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1 **Management of fluvio-coastal dynamics in the Tiber delta during the Roman**
2 **period: Using an integrated waterways system to cope with environmental**
3 **challenges at Ostia and Portus**

4 Ferréol Salomon¹, Kristian Strutt², Dragana Mladenović², Jean-Philippe Goiran³, and Simon Keay²⁺

5 ¹ Laboratoire Image Ville Environnement (UMR 7362), Centre National de la Recherche Scientifique
6 (CNRS)/Université de Strasbourg, 3 rue de l'Argonne, 67000 Strasbourg, France ;
7 ferreol.salomon@live-cnrs.unistra.fr

8 ² University of Southampton, Department of Archaeology, Faculty of Humanities, Avenue Campus,
9 Southampton SO17 1BF, UK ; K.D.Strutt@soton.ac.uk ; mladenovicd@yahoo.com ;

10 ³ Archéorient (UMR 5133), Centre National de la Recherche Scientifique (CNRS)/Université Lyon 2,
11 MOM, 7 rue Raulin, 69007 Lyon, France jean-philippe.goiran@mom.fr

12
13 **Abstract.** – The modern Tiber delta includes two river mouths flowing into the Tyrrhenian sea,
14 the Fiumara to the South and the Fiumicino to the North. While the Fiumara is a natural
15 channel, the Fiumicino is a canal that was initially excavated during the Roman period. Two
16 major Roman archaeological sites are associated to these two watercourses: Ostia, founded
17 between the 4th and the 3rd c. BCE, built at the mouth of the Fiumara; and Portus, founded in
18 the 1st c. CE, built with a series of canals including the Fiumicino (*Fossa Traiana*) three
19 kilometres north of Ostia. In this paper we shall explore strategies used by the Romans on
20 these two sites to manage river mouth environments, characterised by high fluvial
21 sedimentation inputs and rapid fluvio-coastal mobility. We will observe possible urban
22 adjustments to natural constraints at Ostia, and demonstrate how Portus was from inception
23 designed to reduce fluvial sedimentation in the harbour basins and to lower lateral mobility
24 of the canals, building on the experience from Ostia. Finally, we will propose the existence of
25 an integrated system of management for the watercourses at Portus and Ostia in the Imperial
26 period.

27 **Keywords:** geoarchaeology, watercourse management, Roman canals, Roman harbours, Ostia
28 and Portus, Tiber delta.

29
30 **Figure 1.** – Site location – Two archaeological sites at the mouth of the River Tiber during the
31 Roman period

32 **Figure 2.** – Map of the orientation of the structure/features in Ostia and Portus

33 **Figure 3.** – Diagram of the orientation of the archaeological structures/features in Ostia and
34 Portus

35 **Figure 4.** – Fluvial mobility and harbour construction along the River Tiber – Synthesis of
36 chronostratigraphical data

37 **Figure 5.** – From the canals to the harbours of Portus – Synthesis of chronostratigraphical data

38 **Figure 6.** – River mouth management in the port-city of Ostia and the artificial harbour
39 complex of Portus

40

41 INTRODUCTION

42 Located at the mouth of the River Tiber (**Figure 1**), Ostia and Portus were essential for
43 the economic and transport connectivity of Rome, linking the city with the Mediterranean Sea.
44 Ostia was initially a fortified colonial settlement built on the left bank of the river mouth of
45 the River Tiber, and eventually became a significant port-city over time (Calza et al. 1953; Zevi
46 2002; Heinzelmann 2021). By contrast, Portus was built *ex novo* with the aim of creating an
47 Imperial harbour installation (Lugli and Filibeck 1935; Keay et al. 2005; Keay 2012). Both
48 provided harbour facilities for ships to load and unload different kinds of goods. Both,
49 however, faced significant environmental risks and constraints. River mouths are
50 geomorphologically unstable environments. Riverbanks and coastlines can be modified by
51 single events (floods/storms) and on a seasonal basis. This is particularly true during high
52 frequency changes and exceptional events (Noli et al. 1996; Bencivenga et al. 2000). Generally,
53 coastal risks during the Roman period are expressed in terms of coastline mobility (Vella et al.
54 2000; Brückner 2019), storms (Sabatier et al. 2010, 2012) or tsunamis (Luque et al. 2002; Dey
55 and Goodman-Tchernov 2010). Studies considering fluvial risks during the Roman period focus
56 mainly on flood intensity and frequency, their extent (Le Gall 1953; Berger et al. 2003; Ollive
57 et al. 2006; Arnaud-Fassetta 2008; Arnaud-Fassetta et al. 2009), and adjustment to water
58 levels (Bravard et al. 1990; Allinne 2007, 2015; Leveau 2017). Many studies focus on the 1st c.
59 BCE – 2nd c. CE, when a hydro-sedimentary crisis can be observed (Cherkauer 1976; Bravard et
60 al. 1992; Brown and Ellis 1995; Arnaud-Fassetta and Landuré 2003; Ollive et al. 2006; Berger
61 and Bravard 2012). The construction of Portus has also been studied in relation to this specific
62 palaeoclimatic context (Salomon 2013), also called the Roman Climate Optimum (Harper and
63 McCormick 2018; Strutt 2019). By contrast, fewer studies have considered the consequence
64 of fluvial lateral mobility on Roman cities (Bravard and Presteau 1995; Franc and Vérot-
65 Bourrély 2015; Salomon et al. 2018).

66 Ostia and Portus offer an interesting case study for observing structural adjustments
67 to fluvio-coastal dynamics. In this paper, we propose a hypothesis that the port-city of Ostia
68 and the port complex at Portus formed an integrated water management system in the delta
69 of the Tiber, developed over time to combat specific environmental challenges. The first
70 source of evidence that we draw on are the physical remains of structures and archaeological
71 features at Ostia and Portus concentrating on their planning and orientation. We
72 contextualize this evidence with data from geoarchaeological cores collected from the study
73 area, discussing the sedimentological (sediment deposition-erosion) and geomorphological
74 (lateral mobility¹ aspects of the Tiber channels, canals, and sedimentation/erosion of the river
75 mouth bars) issues related to the Tiber in Ostia and the canals of Portus. Hydrological

¹ Lateral mobility of a channel or a canal is a specialist term relating to a displacement of the riverbanks in a planimetric view.

76 constraints (e.g. floods) will not be directly discussed in this paper, but they remain of primary
77 importance during the Roman period (Le Gall 1953; Salomon 2013).

78 MATERIAL AND METHODS

79 Two sets of data are considered in this paper. First, the urban fabric of Ostia and Portus
80 will be analysed and compared, seeking tangible evidence of incorporation of harbour
81 infrastructure and river water management into the planning of the sites. A synthesis of the
82 geoarchaeological cores drilled in the palaeochannels and harbour of Ostia is then presented
83 and compared to the cores drilled in the canals of Portus, allowing us to assess this evidence
84 and elaborate on the interactions between the Tiber, the canals, the harbours and the layout
85 of Ostia and Portus.

86 *Urban fabric*

87 The urban morphology of Ostia reveals an existence of districts within the city (Fluvial,
88 Coastal, River mouth) and possible adjustments of the urban fabric to the mobility of the
89 riverbanks has already been observed (Salomon et al. 2018). In this paper, we apply the same
90 type of GIS analysis of the orientation of the archaeological features to Portus, while using the
91 existing case study of Ostia as a *comparandum* aimed at comparing and contrasting the
92 observed patterns (Figure 2 and 3).

93 The shapefile of Ostia has been drawn based on excavated archaeological structures
94 (roads, walls, etc.). By contrast, Portus has not been extensively and continuously excavated.
95 The dataset from Portus is based on the map from Keay et al. (2005). It represents a mix of
96 visible excavated *archaeological structures* (Lanciani 1868; Lugli and Filibeck 1935; Testaguzza
97 1970; Paroli 2004; Keay et al. 2005) and *archaeological features* identified from geophysical
98 survey (Keay et al. 2005). Archaeological features are interpretations of magnetic anomalies
99 and may or may not be actual archaeological structures from the Roman period. However, the
100 quality of the magnetic signal from archaeological structures in and around Portus is of
101 particularly good quality (Keay et al. 2005, 2020). The interpretations from 2005 were also
102 largely confirmed by later excavations conducted by the University of Southampton in the
103 area of the *Palazzo Imperiale* between the Claudian and Trajanic basins (particularly the extent
104 and the orientation of the main buildings) (Keay et al. 2011, in press).

105 The GIS database includes the shapefiles for Ostia and Portus in the coordinate system
106 WGS 84 / UTM 33N (EPSG: 32633). Transverse Mercator projection is conformal since it
107 preserves angles. The preservation of the angles is essential for the analysis. Orientations of
108 archaeological structures and features were calculated in the QGIS software within the range
109 0° to 179°. In order to compare Ostia and Portus, classes of orientations were defined every
110 10° and assigned different colour values. The maps containing orientation analysis of the two
111 sites are presented in Figure 2. Figure 3 presents the orientation of the structures and features
112 to a degree. We can observe that the dataset of Ostia (96915 lines distributed according to
113 the Y-axis on the right) is more detailed than the one available for Portus (3594 lines
114 distributed according to the Y-axis on the left). The dataset from Portus will in future be made
115 more complete by research currently being conducted by the Parco Archeologico di Ostia
116 Antica, the University of Southampton (Keay et al. 2011, in press), the École Française de Rome

117 (Bukowiecki and Panzieri 2013; Bukowiecki et al. 2018), and the Universidad Huelva (Bermejo
118 et al. 2018), but the overall orientation of the main features of the site will not change.

119 ***Geoarchaeological cores***

120 For the last 20 years, much geoarchaeological fieldwork involving sedimentary drillings
121 has been conducted at Ostia (Goiran et al. 2014; Hadler et al. 2015; Salomon et al. 2018) and
122 Portus (Arnoldus-Huyzendveld 2005; Bellotti et al. 2009; Giraudi et al. 2009; Goiran et al.
123 2010). These cores were studied using a large range of palaeoenvironmental analyses (*e.g.*
124 Pollens: Sadori et al. 2010, Pepe et al. 2016; Ostracods: Mazzini et al. 2011; Geochemistry:
125 Delile et al. 2014; Foraminifers: Bella et al. 2011, Hadler et al. 2015).

126 In this paper, we use a selection of cores drilled in the fluvial environments around
127 Ostia and in the canals around Portus (Figure 1). For Ostia we chose two cores drilled in the
128 palaeomeander, immediately upstream of the *Porta Romana* (Cores MO-3 and MO-1 from
129 Salomon et al. 2017), and two cores drilled downstream of the city near the river mouth, and
130 in the fluvial harbour of Ostia next to the *Palazzo Imperiale* (Core PO-2 from Goiran et al. 2014;
131 Core ISF-1 from Salomon et al. 2018). For Portus, we chose, on the one side, cores drilled in
132 the *Canale Romano* (Core CN-1 from Salomon et al. 2014), the *Canale Traverso* (Core CT-1
133 from Salomon et al. 2012), and the harbour pool of Portus (TR-14 from Goiran et al. 2010 and
134 Delile et al. 2014), and on the other side, cores drilled in the Portus to Ostia Canal (Cores CPO-
135 2 and 3 from Salomon et al. 2020). These cores will provide evidence of the lateral stability or
136 mobility of the palaeochannels/canals, but also the hydrodynamic conditions during their
137 periods of activities and their periods of abandonment.

138 Only a few of the palaeoenvironmental analyses are reported in Figures 4 (Ostia) and
139 5 (Portus). For the aims of this paper we focus on the stratigraphic logs, a short description of
140 the facies, the texture (*coarse fraction* > 2 mm; 2 mm > *sand* > 63 µm ; and *silts and clays* < 63
141 µm), and the radiocarbon dates recalibrated according to Reimer et al. (2020). These essential
142 data provide chronostratigraphical evidence and a basic proxy of the hydrodynamic conditions
143 during the deposition of the sediments.

144 **RESULTS OF THE GIS AND PALAEOENVIRONMENTAL ANALYSES**

145 **Orientations of archaeological structures and features at Ostia and Portus**

146 Ostia is generally considered to have grown organically from a fortified early
147 settlement (*Castrum*) built between the 4th and the 3rd c. BCE (Zevi 2002). Initially, the *Castrum*
148 was built not far from the left riverbank of the Tiber (Constans 1926; Salomon et al. 2018). The
149 last section of the *via Ostiensis* coming from Rome towards the sea corresponds to the
150 *decumanus* of the *Castrum* that the city was built around. Interestingly, the *decumanus*
151 displays slightly different orientations within Ostia (Sclavi et al. 2016). The alignment of the
152 eastern and western gates of the *Castrum* probably best represent the initial orientation of
153 the *decumanus* (Calza et al. 1953), while the sections of the *decumanus* leading to *Porta*
154 *Romana* could have been modified through time in response to urban dynamics along the
155 street. Sclavi et al. (2016), put the orientation azimuth of the *decumanus* within the *Castrum*
156 at 58.14° (238.14°) and the section of the *decumanus* the closest to *Porta Romana* at 60.48°

157 (240.48°), measured on the ground with a professional GPS (averaging 100 measures per point
158 with $\pm 0.5^\circ$ uncertainty). According to georeferenced maps we collected, the orientation of
159 the *Castrum* from the eastern to the western gate measures $61^\circ \pm 1^\circ$ ($241^\circ \pm 1^\circ$). A large part of
160 the urban fabric of Ostia that grew out of the *Castrum* conforms to the orientations of the
161 *decumanus* and the *cardo*; e.g. the orientation of streets within the Fluvial district ranges
162 between 61° and 63° . The coastal and river mouth areas do not follow the same pattern and
163 might follow other features, such as the *Via Laurentina*, *Via della Foce*, *Via del Mare*, and
164 possibly palaeocoastlines and palaeoriverbanks.

165 At Portus, the main excavated sections of Claudian moles are oriented at $62^\circ \pm 1^\circ$
166 ($242^\circ \pm 1^\circ$) (Figure 2). Similar orientations are recorded in the area of the *Darsena*. Trajan's
167 architects used this orientation for sides II and V of the new hexagonal basin. Following
168 geometric rules, sides III and VI are at $32^\circ \pm 1^\circ$ ($112^\circ \pm 1^\circ$) and sides I and IV are at $92^\circ \pm 1^\circ$
169 ($272^\circ \pm 1^\circ$). The eastern part of the *Canale Romano* (upstream) is aligned with the structures
170 located east of Portus (the *via Portuensis* and the aqueduct). Upstream, the canal is oriented
171 at $77^\circ \pm 1^\circ$ and downstream it conforms to the side III of the hexagonal basin. The northern
172 canal is out of the main grid of planned features of Portus with $104^\circ \pm 1^\circ$ on the left riverbank
173 and $106^\circ \pm 1^\circ$ on the right riverbank. The actual orientation of the *Fossa Traiana* – Fiumicino
174 is difficult to characterise due to small curves in its outline. It was probably related to the
175 orientation of the side IV of the hexagon. The *Canale Traverso* conforms to the Claudian
176 orientations. The left riverbank of the Portus to Ostia canal is a straight line oriented at $152^\circ /$
177 $332^\circ \pm 1^\circ$, while interestingly, the right riverbank is irregular and its orientation cannot be
178 measured.

179 Evidence of fluvial lateral mobility at Ostia and Portus

180 The two cross-sections of cores selected for Ostia demonstrate fluvial lateral mobility
181 during the Roman period (Figure 4). All cores are characterised at their base (Units A) by yellow
182 layered sands corresponding to shoreface deposits from the 1st part of the 1st millennium BCE
183 (Unit A in Core PO-2) or before (Salomon 2020).

184 Coarse sands and small pebbles are the bedload-derived facies of the deltaic Tiber
185 (Salomon et al. 2017). They are observed in most of the stratigraphy of Core MO-3 and
186 correspond to the point bar deposits of the palaeochannel of Ostia. Similar point bar
187 successions are observed in Core TEV-4A (Hadler et al. 2020). Core MO-1 demonstrates a
188 decrease of the grain-size from Units B and C (composed of coarse sands and pebbles) to Unit
189 D (composed of sand) and Unit E (composed of silts and clays). This decrease in grain-size is a
190 typical stratigraphic succession from a cut-off palaeochannel. Similar stratigraphies of cut-off
191 palaeochannels are also observed in Cores TEV-1, TEV-3A, possibly TEV-2 in the neck of the
192 *Fiume Morto* (Hadler et al. 2020), and possibly below the *cardo* of Ostia (Core CAT-3 in
193 Salomon et al. 2018).

194 At the mouth of the Tiber, Units B, C, and D, from Core ISF-1, contain many layers of
195 different grain-size and facies, from silts and clays to coarse sands. Quick-changing
196 depositional conditions characterise river mouth environments affected by both fluvial and
197 coastal processes. The sedimentation in Core ISF-1 could be related to a migration of the river

198 mouth channel to the south or a contraction of the channel width. The two hypotheses relate
199 to riverbank mobility. On the left side of the Tiber, a harbour was excavated between the 4th
200 and the 2nd c. BCE (Goiran et al. 2014). The harbour muds are sealed by coarse fluvial deposits
201 with sediments presenting a bedload-derived facies (Goiran et al. 2014; Delile and Salomon
202 2020). A large part of the fluvial harbour was filled up in the 1st c. CE (Goiran et al. 2014).

203 Interestingly, all evidence of riverbank mobility in the palaeomeander of Ostia
204 (Salomon et al. 2017; Hadler et al. 2020), north of the *Castrum* (Salomon et al. 2018), or at the
205 river mouth (Goiran et al. 2014; Salomon et al. 2018) is dated to the 1st c. CE at the latest. Most
206 of the evidence of fluvial lateral mobility dates to the second part of the 1st millennium BCE,
207 during the Republican period of Ostia. Morphogenetic activities of the river started again
208 much later in the 10th – 13th c. CE (Hadler et al. 2015; Delile and Salomon 2020) and after 1557
209 CE.

210 The sedimentary cores drilled in the canals around Portus reveal different types of
211 stratigraphical successions (Figure 5). Three canals will be presented: the *Canale Romano*, the
212 *Canale Traverso*, and the Portus to Ostia Canal. The first cross-section shows the *Canale*
213 *Traverso* leading to Fiumicino (*Fossa Traiana*), and then the *Canale Traverso* and the Portus
214 pool between the harbours of Claudius and Trajan. Similar to the area of Ostia, all cores reach
215 a Unit A composed of yellow layered sand corresponding to shoreface deposits. These
216 deposits date back to the first part of the 1st millennium BCE or earlier (Giraudi 2004; Bellotti
217 et al. 2007; Salomon 2020).

218 Core CN-1 from the *Canale Romano* reveals the typical stratigraphy of a cut-off channel
219 (Salomon et al. 2014). Units B and C are composed of medium-to-coarse sands, suggesting
220 bedload-derived facies. A sharp limit marks the change from the coarse deposits in Unit C to
221 the fine deposits in Unit D characteristic of sediment deposited after a cut-off. Finally, the
222 canal is covered by fine floodplain deposits (Unit E). No core is available yet from the Fiumicino
223 (*Fossa Traiana*) since the canal is still in activity.

224 Core CT-1 drilled in the *Canale Traverso* has more in common with a protected harbour
225 stratigraphy (Core TR-14) than that of a fluvial canal (Core CN-1). No bedload-derived facies
226 are observed at the bottom of the canal. Muds from Unit B were found directly lying on
227 shoreface sands (Unit A). Coarse material is observed in Unit D relating to the second phase
228 of use of the canal. The sedimentation in the canal was likely controlled by dredging (Salomon
229 et al. 2012) and possibly also by a sluice-gate (Testaguzza 1970; Lisé-Pronovost et al. 2019).

230 No lateral mobility is observed in the magnetometer survey around Portus for the
231 *Canale Romano* and the *Canale Traverso* (Keay et al. 2005). However, along the two canals
232 high local magnetic fields are observed (Keay et al. 2005). These certainly indicate structures
233 along the canals rather than lateral mobility. The two canals were probably articulated by built
234 riverbanks or quays similar to the Fiumicino - *Fossa Traiana* (Testaguzza 1970).
235 Palaeoenvironmental analyses of the cores from the Northern Canal are currently in process
236 of being studied. Magnetometer survey revealed no lateral mobility of the canal, nor any
237 features that could be associated with a built riverbank.

238 The lower part of Figure 5 shows a cross section of the Portus to Ostia Canal. The two
239 cores CPO-2 and 3 can be compared to the cores from the palaeomeander of Ostia (MO-1 and
240 MO-3). Core CPO-3 shows bedload-derived facies up to the Roman sea level in units B and C,
241 similar to point bar deposits. However, Core CPO-2 demonstrates first a Unit B composed of
242 coarse sands and gravels and then fine deposits (Unit C). These two stratigraphic successions
243 led us to consider a lateral mobility of the Portus to Ostia canal (Salomon et al. 2020). In the
244 area of the cross section, magnetometry revealed lateral mobility, but no features relating to
245 built riverbanks.

246 DISCUSSION

247 Ostia, a port-city affected by rapid fluvial sediment deposition and lateral mobility of the 248 river channel

249 The *Castrum* at Ostia was originally built in the 4th – 3rd c. BCE to control access to the Tiber
250 channel from the sea (Vaglieri 1911; Calza et al. 1953). By the end of the Republican period,
251 Ostia's close association with the river (Heinzelmann and Martin 2002; Goiran et al. 2014) and
252 the coastlines (Strabo V, 3, 5) was shaping the urban fabric through harbour interfaces and
253 their mobility (Salomon et al. 2018), turning Ostia into a port-city (Zevi 2001, 2002). Along the
254 shore, possible harbour structures were built between the end of the 1st c. BCE/1st c. CE and
255 the beginning of the 3rd c. CE (Raddi and Pellegrino 2011). Little is, however, known about the
256 coastal interface management for earlier periods.

257 With the urbanisation of the two sides of the river (Germoni et al. 2018; Keay et al. 2020), the
258 harbour within Ostia took a linear form along the banks of the Tiber. Along the left bank of the
259 Tiber, one or several small harbours indented the riverbanks. Geoarchaeological evidence
260 confirmed the existence of one of these small harbours at the mouth of the Tiber (Goiran et
261 al. 2014). Meanwhile, a thick layer of fine deposits observed north of the *Castrum* could
262 suggest the existence of similar harbour deposits (Core CAT-3 Unit C in Salomon et al. 2018);
263 the *molo repubblicano* in the palaeomeander of Ostia could also be interpreted as a harbour
264 structure (Pannuzi et al. 2021).

265 The linear harbour of Ostia indented by small basins was clearly exposed to fluvial and
266 coastal risks. The main problem reported by ancient authors is related to the Tiber access for
267 maritime ships due to the formation of river mouth bars. This frequent problem was notably
268 reported in 205–204 BCE (Livy, *Ab Urbe Condita*, 29.14.11; Ovid, *Fasti* 4.291–304), and at the
269 end of the 1st c. BCE-beginning of the 1c. CE (Dionysius of Halicarnassus, *Antiquitates Romanae*
270 3. 44; Strabo 5.3.5). Though these bars appear to have formed regularly at the river mouth,
271 such unsteady morphologies are not easy to identify using sedimentary cores.

272 The channel of the Tiber conveyed water and sediment through the city of Ostia.
273 Consequently, small harbour basins along the river were exposed to quick sedimentation.
274 Unfortunately, the estimation of the sedimentation rate in the harbour at the river mouth is
275 particularly difficult to ascertain. The calibrations of the radiocarbon dates performed in the
276 harbour muds (Core PO-2, Unit B in Figure 4) offer dates ranging from the 4th to the 2nd c. BCE
277 (Goiran et al. 2014). During this first phase, the harbour was maybe prone to quick fine
278 sedimentation, but coarse material derived from the bedload did not reach the harbour.

279 However, during the second phase, the harbour was sealed by 2.5m of coarse material
280 deposited during flood events (Core PO-2, Unit C - Goiran et al. 2014; Delile and Salomon
281 2020). Additionally, the regular modification of the profile of the river channel at the entrance
282 to the harbour might have affected access (Goiran et al. 2017).

283 Regarding the river channel itself, fluvial mobility possibly eroded infrastructure, like the
284 *via Ostiensis* to the north-east of Ostia (Bertacchi 1960; Arnoldus-Huyzendveld and Paroli
285 1995; Salomon et al. 2017), or moved the riverbanks away from the city, such as those north
286 of the *Castrum* (Constans 1926; Salomon et al. 2018).

287 **Portus, a harbour complex planned to reduce river mouth risks**

288 Portus is the result of two main phases of planning. Founded during the reign of the
289 emperor Claudius (mid 1st c. CE), it was reorganised at the beginning of the 2nd c. CE by the
290 emperor Trajan (Lugli and Filibeck 1935; Keay et al. 2005). Due to this Trajanic intervention
291 some of the details of the initial Claudian plan are not fully known. Other phases of
292 construction have also been identified, notably during the reigns of Nero and Hadrian, but
293 these interventions did not significantly affect the plan established by their predecessors
294 (Keay et al. 2005).

295 While Ostia may be understood as a port city, we suggest that Portus ought to be
296 considered as a harbour complex. In terms of planning, while there is a fort at the centre of
297 Ostia, Portus is organised around its harbour basins. No residential occupation has been
298 attested at the site (Keay et al. 2020, p. 159), and it is only at the beginning of the fourth
299 century CE that Portus became an urban settlement with municipal status (*cf. CIL XIV 4449*,
300 dated to CE 337–345 or 334–341 (Keay et al. 2005).

301 The configuration of Portus suggests that the harbour system was conceived to reduce the
302 fluvial inputs in the harbour basins (Figure 1 and 6). The harbour basins and the Tiber channel
303 were not directly connected by waterways (Salomon et al. 2012; Salomon 2013). The Northern
304 canal and the Fiumicino (*Fossa Traiana*) are connected upstream to the Tiber with outlets in
305 the sea north and south of Portus. The canal mouth bars would thus form away from Portus
306 and the harbour basins. In between these two channels, the *Canale Romano* is also connected
307 upstream to the Tiber, and instead of flowing straight, with the attendant risk of flowing into
308 a harbour basin, the canal curves towards the south, follows one side of the hexagonal basin
309 of Trajan, and empties into the Fiumicino (*Fossa Traiana*). The *Canale Romano* was thus a
310 harbour canal (Salomon et al. 2014) only indirectly connected to the Trajanic harbour via the
311 side III of the Hexagonal basin, possibly to facilitate transshipment.

312 Nevertheless, connections existed between the fluvial waterways and the harbour basins.
313 The northern entrance to the Claudian basin (Goiran et al. 2011) and the *Canale Traverso*
314 (Salomon et al. 2012; Lisé-Pronovost et al. 2019) are indirectly connected to the Tiber through
315 the Northern canal and the Fiumicino (*Fossa Traiana*) respectively (Figure 1). This layout
316 reveals a complex flow and sediment routing management planned by Roman engineers.
317 Additionally, the Northern entrance to the Claudian basin and the *Canale Traverso* could have
318 contributed to reduce sediment deposition in the harbour. Models demonstrate that stronger
319 currents induced by winds in the north-eastern channel and the *Canale Traverso* could have

320 reduced rapid sediment infilling in the harbour basin system (Millet et al. 2014). In this
321 context, these stronger currents in the north-eastern channel could have possibly removed
322 sediments deposited at the mouth of the Northern canal. In addition, sluice gates were
323 possibly built in the narrow *Canale Traverso* to better control sediment inputs in the harbours
324 during river floods by blocking both water and sediment discharge towards the harbour basins
325 (Lisé-Pronovost et al. 2019).

326 Roman engineers working in Portus had to deal with fluvial inputs in the harbour basin,
327 but also with riverbank mobility prevention. It should be noted that fluvial erosion affects
328 natural channels as much as canals. Lateral canal mobility is observed on images produced by
329 the magnetometer survey of the Portus to Ostia Canal (Keay and Paroli 2011; Keay et al. 2020)
330 and has been confirmed by sedimentary drillings (Figure 5, lower part) (Salomon et al. 2020).
331 The *Canale Romano*, the Fiumicino (*Fossa Traiana*), and the *Canale Traverso*, however, show
332 evidence of built riverbanks. Archaeological evidence revealed riverbanks along the Fiumicino,
333 at least along the reach south of Portus, and the northern part of the *Canale Traverso*
334 (Testaguzza 1970). Results from geophysical survey identified high magnetic features along
335 the *Canale Romano* and the *Canale Traverso* suggesting built riverbanks and no lateral
336 mobility in the canals. Surprisingly, magnetic surveys revealed no riverbanks and no lateral
337 mobility for the Northern canal. Analyses in progress on cores drilled in the Northern canal
338 will probably shed new light on this feature. A clear pattern emerges: the closer the canal to
339 Portus, the better channelised it was. The channelisation of the canals next to Portus and their
340 shorter width (<50m) compared to the Tiber channel (> 100m) would have made them easier
341 to maintain by dredging.

342 The study of the canal system of Portus thus reveals engineering solutions to
343 sedimentological, geomorphological, and possibly hydrological constraints first faced at Ostia.

344 **From Ostia to the Ostia-Portus system**

345 Portus was clearly not conceived independently from Ostia (Keay 2012), and the two
346 sites present an integrated system of complementary units.

347 In this respect, it is interesting to observe the matching orientation of the original
348 structures at the two sites: the *Castrum* at Ostia and the Claudian structures at Portus.
349 Alignments of the mentioned structures (marked in blue on Figure 2) follow the original axis
350 of the *Castrum* at Ostia (*decumanus* = $62^\circ / 238^\circ \pm 6^\circ$ and *cardo* = $152^\circ / 332^\circ \pm 6^\circ$ - Le Gall
351 1975; Sclavi et al. 2016; Sparavigna 2017). Ostia's original orthogonal grid orientation of c.
352 238° is solar and corresponds to the Winter Solstice Sunset at the time of the town's
353 foundation (Sclavi et al. 2016). Solar orientation was not uncommon among Roman colonies
354 in Italy or in towns founded across the Roman Empire (Magli 2008, though note that the
355 orientation value for Ostia used in Table 1 is off by 10°), and though Roman town foundation
356 ritual incorporated a symbolic dimension, in practice the laying out of the new town grid was
357 predominantly governed by local topography (González-García and Magli 2015; Orfilia Pons et
358 al. 2017). At Ostia, local factors included the positions of the coastline and the riverbanks,
359 limitations imposed by the salt lagoon of Stagno di Ostia, the prevailing winds, and any pre-
360 existing land division and road infrastructure.

361 Winds have been given particular consideration in Vitruvius, the only surviving Roman
362 architecture treatise that deals explicitly with city foundation. The *Castrum* of Ostia conforms
363 fully to the advice given (Vitruvius, *De Architectura*, 1.6.8): the predominant NE and SE winds
364 would indeed break upon the walls of the fortress, as recommended (*cf.* Figure 1). The
365 *Castrum* thus positioned was also aligned with the riverbank (Figure 2), the continued
366 importance of which is reflected in the orientation of the Fluvial district, which although
367 representing a later organic growth of the town still respects the first alignment. At Portus,
368 harbour engineers repeated the same alignment, matching that of Ostia, time and time again
369 – in the original layout of Claudius, the enlargement of Trajan, and the large warehouse block
370 added in the Severan period. Bearing in mind that land division on the Isola Sacra is most
371 probably late 1st century CE in date (Keay et al. 2020: 151), and there is no evidence yet for
372 any land division on either the Isola Sacra or at Portus predating the construction of the
373 Claudian Harbour, it is clear that the orientation of structures and features at Portus was not
374 dictated by a pre-existing land grid, but that it was either copied from Ostia or decided upon
375 based on the same environmental considerations.

376 Wind and water swell direction would have been even more important in designing a
377 harbour environment than a town, and the orientation that offered protection from the
378 prevailing winds must have been seen as advantageous. Preliminary modelling does in fact
379 suggest that the alignment and height of the structures surrounding the Trajanic basin was
380 effective in protecting it from wind, and the same is most likely the case for the *Darsena* (Keay
381 et al. 2021a, pp. 390–391). Unfortunately, we cannot tell how successfully the harbour design
382 combatted the destructive force of water swells, as we currently cannot reconstruct the
383 position of the original Portus harbour entrance with absolute certainty.

384 While some canals display orientation independent of either Portus or Ostia (the upstream
385 reach of the *Canale Romano*, the Northern Canal), most likely for hydrological reasons, other
386 elements of the canal network align with the Trajanic layout of Portus (the downstream reach
387 of the *Canale Romano* follows side III of the Trajanic hexagonal basin, *Canale Traverso* that of
388 the district of the *Darsena*). The Portus to Ostia canal, on the other hand, seems to conform
389 to the original orientation of Ostia and later of Portus (the left/eastern bank not affected by
390 lateral erosion). This alignment of the navigable link between Ostia and Portus adds to the
391 evidence of the existence of a general plan regulating the River Tiber mouths in the Imperial
392 period.

393 Lateral mobility of the Tiber in Ostia seems to stop between the end of the 1st c. BCE and the
394 beginning of the 3rd c. CE (Salomon et al. 2017, 2018). It restarts in the 10th–13th c. CE at least
395 with fluvial coarse deposits observed in the river mouth harbour of Ostia (Hadler et al. 2015;
396 Delile and Salomon 2020). Several hypotheses can be proposed to explain the end of the
397 lateral mobility of the Tiber in Ostia during the Imperial period and for a millennium. Climatic
398 variations could have reduced the intensity and the frequency of the Tiber floods during this
399 period; palaeoclimatic data, however, do not confirm this hypothesis for the long period under
400 consideration (*e.g.* hydroclimatic crisis in the 8th c. CE - Le Gall 1953; Berger and Bravard 2012;
401 McCormick et al. 2012 - is yet to be observed in the sediments of Ostia). Alternatively, the
402 creation of large canals at Portus would have locally diverted large amounts of water and the

403 flow competence of the river could have been largely reduced at Ostia, notably limiting the
404 lateral erosion. It should be noted that while all the dates related to the coarse fluvial deposits
405 at Ostia indicate periods before the 1st c. CE (Goiran et al. 2014; Hadler et al. 2015, 2020;
406 Salomon et al. 2017, 2018; Vött et al. 2020; Delile and Salomon 2020), the radiocarbon dates
407 from the canals of Portus fit in a timespan ranging from the middle of the 1st to the 7th c. CE.
408 It is also possible that some of the solutions applied to the canals of Portus would have also
409 been adopted for the natural channel of the Tiber at Ostia, with built riverbanks facilitating its
410 channelization. In this case, Portus was not the sole solution to the problems at Ostia, but
411 Ostia itself also adapted against fluvial hazards.

412 Additional studies would be necessary to reconstruct precisely the mobility of the
413 downstream reach of the Tiber and the management of the riverbanks of Ostia between the
414 Republican and the Imperial period. The long history of Ostia would offer the possibility of
415 detailing the temporal trajectory and the different phases of fluvial management during the
416 Roman period.

417 CONCLUSION

418 The main hazards recorded by ancient texts for the port-city of Ostia were the large amount
419 of sediment deposited at the river mouth affecting the harbour and the presence of river
420 mouth bars constraining the access to large maritime ships. Geoarchaeological sedimentary
421 drillings confirmed the important sedimentation at the river mouth (Goiran et al. 2014;
422 Salomon et al. 2018, 2020) and revealed the importance of the lateral mobility of the Tiber in
423 Ostia (Salomon et al. 2017, 2018). This study demonstrates how a city like Ostia tried to
424 manage dynamic river mouth environments through time, and how the Imperial harbour
425 facility at Portus was planned from its foundation with these problems in mind (Figure 6).

426 **Fluvial mobility.** During the Republican period, Ostia was founded along the natural channel
427 of the Tiber. The city expanded and eventually urbanised the two banks of river mouth
428 (Germoni et al. 2018; Keay et al. 2020). During the Republican period, the river moved laterally
429 and Ostia adjusted to these changes by rebuilding riverine infrastructures (Salomon et al.
430 2017, 2018). A few kilometres to the north, in the middle of the 1st c. CE, the maritime harbour
431 at Portus was conceived away from the Tiber and its direct erosion. Nevertheless, canals had
432 to be excavated to connect Portus to the Tiber and allow direct transshipment via the river to
433 Rome. Built riverbanks were used in the canals close to Portus in order to limit their lateral
434 mobility (Fiumicino – *Fossa Traiana*, *Canale Romano*, *Canale Traverso* and possibly some parts
435 of the Portus to Ostia canal). These riverbanks are currently known via geophysical survey
436 alone (Keay et al. 2005, 2020).

437 **Water and sediment routing.** In Ostia, the Tiber flowed through the city with a high sediment
438 discharge during floods. Consequently, the harbours excavated along the Tiber were more
439 prone to be filled by sediments. In Portus, the canal system dispatched the main water and
440 sediment discharges of the Tiber to the south and north of Portus. Additionally, the connection
441 between the river flow and the harbour basins was indirect (e.g. a secondary connection via
442 channels/canals, transshipping between the Trajanic harbour and the *Canale Romano*). While
443 the river channel and the harbours are joint or closely interconnected in Ostia, the river system
444 (including canals) and the harbour basins are separated at Portus (Figure 6).

445 Finally, the corresponding orientation of archaeological structures observed at Ostia, the
446 harbour of Claudius and Trajan, and the Portus to Ostia canal that aimed at reducing the
447 adverse impact of wind and likely also waves, further supports the existence of a common
448 planning logic. The management of sediment and water discharge was, furthermore,
449 conceived in considering the possibility of navigation between the different harbour units of
450 Ostia and Portus (the Tiber channel, canals, harbour basins of Ostia and Portus), indicating the
451 existence of a single integrated water management and harbour system.

452

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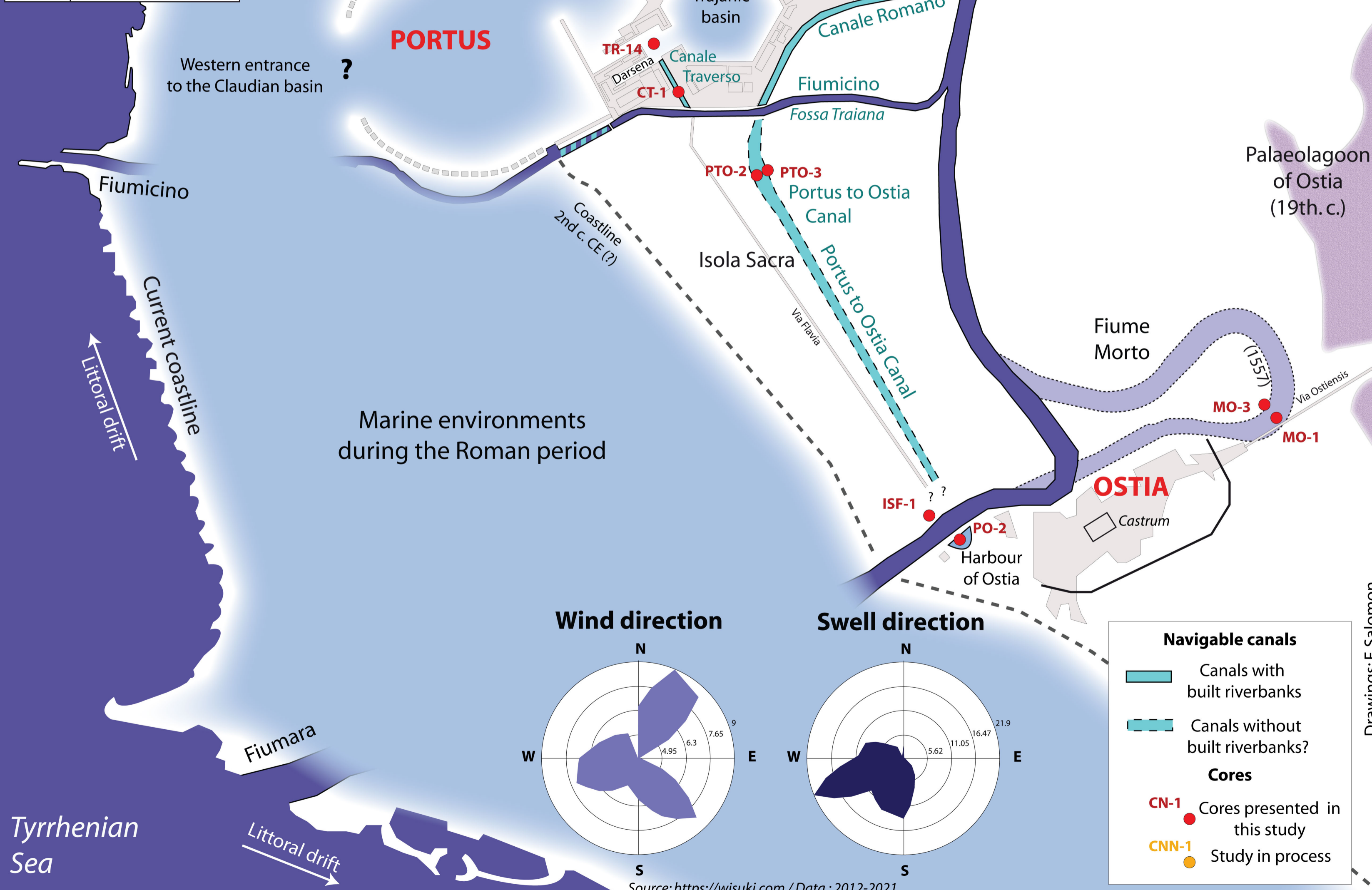
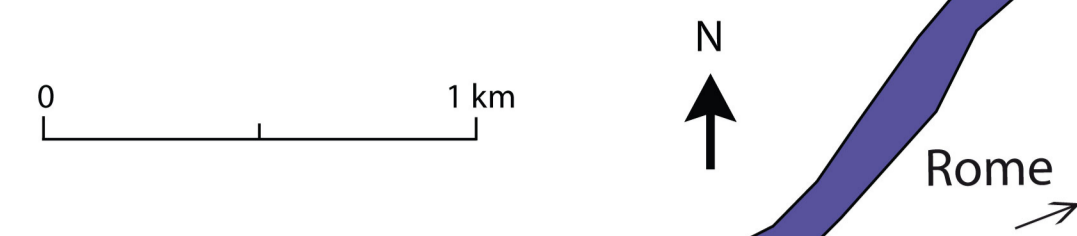
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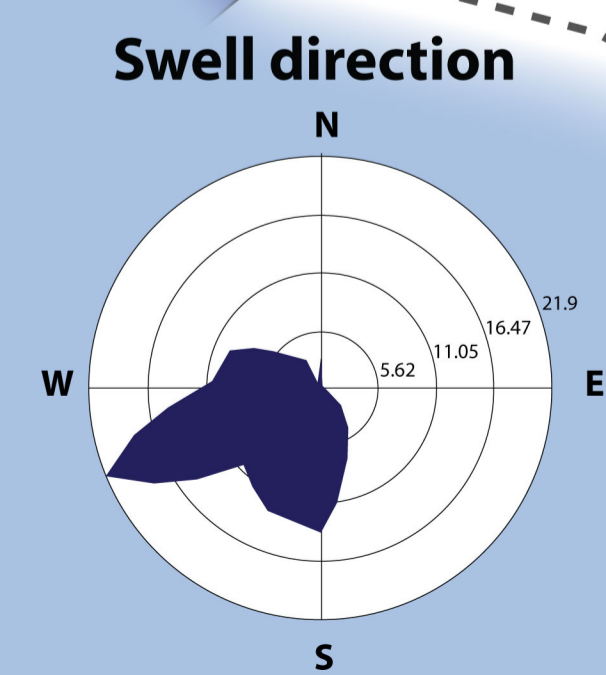
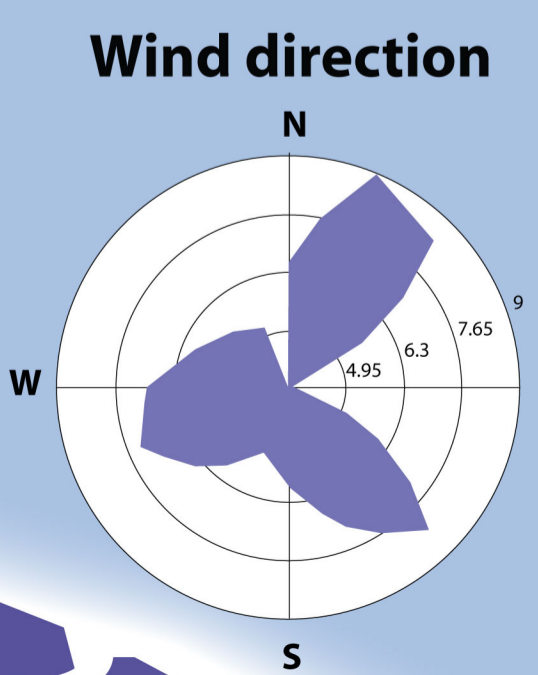
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Marine environments during the Roman period



Navigable canals

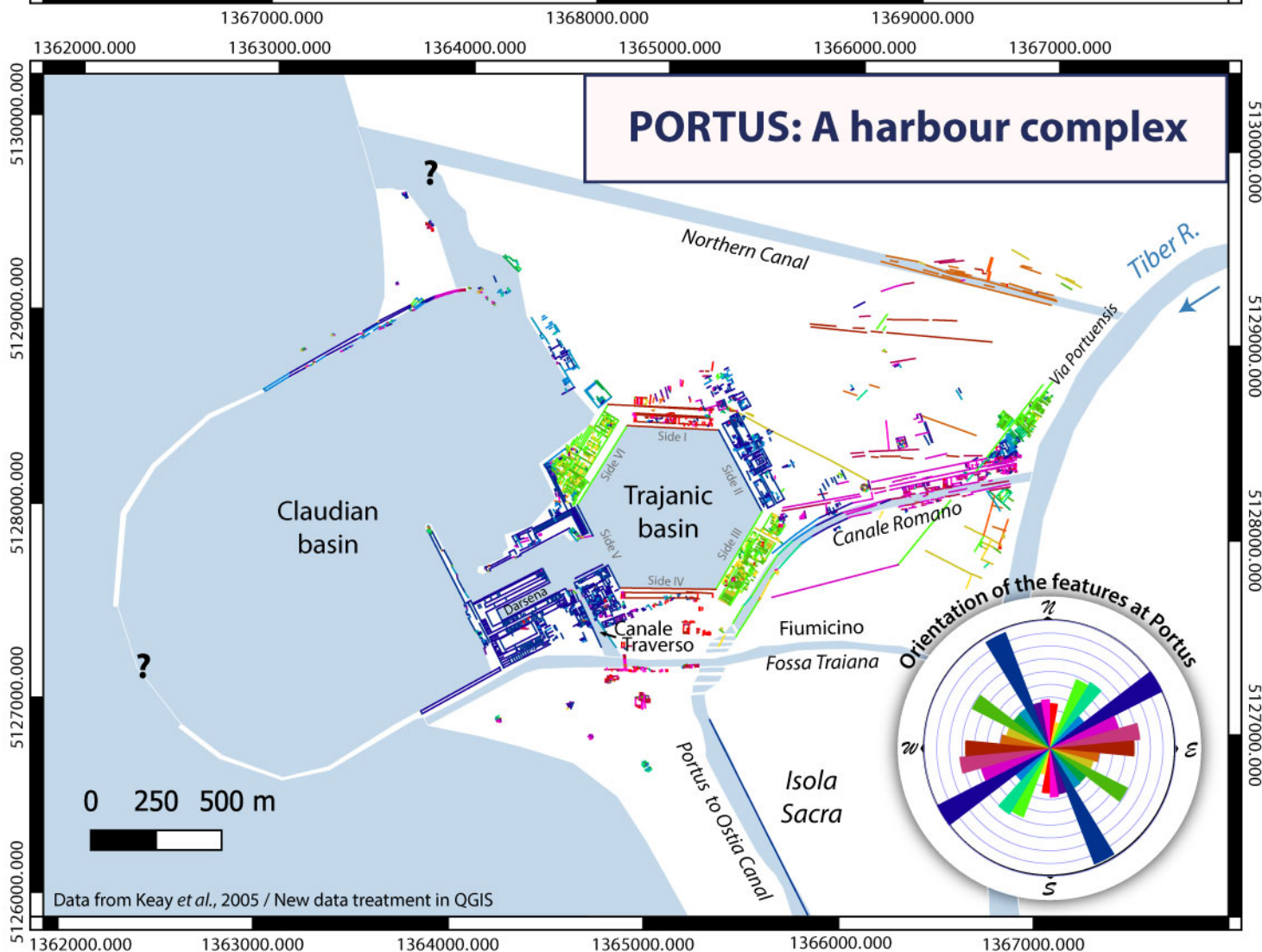
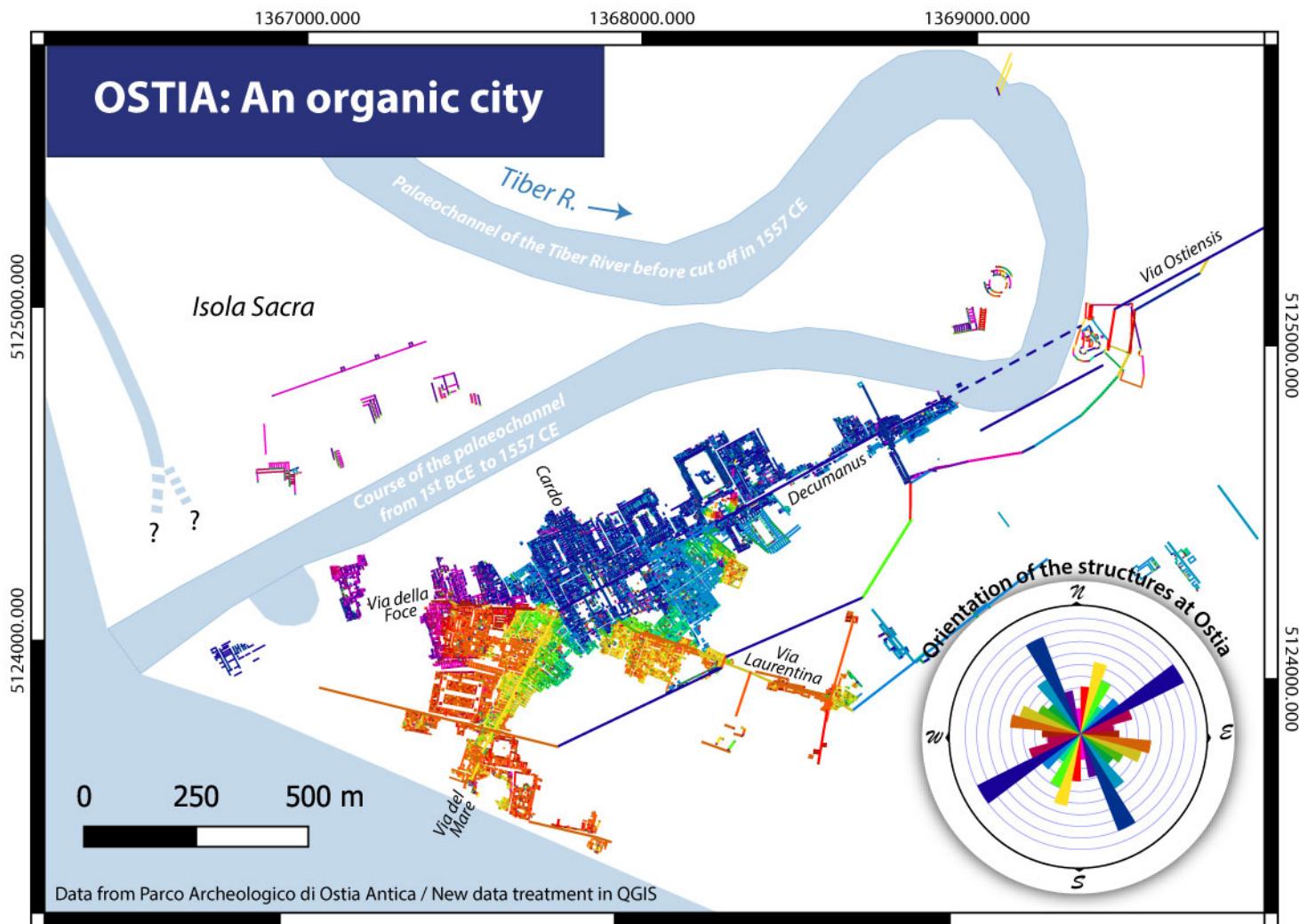
- Canals with built riverbanks
- Canals without built riverbanks?

Cores

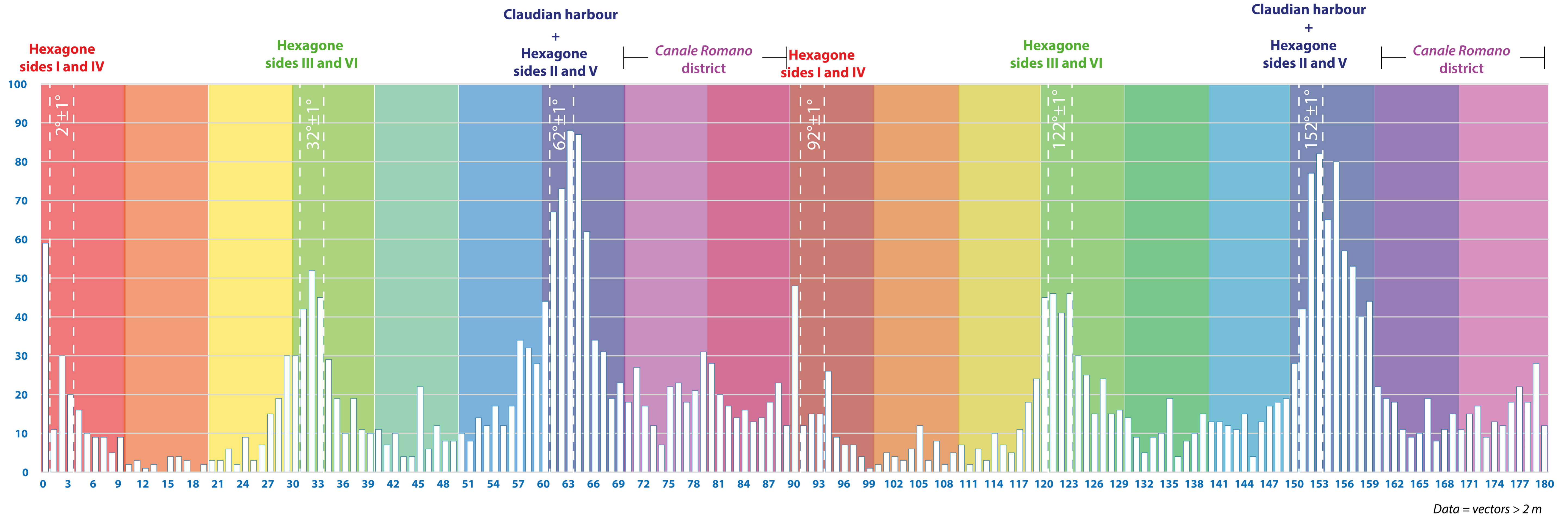
- CN-1 Cores presented in this study
- CNN-1 Study in process

Source: <https://wisuki.com/> / Data : 2012-2021

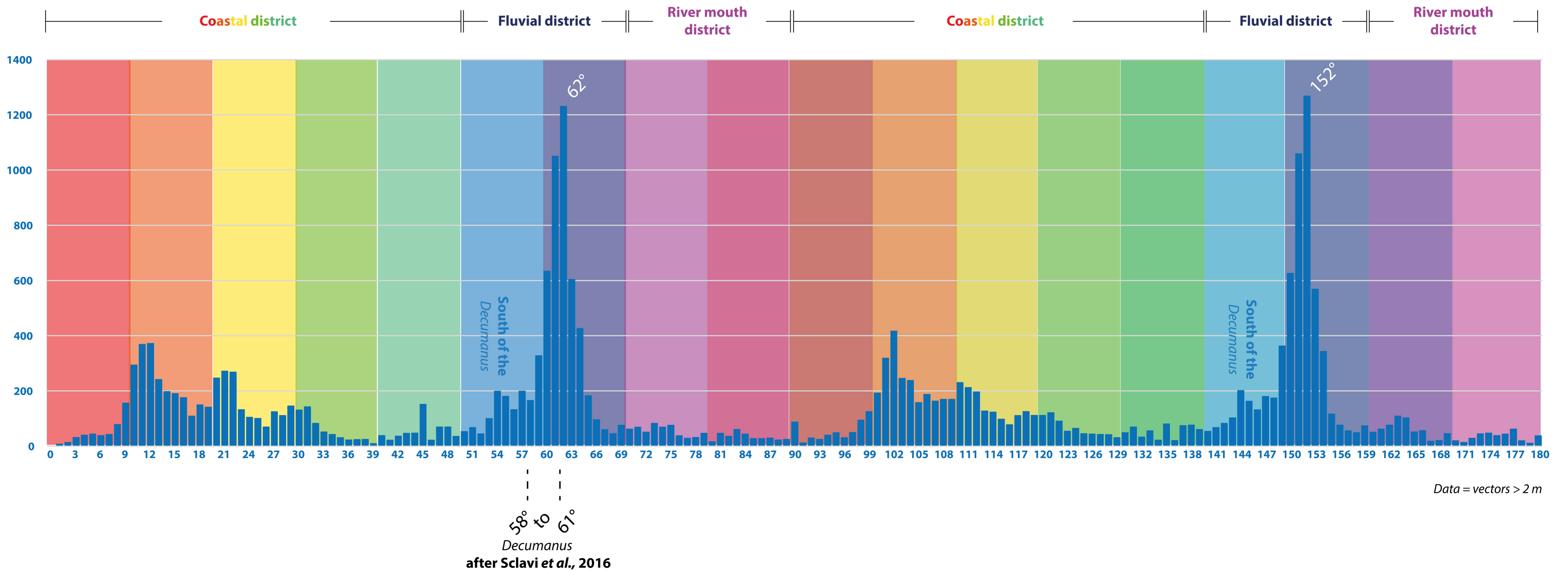
Drawings: F. Salomon



PORTUS



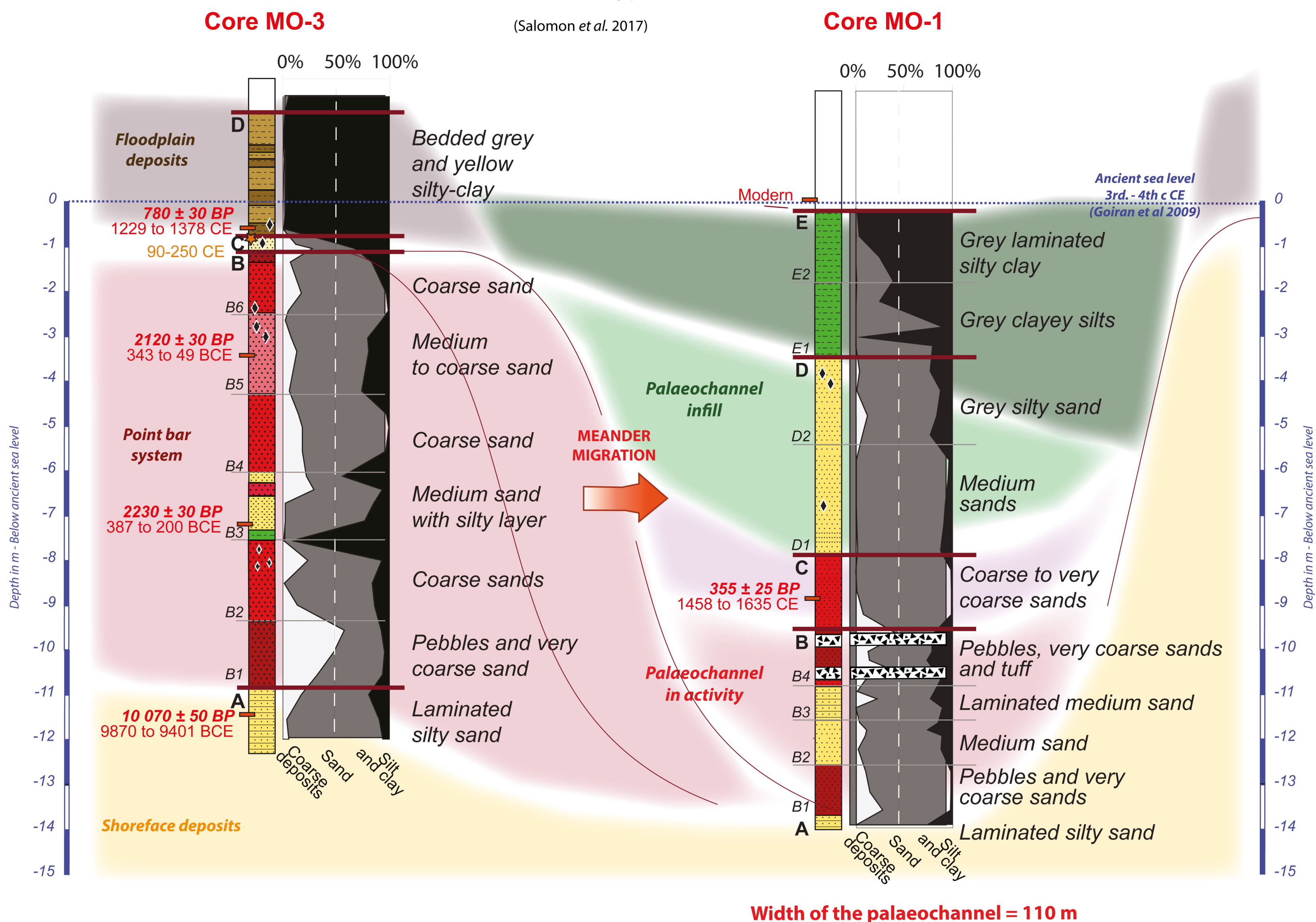
OSTIA



MEANDERING TIBER CHANNEL IN OSTIA

PALAEOCHANNEL OF THE TIBER >>> LATERAL MOBILITY

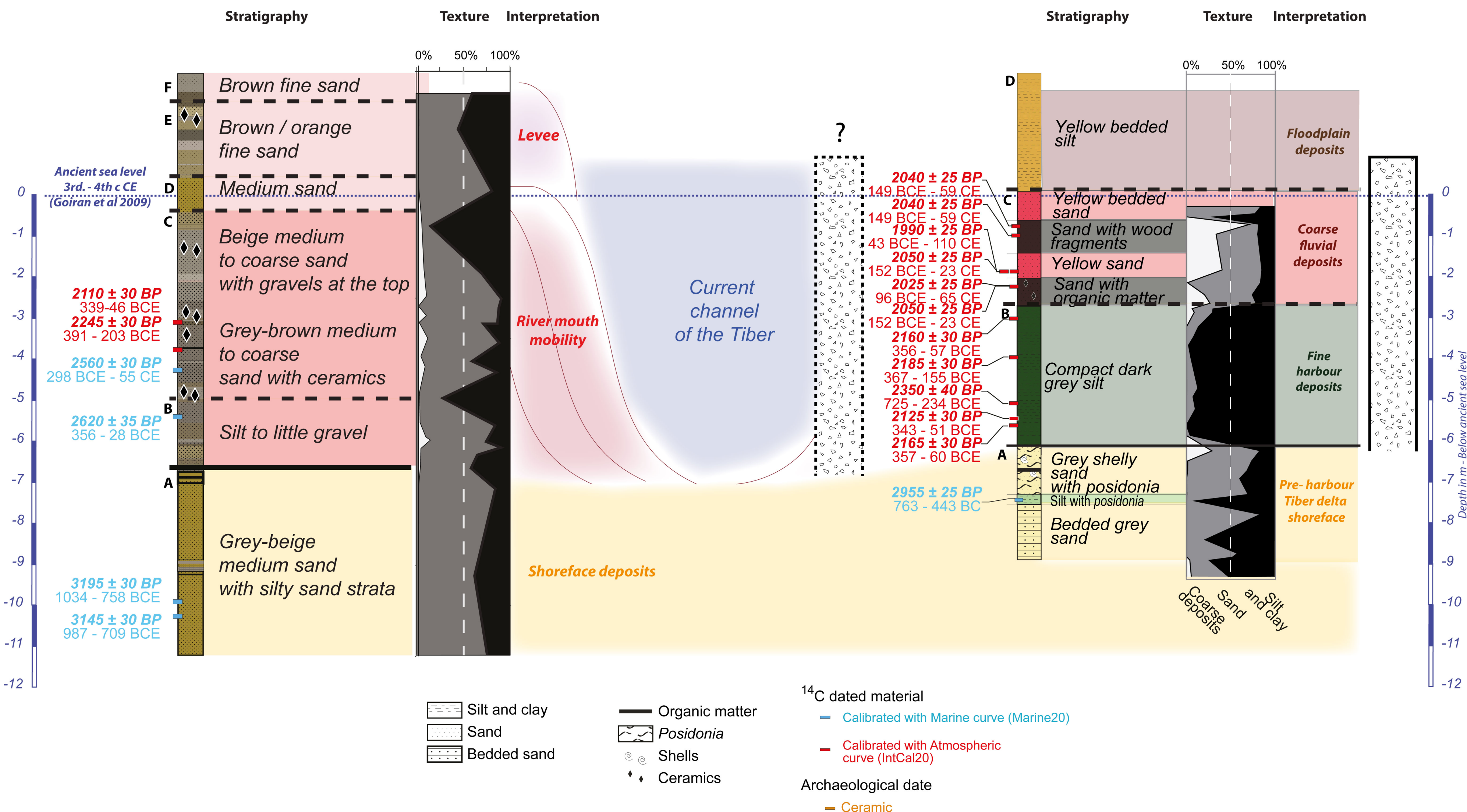
(Salomon et al. 2017)



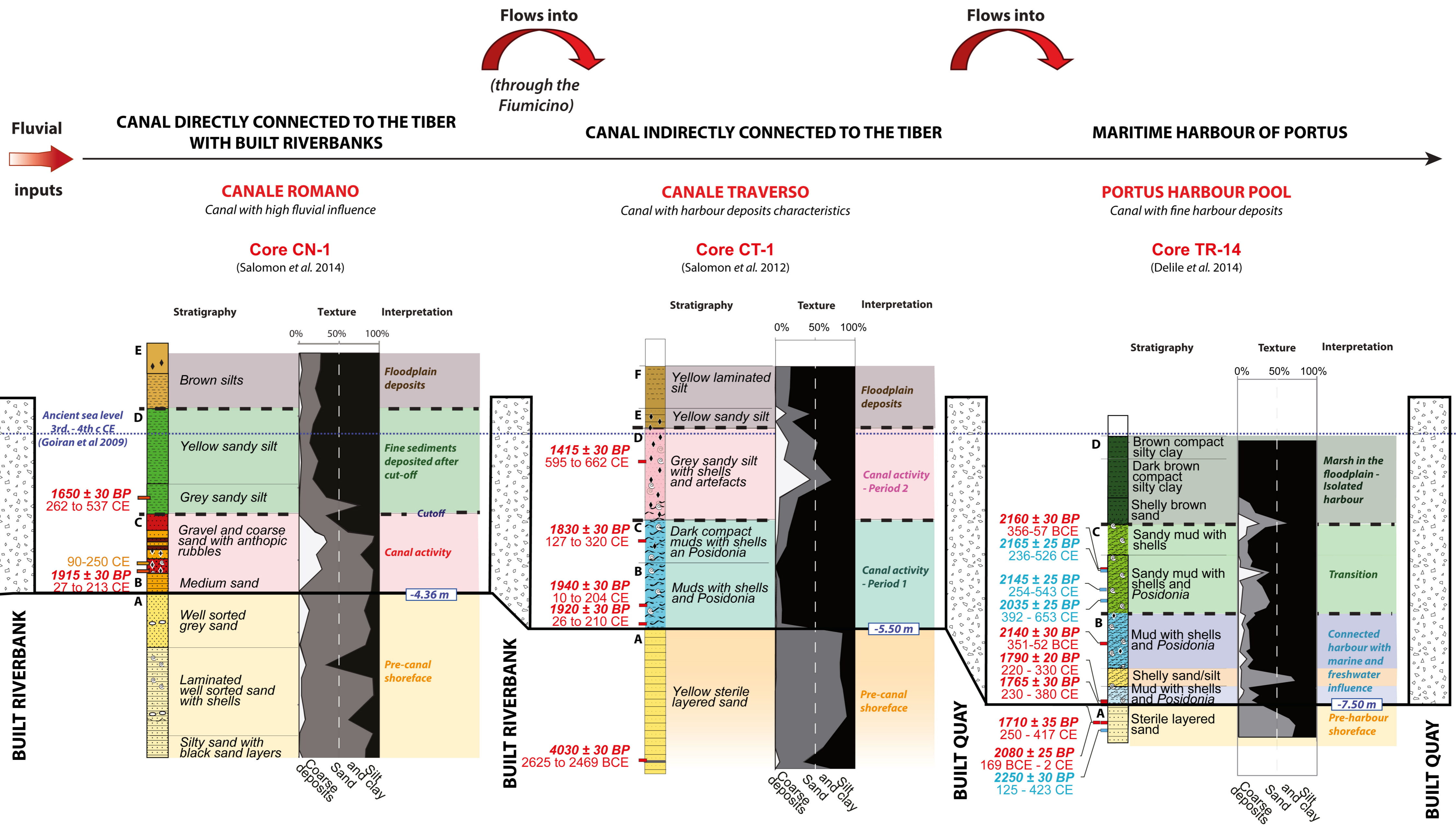
FLUVIAL HARBOUR ALONG THE TIBER CHANNEL

RIVER MOUTH Core ISF-1 (Salomon et al. 2018)

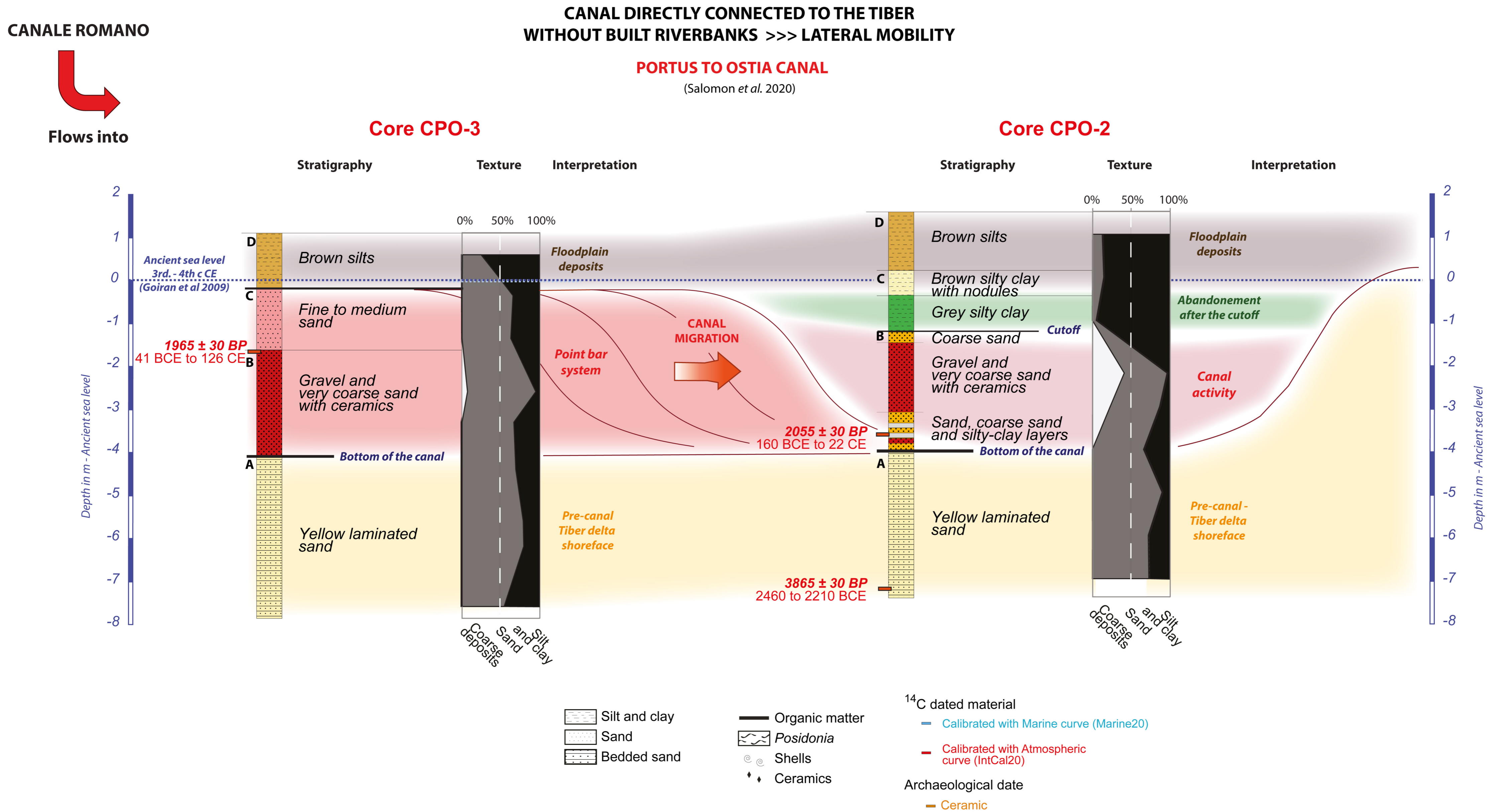
HARBOUR OF OSTIA Core PO-2 (Goiran et al. 2014)



CONNECTING PORTUS TO THE TIBER RIVER



CONNECTING PORTUS TO OSTIA

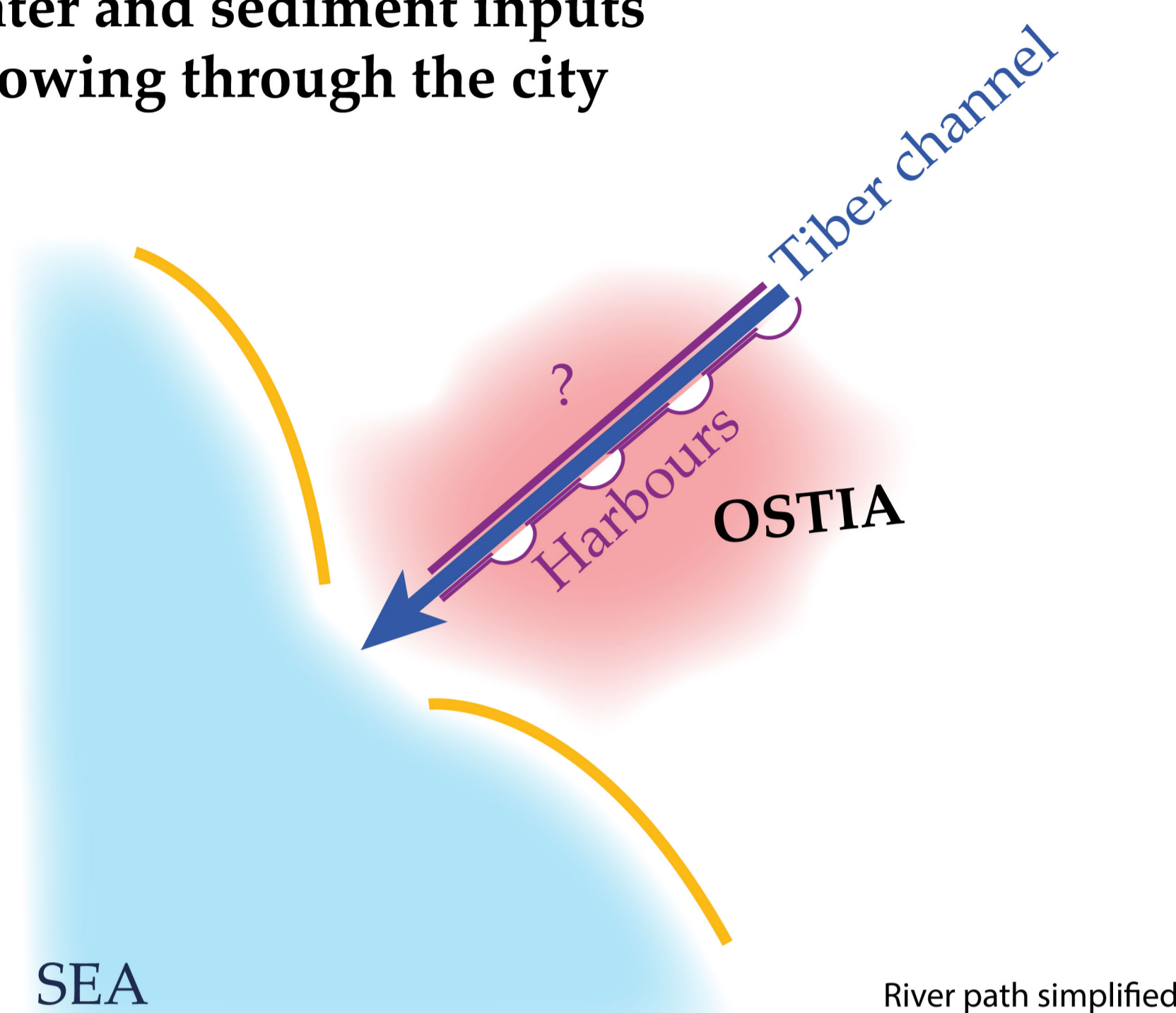


(1) MANAGEMENT OF THE SEDIMENTARY INPUTS

(2) MANAGEMENT OF THE INTERFACE MOBILITY

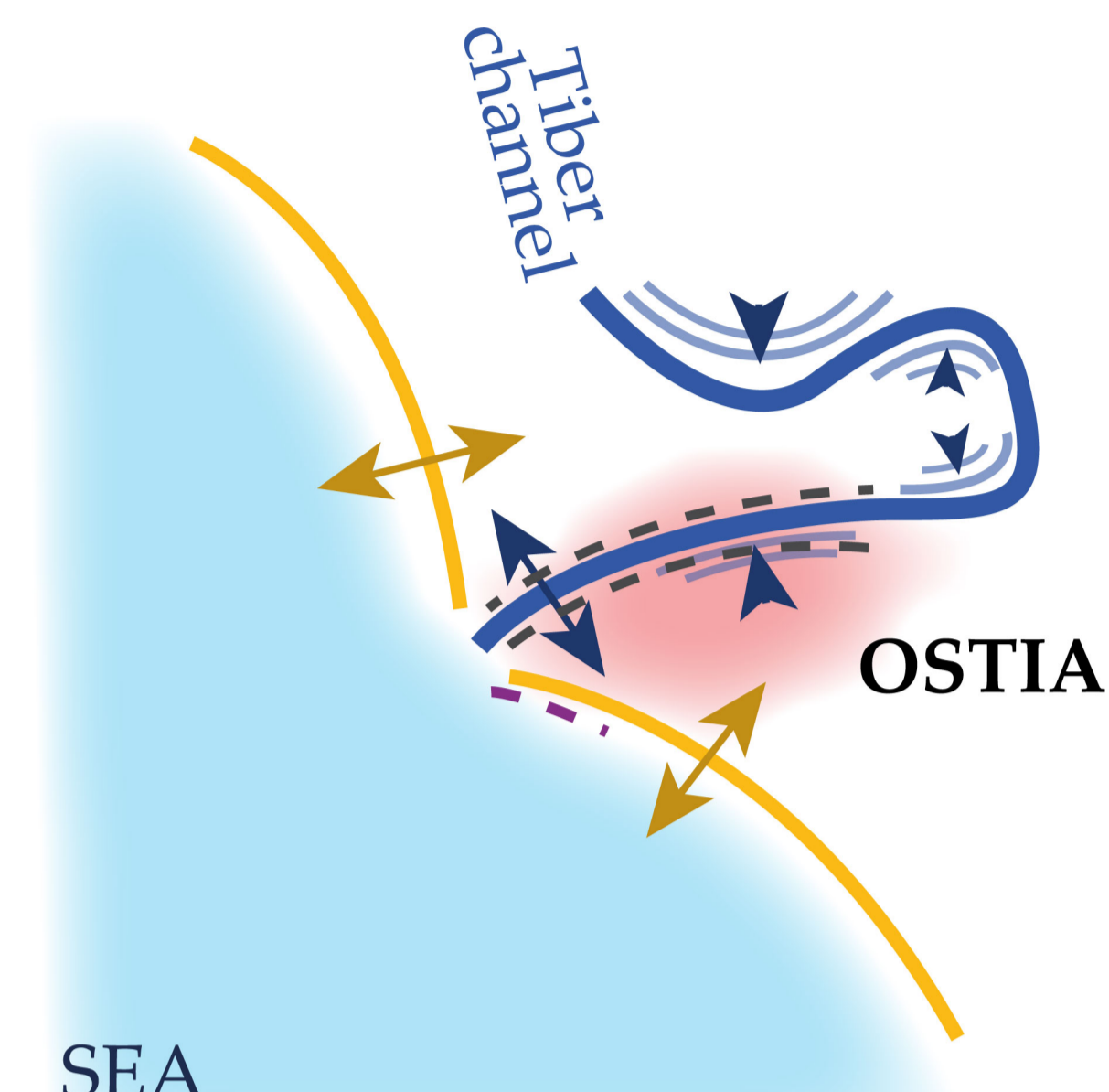
OSTIA
The port-city complex
(f. 4th/3rd c. BC)

Water and sediment inputs flowing through the city



- > Control of the sedimentation between the channel and the harbour(s) not known (?)
- > Dredgings (river mouth, river channel and harbours)

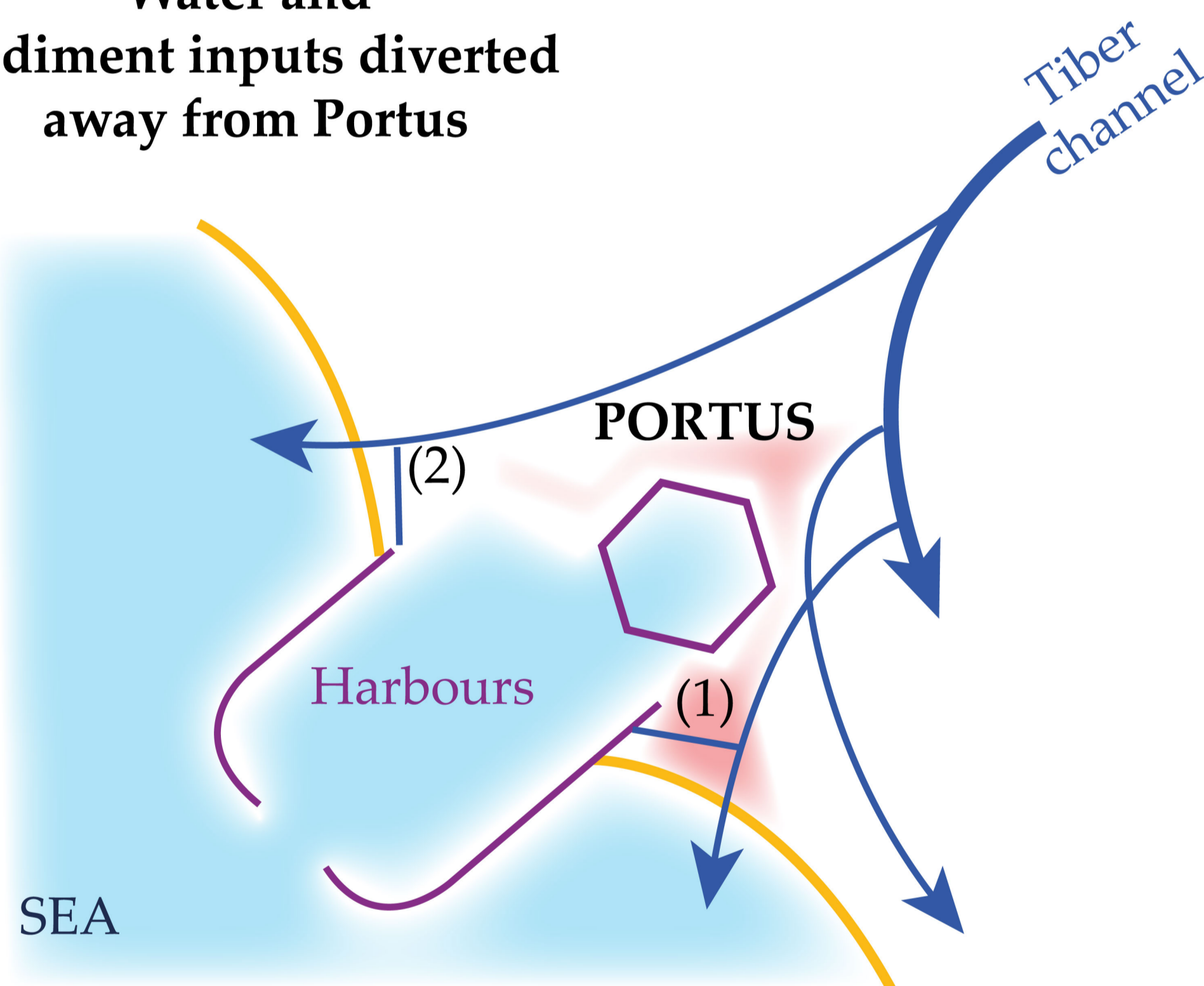
Meander and river mouth mobility
(Republican / Early Imperial period)



- > Adjustment of the waterfronts;
- > Channelisation of the river channel (?)
- > Longshore defence (?)

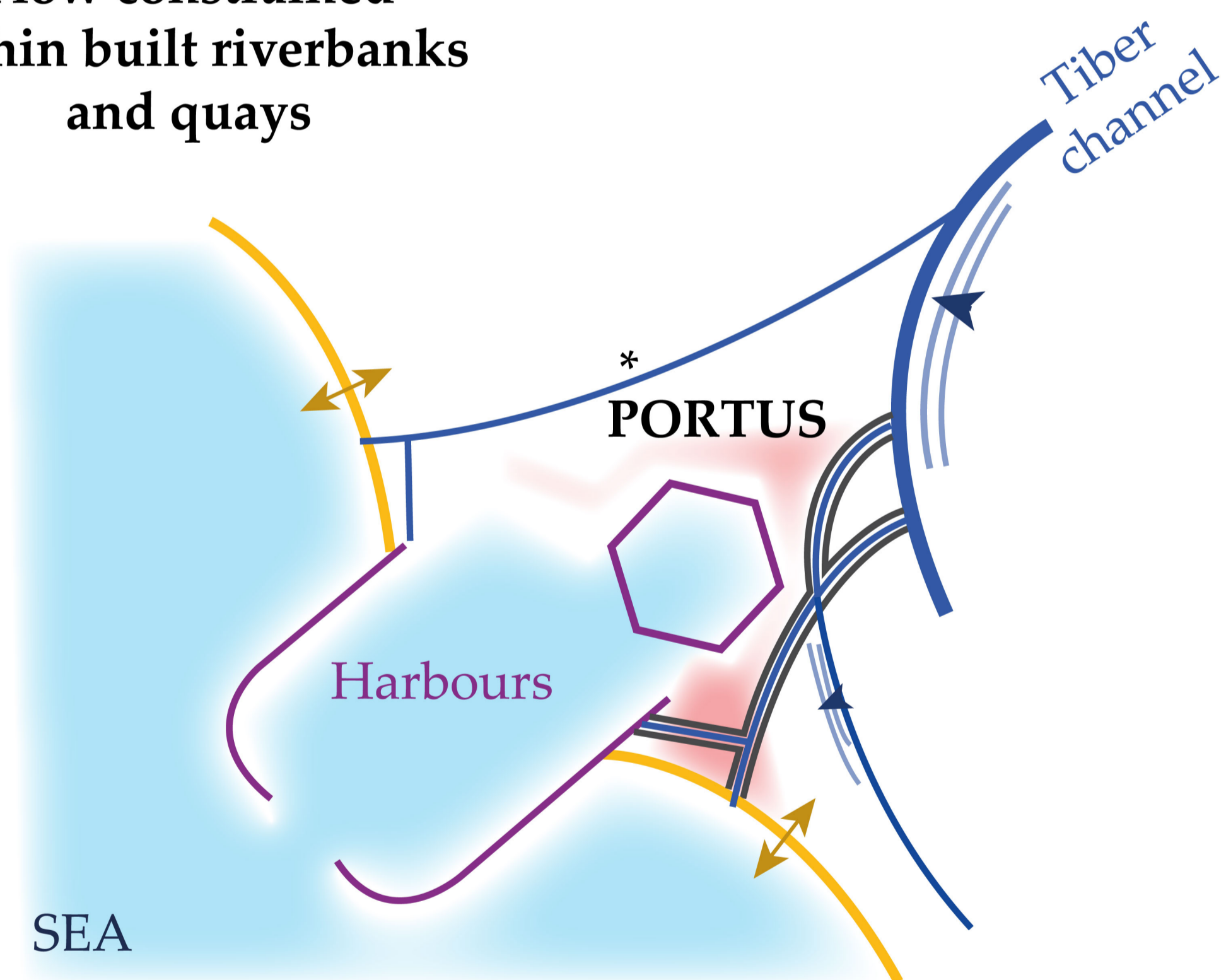
PORTUS
The artificial harbour complex
(f. 1st/2nd c. AD)

Water and sediment inputs diverted away from Portus

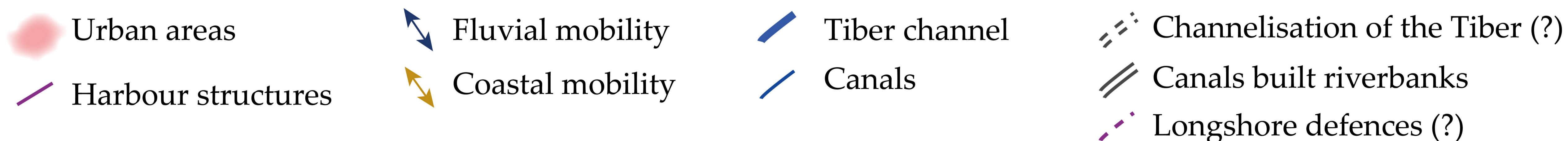


- > Complex network of canals routing sediments away from the harbour basins ;
- > Dredgings and sediment flushings in the harbours and canals.

Flow constrained within built riverbanks and quays



- > Only the canals around the Trajanic basin offer built riverbanks (Portus to Ostia canal?)



(1) Canale Traverso
(2) Northern entrance

* No evidence of lateral mobility of the Northern Canal (?)