly-8040	Organic matter	Modern	-	Modern	Modern	Salomon et al., 2017
MO-1	MO-1 / 1143	11.43	-9.64	Ly-8041	Bone	355	25	AD 1454 to 1634	496 to 316	Salomon et al., 2017
MO-2 (+1.7m)	MO-2 / 260	2.6	-0.9	Ly-8788	Wood	Modern	-	Modern	Modern	Salomon et al., 2017
MO-2	MO-2 / 8.88 m	8.88	-7.18	Ly-8780	Wood	2035	30	159 BC to AD 50	2109 to 1900	Salomon et al., 2017
MO-2	MO-2 / 9.70m	9.7	-8	Ly-8044	Wood	2160	25	356 to 112 BC	2306 to 2062	Salomon et al., 2017
MO-2	MO-2 / 17.70 m	17.7	-16	Lyon-8807	Shell*	9370 <i>Rejected</i>	45	8390 to 8180 BC	10340 to 10130	<i>New date</i>
MO-2	MO-2 / 17.80m	17.8	-16.1	Lyon-8042	Posidonia*	7545	35	6160 to 5975 BC	8525 to 7925	<i>New date</i>
MO-2	MO-2 / 17.80m / 2	17.8	-16.1	Lyon-8043	Posidonia*	7600	40	6205 to 6015 BC	8155 to 7965	<i>New date</i>
MO-2	MO-2 / 18.85 m	18.85	-17.15	Lyon-8790	Wood	7655	40	6590 to 6440 BC	8540 to 8390	<i>New date</i>
MO-2	MO-2 / 19.95 m	19.95	-18.25	Lyon-8789	Wood	8070	40	7175 to 6830 BC	9125 to 8780	<i>New date</i>
MO-2	MO-2 / 20.70 m	20.7	-19	Lyon-8808	Shell*	7965	40	6575 to 6395 BC	8525 to 8345	<i>New date</i>
MO-3 (+2m)	MO-3 / 3.35 m	3.35	-1.35	Ly-8781	Wood	780	30	AD 1210 to 1281	740 to 669	Salomon et al., 2017
MO-3	MO-3 / 6 to 6.05 m	6.025	-4.025	Ly-8793	Charcoal	2120	30	344 to 51 BC	2294 to 2001	Salomon et al., 2017
MO-3	MO-3 / 10 m	10	-8	Ly-8792	Bone	2230	30	384 to 204 BC	2334 to 2154	Salomon et al., 2017

MO-3	MO-3 / 14.25 m	14.25	-12.25	Ly-8799	<i>Shell*</i>	10070	50	<i>9250 to 8951 BC*</i>	11200 to 10901	Salomon et al., 2017
<b>Area of the Castrum in Ostia</b>										
CAT-1 (+3.82m)	OST-1 / 632	6.32	-2.5	Lyon-11777(SacA 40124)	Organic matter	3325	30	1687 to 1527 BC	3637 to 3477	Salomon et al., 2018
CAT-2 (+4.34m)	OST-2 / 1150	11.50	-7.16	Lyon-11781(SacA 40128)	<i>Posidonia*</i>	3365	30	<i>1383 to 1185 BC*</i>	3333 to 3135	Salomon et al., 2018
CAT-2	OST-2 / 1150	11.50	-7.16	Lyon-11195(SacA 37181)	Wood	6805 <i>Rejected</i>	30	5738 to 5638 BC	7688 to 7588	Salomon et al., 2018
CAT-2	OST-2 / 635	6.35	-2.01	Lyon-11197(SacA 37183)	Organic matter	3220 <i>Rejected</i>	30	1605 to 1425 BC	3555 to 3375	Salomon et al., 2018
CAT-2	OST-2 / 1124	11.24	-6.9	Lyon-11780(SacA 40127)	Organic matter	3720	30	2201 to 2031 BC	4151 to 3981	Salomon et al., 2018
CAT-2	OST-2 / 885	8.85	-4.51	Lyon-11196 (SacA37182)	Organic matter	2500	30	738 to 537 BC	2688 to 2487	Salomon et al., 2018
CAT-2	OST-2 / 613	6.13	-1.79	Lyon-11779 (SacA40126)	Wood	2530	30	797 to 543 BC	2747 to 2493	Salomon et al., 2018
CAT-3 (+4.48m)	OST-3 / 748	7.48	-3	Lyon-11778(SacA 40125)	Charcoal	2170	30	360 to 116 BC	2310 to 2066	Salomon et al., 2018
CAT-3	OST-3 / 780	7.8	-3.32	Lyon-11782 (SacA40129)	Wood	2190	30	361 to 178 BC	2311 to 2128	Salomon et al., 2018
CAT-3	OST-3 / 830	8.30	-3.82	Ly-16569	Wood	2445	35	755 to 409 BC	2705 to 2359	Salomon et al., 2018
CAT-3	OST-3 / 960	9.6	-5.12	Lyon-11783 (SacA40130)	Charcoal	2205	30	370 to 196 BC	2320 to 2146	Salomon et al., 2018
CAT-3	OST-3 / 1110	11.10	-6.62	Lyon-11198 (SacA37184)	Charcoal	3400	30	1767 to 1623 BC	3717 to 3573	Salomon et al., 2018
CAT-3	OST-3 / 1906	19.06	-14.58	Lyon-13721 (SacA48504)	Org. matter	5945	30	4908 to 4727 BC	6858 to 6677	<i>New date</i>
<b>Area of the Roman harbour of Ostia</b>										
PO-2 (+2.40m)	NA	3.78	-1.38	Ly-8059 (GrA)	Wood	2040	25	160 BC to AD 25	2110 to 1925	Goiran et al., 2014
PO-2	NA	4	-1.6	Ly-8060 (GrA)	Wood	2040	25	160 BC to AD 25	2110 to 1925	Goiran et al., 2014
PO-2	NA	4.9	-2.5	Ly-8061 (GrA)	Charcoal	1990	25	44BC to 63AD	1994 to 1887	Goiran et al., 2014
PO-2	NA	4.9	-2.5	Ly-8062 (GrA)	Organic matter	2050	25	164 BC to 16 AD	2114 to 1934	Goiran et al., 2014
PO-2	NA	5.26	-2.86	Ly-8063 (GrA)	Plant material	2025	25	98 BC to AD 52	2048 to 1898	Goiran et al., 2014
PO-2	NA	5.26	-2.86	Ly-8064 (GrA)	Wood	2050	25	164 BC to AD 16	2114 to 1934	Goiran et al., 2014
PO-2	NA	6.045	-3.645	Ly-9096 (GrA)	Wood	2160	30	358 to 108 BC	2308 to 2058	Goiran et al., 2014
PO-2	NA	7.035	-4.635	Ly-9095 (GrA)	Charcoal	2185	30	361 to 172 BC	2311 to 2122	Goiran et al., 2014
PO-2	NA	8.15	-5.75	Ly-9094 (GrA)	Charcoal	2350	40	729 to 361 BC	2679 to 2311	Goiran et al., 2014
PO-2	NA	8.53	-6.13	Ly-9093 (GrA)	Charcoal	2125	30	348 to 52 BC	2298 to 2002	Goiran et al., 2014
PO-2	NA	8.705	-6.305	Ly-9092 (GrA)	Wood	2165	30	359 to 112 BC	2309 to 2062	Goiran et al., 2014

PO-2	NA	10.5	-8.1	Ly-8066 (GrA)	<i>Posidonia*</i>	2955	25	<i>836 to 736 BC</i>	2786 to 2686	Goiran <i>et al.</i> , 2014
PO-2	PO-2 / 1668- 1679	16.74	-14.335	Lyon- 13728(SacA 48511)	Org. matter	3955	30	2570 to 2346 BC	4520 to 4296	New date
PO-2	PO-2 / 2141- 2144	21.43	-19.025	Lyon- 13729(SacA 48512)	Org. matter	6790	30	5727 to 5638 BC	7677 to 7588	New date
PO-1 (+2.36m)	NA	5.3	-2.94	Ly-8045 (GrA)	Wood	2295	30	406 to 231 BC	2356 to 2181	Goiran <i>et al.</i> , 2014
PO-1	NA	5.73	-3.37	Ly-8046 (GrA)	Wood	2055	25	165 BC to AD 4	2115 to 1946	Goiran <i>et al.</i> , 2014
PO-1	NA	10.85	-8.49	Ly-8047 (GrA)	Plant material	2670	30	895 to 798 BC	2845 to 2748	Goiran <i>et al.</i> , 2014
PO-1	PO-1 / 1680- 1720	17.00	-14.64	Lyon- 13722(SacA 48505)	Wood	3720	30	2201 to 2031 BC	4151 to 3981	New date
PO-1	PO-1 / 1850	18.50	-16.14	Lyon- 13723(SacA 48506)	Org. matter	2455 <i>Rejected?</i>	30	756 to 413 BC	2715 to 2363	New date
OST-4 (+4.38m)	OST 4/14 HK	5.72	-1.34	MAMS- 19753	Charcoal	2229	17	376 to 207 BC	2326 to 2157	Hadler <i>et al.</i> , 2015
OST-4	OST 4/19 + PR	6.68	-2.30	MAMS- 19754	Unident. plant remain	2562	19	802 to 597 BC	2752 to 2547	Hadler <i>et al.</i> , 2015

1 Table 1 – Radiocarbon dates - calibrated with the IntCal13 curve - Reimer *et al.*, 2013 (Materials in  
2 blue and with an asterisk are calibrated with the Marine13 curve - Reimer *et al.*, 2013