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Geoarchaeology of the Roman port-city of Ostia: Fluvio-coastal mobility, urban development and resilience

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ABSTRACT

Ostia is one of the most extensively excavated cities of the Roman period. The port-city of Rome, which today lies 4 km from the coastline, was established in a very constrained environment at the mouth of the River Tiber. Based on a review of the geoarchaeological and archaeological research at Ostia, 4 new cores analysed through palaeoenvionmental methods, and 21 new radiocarbon dates, we propose a new model of the fluvio-coastal landscape of Ostia from its origin: (1) the coastline shifted rapidly westward between the 8th and the 6th c. BCE followed by a slow progradation and possible erosion phases until the end of the 1st c. CE; (2) the *castrum* of Ostia (c. late 4th–early 3rd c. BCE) was founded away from the river mouth but close to the River Tiber; (3) between the 4th and the 1st c. BCE, the River Tiber shifted from a position next to the *castrum*, below the northern Imperial *cardo* of Ostia, to 150 m to the north; (4) a possible harbour was established to the north of the *castrum* during the Republican period; (5) the city expanded and a district was built over the harbour and the palaeochannel between the Republican period and the beginning of the 2nd c. CE, showing that Ostia was a dynamic and resilient city during that time. Finally, we suggest the possibility to combine urban fabric analysis (the orientation of the structures) and palaeoenvironmental analysis for reconstructing the evolution of the city in relation to the fluvio-coastal mobility.

1. Introduction

Major fluvial and coastal risks for cities are predicted for the 21st c. due to climate change and anthropogenic pressures. Hazards include floods, storms and quick coastline and river mobility (erosion/sedimentation, sea-level rise, fast sinking due to erosion or groundwater

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pumping) (Miller and Douglas, 2004; Dixon et al., 2006; Hallegatte et al., 2010, 2013; Allison et al., 2016; Syvitski et al., 2009). Additionally, there is a high vulnerability due to a large population living either in a coastal area or on an alluvial plain. More specifically, large river deltas, combining fluvial and coastal hazards, are today populated by approximately 500 million people around the world (Aerts et al., 2009; Bohannon, 2010). Those risks bring major challenges for cities and their surrounding territories (Rosenzweig et al., 2010; Leichenko, 2011; Albrito, 2012; Jabareen, 2013). The extension and the consequences of these risks on human societies are unique in human history, but small scale systems involving complex urban societies also had to face such quick changes in the past.

Located at the mouth of the River Tiber, Ostia was a major port-city connecting Rome to the Mediterranean Sea during the Roman period. Between the 1st c. BCE and the 2nd c. CE, researchers estimate that Ostia could have hosted 10,000 to 50,000 inhabitants (Calza et al., 1953; Meiggs, 1973; Cébeillac-Gervasoni et al., 2006). From its foundation in c. the late 4th–early 3rd century BCE to its abandonment in early Medieval period, Ostia experienced ten centuries of environmental change. At the meeting point between fluvial and coastline dynamics, river mouths are highly mobile environments subject to change by one single event (storm, flood), seasonality or else over longer periods (recurrence of events) that could have affected the development of Ostia. Other acute hazards like earthquakes, tsunami and/or quick subsidence, could also have affected the city, even if they are still largely debated at Ostia (Galadini and Galli, 2004; Hadler et al., 2015).

Ostia is not the only ancient city to have experienced such hazards in the Mediterranean Sea. The impact of flooding on Roman cities and territories has previously been studied in Rome (Le Gall, 1953; Aldrete, 2007; Leveau, 2008), and on different alluvial plains across the Roman world through interdisciplinary research (Vita-Finzi, 1969; Bravard et al., 1990; Brown, 1997; Allinne, 2007; Arnaud-Fassetta et al., 2010). Ancient cities located near a river mouth in the Nile Delta (Stanley et al., 2004; Stanley, 2005; Stanley and Toscano, 2009) and Meander Delta (Brückner, 1997; Brückner et al., 2002) have experienced particularly high natural stresses leading fully or partly to their abandonment.

Located at a river mouth, Ostia did not experience natural hazards that led to its abandonment. Fluvial erosion has possibly been recorded during the Roman period on the eastern side of Ostia on the *via Ostiense* (Salomon et al., 2017), river mouth mobility was active at least at the end of the 1st millennium BCE close to the harbour of Ostia (Salomon et al., 2014b), the harbour of Ostia was filled-up by flood deposits dated between the 2nd c. BCE and the 1st c. CE (Goiran et al., 2014; Hadler et al., 2015; Sadori et al., 2016) together with possible coastal storm deposits (Hadler et al., 2015; Sadori et al., 2016). However, after those events, strong urban development is recorded at Ostia at the beginning of the 2nd c. CE (Calza et al., 1953; Meiggs, 1973; Adembri, 1996; Pavolini, 2006) and archaeological evidence shows building activities at sites in the vicinity of the forum at the centre of Ostia (Gering, 2014) and seafront in Late Antique Ostia (David et al., 2014). Similarly, in 238 CE, the *via Severiana* running mostly along the coast between Ostia and Terracina was restored (CIL X 6811, Brandizzi-Vittucci, 1998). According to ancient texts, the city was still an active harbour in the 4th c. CE (387 CE), when Augustine of Hippo and his mother went to *Ostia Tiberina* in order to embark for Africa (Augustine, n.d., IX, 8–12).

Interestingly, Ostia seems to show a resilience over centuries, from the Republican period to Late Antique period. Using a multidisciplinary approach, this paper reconstructs the fluvio-coastal dynamics and explores their interactions with Ostia over time: Where was the coastline located, and where did the River Tiber flow when the initial fort of Ostia (*castrum*) was founded? To what extent did the coastline and the River Tiber channel move during the Roman period? How did these changes affect the development of Ostia? New sedimentary cores drilled in Ostia and palaeoenvironmental analysis together with archaeological and textual evidence will allow us to reconstruct coastal and river palaeodynamics. Additionally, a GIS analysis of the roads and structures of Ostia will lead to an understanding of the urban fabric of Ostia aiming to seek a possible imprint of the fluvial and coastal mobility in the geometry of the city.

2. Geological and archaeological context

2.1. The Tiber Delta and its river mouths

Deltas are well known to be very dynamic environments, particularly at the river mouths (Wright, 1977; Ashton and Giosan, 2011; Fagherazzi et al., 2015). Several studies have focused on the reconstruction of Mediterranean river mouth mobility from short (single flood or earthquake event) to long term (Holocene) (Brückner, 1997; Stanley et al., 2004; Vella et al., 2005; Maillet et al., 2006a, 2006b; Lichter et al., 2011; Anthony et al., 2014). At the meeting point between fluvial and marine processes, between salt and freshwater, a river mouth combines complex and quick changes of progradation/erosion of the coastline, lateral mobility of the river channel and a very instable sub-bottom topography. Rapid change at a decennial scale has been reconstructed using aerial photography and satellite imagery since the beginning of the 20th c. at the mouth of the River Tiber (Ministero per i Beni Culturali e Ambientali, 1986) and using old maps and coastal towers over the last five centuries (Le Gall, 1953; Giraudi, 2004; Bersani and Moretti, 2008; Salomon, 2013).

The reconstruction of the evolution of the Tiber delta during the Holocene shows a transgressive phase initiated around 14,000–13,000 cal BP followed by a progradational phase starting between 7000 and 5000 cal BP (Bellotti et al., 1995; Giraudi, 2004; Marra et al., 2013; Milli et al., 2016). Different periods of progradation were identified for the Tiber delta from 6000 cal BP (Giraudi, 2004; Bellotti et al., 2007) while several periods of coastal progradation were identified in the time span of this study using radiocarbon dates: between the end of the 3rd millennium BCE and the end of the 1st millennium BCE; during the first part of the 1st millennium BCE; and during the Roman period (Giraudi, 2004). OSL dates were taken on the beach ridges on the southern part of the Tiber delta and revealed successive phases of progradation between the middle of the 3rd millennium BCE and the middle of the 1st millennium CE (Bicket et al., 2009).

The model for the mobility of River Tiber during the Holocene suggests a shifting of the channel from the northern part of the Tiber delta to the southern part, where the Tiber flows today. An important change seems to occur in the first part/middle of the 1st millennium BCE, with an avulsion of the channel from an area somewhere near the future site of Portus (the Imperial port) to a location next to Ostia Antica (Giraudi et al., 2009; Bellotti et al., 2011). The formation of the palaeomeander of Ostia occurs sometime afterwards (Bertacchi, 1960; Arnoldus-Huyzendveld and Pellegrino, 1999; Shepherd, 2006; Salomon et al., 2017). It migrates until the 1st–3rd c. CE, and the upstream channel continues to move probably until 1557 when a major flood starts the cut off of the palaeomeander (Pepe et al., 2016; Salomon et al., 2017). The palaeomeander was definitively cut off by 1562 (Pannuzi, 2009).

Geoarchaeological studies crossing palaeoenvironmental data with archaeological data have been undertaken primarily at Portus established in the middle of the 1st c. CE (Arnoldus-Huyzendveld, 2005; Bellotti et al., 2009; Giraudi et al., 2009; Goiran et al., 2010; Sadori et al., 2010; Salomon et al., 2012; Pepe et al., 2013; Delile et al., 2014a, 2014b), as well as on its canals (Salomon, 2013; Salomon et al., 2014a) and the harbour of Ostia (Goiran et al., 2014; Hadler et al., 2015; Sadori et al., 2016). Comparatively less research has focused upon the River Tiber itself (Segre, 1986; Arnoldus-Huyzendveld and Paroli, 1995; Salomon et al., 2014b, 2017; Pepe et al., 2016) and the coastline (Giraudi, 2004; Bicket et al., 2009) during the Roman period, and limited palaeoenvironmental data is available for Ostia.

2.2. The origins of Ostia and the urban growth of the city

The city of Ostia is indivisible from its location at the mouth of the River Tiber. The Latin toponym *Ostia* comes from *Ostium* meaning "river mouth". Additionally, this strategic position led the city to grow and spread, which was also linked to the growth of Rome only 20 km upstream. The foundation of Ostia and its role at that time remain unclear. At least three reasons justified the foundation and the development of Ostia: (1) the management of the salt works in the lagoons (Livy, n.d.-a, b, *Ab Urbe condita*, I, 33, 6–9); (2) the establishment of a fluvio-maritime port downstream of Rome (Aurelius Victor, n.d., *De vir. Ill, V.3*; Ennius, n.d., *Annals*, frag 22); and (3) the control of access to the River Tiber from the Tyrrhenian Sea (Calza et al., 1953; Zevi, 2001a).

Traditionally, Roman texts date the origin of Ostia back to the 7th c. BCE during the reign of Ancus Marcius – 646–616 BCE (Cicero, n.d. *De Re Publica*, II, 3, 5; Florus, n.d., I, 4, 2; Pliny, n.d. *H.N.*, III, 56; Strabo, n.d., V, 3, 5). However, archaeological evidence suggests that the origin of the city of Ostia is related to the so called *castrum*, a massive structure of 193 × 120 m built in blocks of tuff and dated to between the late 4th and early 3rd c. BCE (Martin, 1996; Zevi, 1996, 2002), with a *terminus post quem* in 267 BCE – dated to c. 400–340 BCE after Meiggs (1973), c. 425–400 after Coarelli (1988), and late 4th-early 3rd BCE after Martin (1996). This structure is interpreted as a military fortress (Calza et al., 1953; Pohl, 1983; Zevi, 1996). The *castrum* corresponds to the earliest building clearly identified at Ostia and defines the later *cardo* and the *decumanus* of the city. Roads that probably existed before the foundation of the *castrum* at the mouth of the River Tiber are still visible in the street network of Ostia (Becatti, 1953; Mar, 1991; Zevi, 1996). Initially, the southern *cardo* (*via Laurentina*) and the *via della Foce* were possibly segments of a single road, and a road followed roughly the later route of the *via Ostiensis*.

In the 19th c., archaeologists studying the urbanism of Ostia suggested the possibility of a displacement of the settlement from east to west, following a possible progradation of the coastline towards the west (Canina, 1830). This hypothesis was mostly based on intuition rather than archaeological evidence. At the beginning of the 20th c., however, the discovery and the excavation of the *castrum* of Ostia (Calza et al., 1953; Vaglieri, 1911) provided evidence for the origin of urbanism at Ostia. Based on this new discovery, the archaeologist L.-A. Constans (1926) was the first to hypothesise the existence of a palaeochannel of the River Tiber closer to the *castrum* at its origin. Constans (1926) notes that the distance between the modern channel and the *castrum* (*circa* 250 m) was not in accordance with the function of the fortress designated to control the access to the River Tiber and to prevent any other communities installing a similar stronghold. Additionally, Constans (1926) suggests a lateral fluvial mobility of the River Tiber during the Roman period taking into account the existence of a public area (*ager publicus* of *praetor urbanus* C. Caninius) between the *decumanus* and the River Tiber dated to the 2nd c. BCE and the stones delineating the limit of the Tiber riverbanks dated to the first part of the 1st c. CE - *cippi* (Figs. 1 and 2). Despite the strong arguments put forward by Constans (1926), J. Le Gall (1953) in his fundamental work on the River Tiber during the Roman period (still a reference for the topic) rejects this hypothesis. Le Gall (1953) considers that it was impossible for the River Tiber to flow alongside the *decumanus* without flowing straight into the *castrum*. Since then, the debate over a possible link between the River Tiber and the *castrum* has been put to one side due to a lack of further evidence.

In 267 BCE, Ostia was used as a naval station during the first Punic war (Carcopino, 1929; Zevi, 2001a). During the mid to late Republican period Ostia became a port crucial to the food supply system of Rome and the first warehouses in Ostia can be dated to the 1st c. BCE (Meiggs, 1973). Between 63 and 58 BCE the city walls were built and enclosed an area of around 70 ha (Zevi, 2001b). During the Augustan period new public buildings were constructed at Ostia including the theatre built by Agrippa and the first phase of the *Piazzale delle Corporazioni* just to the north. Further significant transformations to the urbanscape of Ostia took place towards the end of the 1st c.–2nd c. CE, in particular during the Hadrianic period (Calza et al., 1953; Meiggs, 1973; Heinzelmann, 2002; DeLaine, 2002).

At the end of the 2nd c. CE the building activity in Ostia began to slow, although further structures were built towards the sea beyond the *Porta Marina* until the 4th c. CE with evidence of phases of activity later in the 5th c. CE (David et al., 2014; Turci, 2014). Late antique remodellings of extant buildings have been detected in the vicinity of the *Forum* of Ostia (in the centre of Ostia), dated to the 4th and 5th c. CE (Gering, 2014). However, Ostia was slowly abandoned in late antique and early medieval periods.

Stöger (2011) summarised the current situation as "If studies on *Ostia* are abundant, there are still questions to measure and to date the urban spread, and to delimit the maximal extension of the city". The new approach considered here brings together the urban archaeological evidence with geoarchaeological studies with the aim of renewing the discussion about the urban evolution of Ostia in relationship to its environment.

3. Concepts and methods

3.1. Archaeology, geoarchaeology and the urban fabric

A digital map of Ostia (Fig. 2) was produced in order to perform an analysis of the urban fabric. It is formed by the streets, walls and roads discovered by the archaeological excavations, the structures visible through aerial photography and the geophysical survey results published for the area. Ostia offers one of the best case studies for studying urbanism during the Roman period (Parkins, 2005; Stöger, 2011). The data presented here, whilst not exhaustive, illustrate most of the major discoveries. From the foundation of the *castrum* in the late 4th- early 3rd c. BCE to the abandonment of the city during Late Antique/early Medieval period, the city records almost 1000 years of active urban history. The Roman Ostia visible today is a palimpsest with buildings mainly dating to the Imperial period and especially from the 2nd century CE. The city is known extensively but only recently has precise stratigraphy been systematically recorded for establishing more complex reconstructions through time. Every year, excavations reveal further stratigraphy, new structures and several temporal trajectories of districts and buildings (Perrier, 2007; David et al., 2014; Gering, 2014). Amongst other indicators, the study of bricks stamps provides amongst the most precise dates for the construction of the walls of buildings at Ostia (DeLaine, 2002). Due to this chronological complexity, this analysis of the urban fabric focuses primarily on the physical aspects of urbanism.

It is assumed that the geometry or urban fabric of Ostia reflects both natural and anthropic factors shaping the city across time (coastline and channel location, planning strategy, parcellation, economic and social processes *etc.*). Examination of modern cities has shown that landscape features have a strong effect on the urban morphology (see estuarine shoreline constraints or the mountainous topography effects on the urban fabric in Mohajeri, 2012 and Mohajeri et al., 2013). Archaeogeographical studies of land division, allotment and urban fabric reveal the preservation of morphologies over centuries and millennia (Gauthiez et al., 2003; Chouquer, 2008; Noizet et al., 2013; Brigand, 2015; Robert and Sittler, 2016). Geoarchaeological research has mainly focused on agrarian landscapes during Roman period and the study of both river channel mobility together with the adaptation of land division and allotment (centuriation) (Doukellis and Fouache, 1992) or hydraulic landscapes (Berger, 2008; Bernigaud et al., 2014). This study focuses upon the orientation of the urban structures of Ostia in order to identify districts with external landscape constraints defined as coastline, river channel or the river mouth itself. The area of the *castrum* is one of the best studied areas in Ostia with regard to the evolution of the urban patterns from the late 4th–early 3rd c. BCE to the 5th c. CE (Calza

Fig. 1. Location map and boreholes drilled at Ostia. The representation is a composite and illustrates different periods in time. The river course and the coastline are indicative. The structures excavated or identified through geophysical survey for the Roman city of Ostia are shown in white.

et al., 1953; DeLaine, 2002; Gering, 2014). It reveals the permanency of street and building orientations during different phases of the evolution of the city; however a change in the alignments can be observed (Calza et al., 1953) (see *castrum* area in Fig. 6). The northern entrance of the *castrum* is not aligned with the building interpreted as the Republican *capitolium* group (Calza et al., 1953) and the Hadrianic *capitolium* group (DeLaine, 2002). It is suggested here that there was a possible inheritance of the orientation of features across time in the palimpsest of the urban fabric of Ostia. On this basis, a series of geoarchaeological methods are proposed in order to read the urban fabric in the light of the palaeoenvironmental results (see Discussion section).

3.2. Analysis of the urban fabric – directional statistics

The roads and walls have been digitalized from geo-referenced maps published in *Scavi di Ostia I: Topografia Generale* (Calza et al., 1953). In addition, structures that have been excavated since then or observed by aerial photography have also been included (Meiggs, 1973; Pellegrino et al., 1995; Martin et al., 2002; Pavolini, 2006). Recent discoveries made by geophysical survey (Keay et al., 2014) on the northern side of the River Tiber channel at Isola Sacra have been also integrated into the map of Ostia.

Due to the complexity of isolating and delimiting walls, as well as the existence of curved walls or multi-curved, the polylines forming the base map of Ostia have been split into several segments. Using this data, it has been possible to calculate the street orientation using GIS software. Different colours have been used to visualize the distribution of street orientations on the map of Ostia and on a rose diagram (Swan et al., 1995; de Smith et al., 2009; Mohajeri et al., 2013). A discretization was applied to a group of walls which have a similar orientation. The rose compass (Fig. 2) shows the number of polylines and their orientations into different classes (further details about the classes can be found in Supplementary data 1).

3.3. Palaeoenvironmental analyses

Four new cores were drilled using a mechanical rotary coring device in the Roman city of Ostia: Core CAT-1 (41°45′19.21″N/12°17′27.24″E/+3.82 m), Core CAT-2 (41°45′19.38″N/12°17′14.24″E/+4.34 m), Core CAT-3 (41°45′17.39″N/12°17′15.81″E/+4.48 m) and TB-1 (41°45′2.18″N/12°16′40.66″E/+1.24 m). In addition, new palaeoenvironmental analyses have been conducted on Core ISF-1

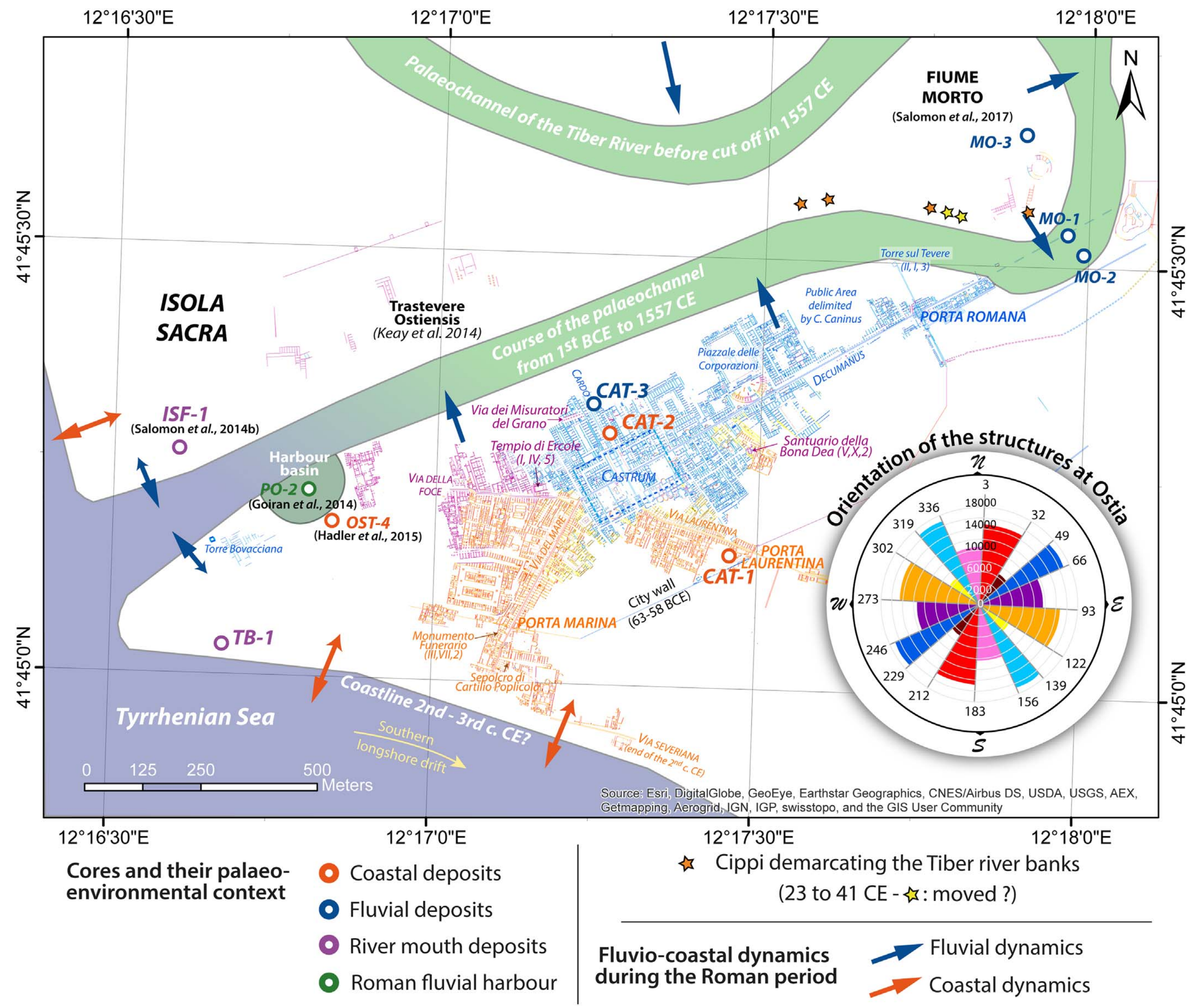

Fig. 2. Directional analysis of the buildings and roads of Ostia and the cores in their palaeoenvironmental context. The rose diagram shows the general trend of orientation of all of the vectors/structural segments. The colours of the structures refer to the different orientations. The rose diagram is in degrees and the circular values equate to the number of vectors/structures in each class of direction (weight).

(41°45′15.98″N/12°16′35.06″E/+2.24 m) generating new dates (Salomon et al., 2014b).

The determination of the different stratigraphical units was undertaken using magnetic susceptibility measurements. Similar methods have already been applied and shown their relevance for the Tiber delta (Salomon et al., 2012). Magnetic susceptibility was measured every centimetre using a Bartington MS2E1 (Dearing, 1999) and is expressed in CGS (SI = CGS value × 0.4). Similar measurements have previously been taken for the coastal, fluvial, lagoonal, and harbour environments across the Tiber Delta (Delile et al., 2014b; Goiran et al., 2014; Vittori et al., 2015; Salomon et al., 2017).

Several deposits in each stratigraphic unit were sampled (30 samples for 10 m). Wet sieving was performed in order to measure the relative content of the coarse fraction (> 2 mm), sand (2 mm at 63 μm) and silt/clay (< 63 μm). Further detailed grain-size was obtained using a laser grain-size technique carried out with a Malvern Mastersizer 2000 (grain-size indicators express the hydrodynamic context during the deposition - Folk and Ward, 1957; Cailleux and Tricart, 1959). Complementary information about the palaeoenvironmental context was obtained from 10 g of dry sub-sampled sediment. The sediment was placed successively at 550 °C over two hours to measure the content of organic matter and at 950 °C over four hours to measure the carbonate content (Heiri et al., 2001).

In the wet sieved sediments (fraction < 1 mm), all ostracods (small bivalved crustaceans) were picked, normalised to 10 g of sediment weight and identified in order to deduce the characteristics of the environments, in particular the freshwater and marine influences (Carbonel, 1988; Frenzel and Boomer, 2005; Ruiz et al., 2005; Mazzini et al., 2011; Vittori et al., 2015).

The ceramics were identified and dated by Sabrina Zampini (Table 1). Different organic materials were dated by AMS (Accelerator Mass Spectrometry), obtained on the linear accelerator of Saclay (Artemis - University Lyon 1) or by the classic method (University Lyon 1). The calibration has been performed using the curve proposed by Reimer et al. (2013) with the software OxCal (https://c14.arch.ox.ac.uk/oxcal/OxCal.html) (Table 2).

Table 1
Archaeological dates.

Core	Sample	Depth below surface (m)	Depth below sea level (s.l.m - Genoa) (m)	Sample description	Age estimation
CAT-2 (+ 4.34 m)	OST-2/3.23 m	3.23	+ 1.11	Fragment of common ware; fragment of vase of open shape black-gloss pottery	End of the 4th–2nd c. BCE
CAT-3 (+ 4.48 m)	OST-3/6.99 m	6.99	− 2.65	Body sherd of amphora produced in Campania; corresponds probably to a Greco-Italic or Dressel 1	Second half of the 3rd–end of the 1st c. BCE
CAT-3	OST-3/4.85 m	4.85	− 0.51	Body sherd of amphora produced in Campania; corresponds probably to a Dressel 1 or Dressel 2–4	145–135 BCE to 100 CE
CAT-3	OST-3/9.03 m	9.03	− 4.69	Fragment probably of a vase of thin-walled pottery	150 BCE–300 CE
CAT-3	OST-3/7.14 m	7.14	− 2.80	Body sherd of amphora produced in Campania corresponds probably to a Greco-Italic or Dressel 1	Second half of the 3rd–end of the 1st c. BCE

4. Results

4.1. Analyses of the street and wall orientations

Three main orientations characterize the wall and street orientation at Ostia (Fig. 2):

- Group 1: NE-SW (dark blue – 49–66°/229–246°) and NW-SE (light blue – 139–156°/319–336°);
- Group 2: NNE-SSW (red – 3–32°/183–212° and brown – 32–49°/212–229°) and WWN-EES (orange – 93–122°/273–302° and yellow 122–139°/302–319°);
- Group 3: NS (pink – 156–183°/336–3°) and EW (purple – 66–93°/246–273°).

The main group is located along the eastern *decumanus* and in the area of the *castrum*. The structures present an orientation NE-SW (dark blue) and NW-SE (light blue) as this urban area developed along the River Tiber. The northern part of the *decumanus* (*ager publicus*) and the *castrum* area form a strict perpendicular orientation, with a small deviation which occurs in the southern part of the *decumanus*. This deviation has been included in the range of variation in the model. Buildings with a similar range of orientation are located at the river mouth, next to *Torre Bovacciana*, and towards the south. The two areas offer completely different patterns in the area along the *decumanus*. Firstly, Insula XI. 1 (*Tempio Collegiale*), Insula XI. 2 (*Caseggiato del Temistocle*) and the Insula X. 3 (*Terme del Nuotatore*) in *Regio 5* are oriented similarly to group 2 (see topographical dictionary: http://www.ostia-antica.org/dict.htm or Calza et al., 1953). In the same building complex, the *Santuario della Bona Dea* (Insula X. 2) has a similar orientation to group 3. Likewise, the *via dei Misuratori del grano* which is associated with *Portico del Piccolo Mercato* (Regio 1, Insula VIII. 1) has a similar orientation to group 3. To the east, two walls of Insula IV. 5 (*Caseggiato dei Doli*), and the northern wall of Insula III. 6 (Regio 1, *Caseggiato*) have the same characteristics. The structures visible in this area form part of the *Capitolium* group which has been dated using brickstamps to the first part of the 2nd c. CE (DeLaine, 2002).

The second group are oriented NNE-SSW (red) and WWN-EES (orange) and developed in the south-western part of the city, along the *via della Foce* and *via Laurentina* (southern *cardo*). When compared to groups 1 and 2 there is a wider variation in the orientations. A more detailed analysis may perhaps reveal further variabilities, however for the purposes of this analysis they are included in the same group. A complementary group can also be included relating to structures oriented NE-SW (dark red – 32–49°/212–229°) and NW-SW (yellow – 122–139°/302–319°). One district is located along *via del Mare* (around the *Schola del Traiano* – 4, V. 16) and the second *via Laurentina* (around the *Molino*, 1, XIII. 4). The urban fabric in the southwestern part was controlled by the same factors, with the urban area facing towards the sea.

Finally, group 3 is oriented NS (pink) and EW (purple) and is characterized mainly by the urban areas on both sides of the palaeo-Tiber river mouth. It also includes isolated structures to the north and south of the *decumanus* (see above) and one warehouse in the convexity of the palaeomeander of Ostia.

When assessing the roads, it can be observed that the eastern *decumanus*, the northern *cardo* and the intramural *via del Mare* follow a direct route. In contrast, the *extra-muros via del Mare*, the *via della Foce* and the *via Laurentina* (southern *cardo*) have segments with different orientations.

4.2. Palaeoenvironmental analysis

4.2.1. Coastal deposits: analysis of Cores CAT-1 and CAT-2

Core CAT-2 was drilled 170 m from the current Tiber channel, on the northern *cardo*, south of CAT-3 at the foot of the *castrum* (Figs. 3, 5

Table 2
Radiocarbon dates (Materials in red are calibrated with the Marine13 curve - Reimer et al., 2013).

Core	Sample	Depth below surface (m)	Depth below sea level (s.l.m - Genoa) (m)	Lab. sample	Dating support	^{14}C yr B.P.	±	Activity (pMC)	Age calibrated BC-AD (Reimer et al., 2013) - 2σ
TB-1(+1.24m)	Torre Bovacciana TB1 180-183	1.82	−0.58	Lyon-11214 (SacA37192)	Wood	2090	30	77.07 ± 0.25	195 to 42 BCE
TB-1	Torre Bovacciana TB1 415–420	4.17	−2.93	Lyon-11215 (SacA37193)	Bone	2115	30	76.84 ± 0.25	341 to 49 BCE
ISF-1(+2.24m)	Isola Sacra Fiume 1 606–609	6.08	−3.84	Lyon-11216 (SacA37194)	Charcoal	2110	30	76.88 ± 0.25	204 to 46 BCE
ISF-1	Isola Sacra Fiume 1 693–697	6.95	−4.71	Lyon-11217 (SacA37195)	Wood	2245	30	75.62 ± 0.24	393 to 206 BCE
ISF-1	Isola Sacra Fiume 1 734–737	7.36	−5.12	Lyon-11218 (SacA37196)	*Posidonia**	2560	30	72.69 ± 0.25	367 to 191 BCE
ISF-1	*ISF-1 785* (in Salomon et al., 2014b)	7.85	−5.61	Lyon-9322	*Posidonia**	2620	35	–	455 to 220 BCE
ISF-1	Isola Sacra Fiume 1 879–882	8.81	−6.57	Lyon-11219 (SacA37197)	Charcoal	41500	1500	0.57 ± 0.11	–
ISF-1	Isola Sacra Fiume 1 910	9.10	−6.86	Lyon-11220 (SacA37219)	*Shell**	37040	840	0.99 ± 0.10	40267 to 37697 BCE
ISF-1	Isola Sacra Fiume 1 1298	12.98	−10.74	Lyon-11221 (SacA37220)	*Shell**	3195	30	67.17 ± 0.23	1160 to 930 BCE
ISF-1	Isola Sacra Fiume 1 1330–1335	13.33	−11.09	Lyon-11222 (SacA37221)	*Shell**	3145	30	67.59 ± 0.23	1091 to 881 BCE

(*continued on next page*)

Table 2 (*continued*)

CAT-1(+3.82m)	40121 Ostie OST1 632–633	6.32	−2.5	Lyon-11777 (SacA40124)	Organic matter	3325	30	66.10 ± 0.22	1687 to 1527 BCE
CAT-2(+4.34m)	OST-2/1150	11.50	−7.16	Lyon-11781(SacA40128)	*Posidonia**	3365	30	65.78 ± 0.21	1383 to 1185 BCE
CAT-2	OST-2/1150	11.50	−7.16	Lyon-11195 (SacA37181)	Wood	6805	30	42.85 ± 0.20	5738 to 5638 BCE
CAT-2	OST-2/635	6.35	−2.01	Lyon-11197 (SacA37183)	Organic matter	3220	30	66.97 ± 0.24	1605 to 1425 BCE
CAT-2	OST-2/1124	11.24	−6.9	Lyon-11780 (SacA40127)	Organic matter	3720	30	62.94 ± 0.21	2201 to 2031 BCE
CAT-2	OST-2/885	8.85	−4.51	Lyon-11196 (SacA37182)	Organic matter	2500	30	73.25 ± 0.24	738 to 537 BCE
CAT-2	OST-2/613	6.13	−1.79	Lyon-11779 (SacA40126)	Wood	2530	30	72.99 ± 0.22	797 to 543 BCE
CAT-3(+4.48m)	OST-3/748	7.48	−3	Lyon-11778 (SacA40125)	Charcoal	2170	30	76.35 ± 0.22	360 to 116 BCE
CAT-3	OST-3/1110	11.10	−6.62	Lyon-11198 (SacA37184)	Charcoal	3400	30	65.45 ± 0.23	1767 to 1623 BCE
CAT-3	OST-3/960	9.6	−5.12	Lyon-11783 (SacA40130)	Charcoal	2205	30	76.01 ± 0.22	370 to 196 BCE
CAT-3	OST-3/780	7.8	−3.32	Lyon-11782 (SacA40129)	Wood	2190	30	76.14 ± 0.23	361 to 178 BCE
CAT-3	OST-3/830	8.30	−3.82	Ly-16569	Wood	2445	35	73.76± 0.31	755 to 409 BCE
OST-4(+4.38m)	*OST 4/14HK* (in Hadler et al. 2014)	5.72	−1.34	MAMS-19753	Charcoal	2229	17	–	374 to 208 BCE
OST-4	*OST4/19PR* (in Hadler et al., 2014)	6.68	−2.30	MAMS-19754	Plant remain	2562	19	–	801 to 599 BCE

and 6). Fig. 3 presents a detailed analysis of this core. Core CAT-1 was drilled in the south of Ostia around 200 m of the southern wall of the *castrum* (Fig. 6) close to the *via Laurentina* (southern *cardo*). The two stratigraphic sequences are composed of a lower sandy sequence, with intercalation of organic and silty strata, and a top unit characterized by a high content of anthropic material. A more detailed analysis is proposed for Core CAT-2.

At the bottom of core CAT-2, unit A is composed of an olive coloured well sorted silty sand (75% of sands and 25% of silts and clays) with a magnetic susceptibility mostly below 100 CGS and a median of 40 CGS (7.66 to 7.17 m b.s.l.). There are no coarse sediments (> 2 mm). Few ostracods were observed in sample 1152–1154 (0.3 ostracod/g of dry and raw sediments), indicating a coastal environment (*Pontocythere turbida* and *Palmoconcha turbida*).

Unit B (7.17 to 6.65 m b.s.l.) also has an olive colour and contains a level with *Posidonia* at the bottom. The magnetic susceptibility has values between 35 and 640 CGS with a median of 227 CGS. The sandy fraction represents 50% to 75% and the remaining part corresponds to silt. In some samples, coarse sediments have also been found. The ostracod assemblage (8.9 to 18.2 ostracods/g of dry and raw sediment)

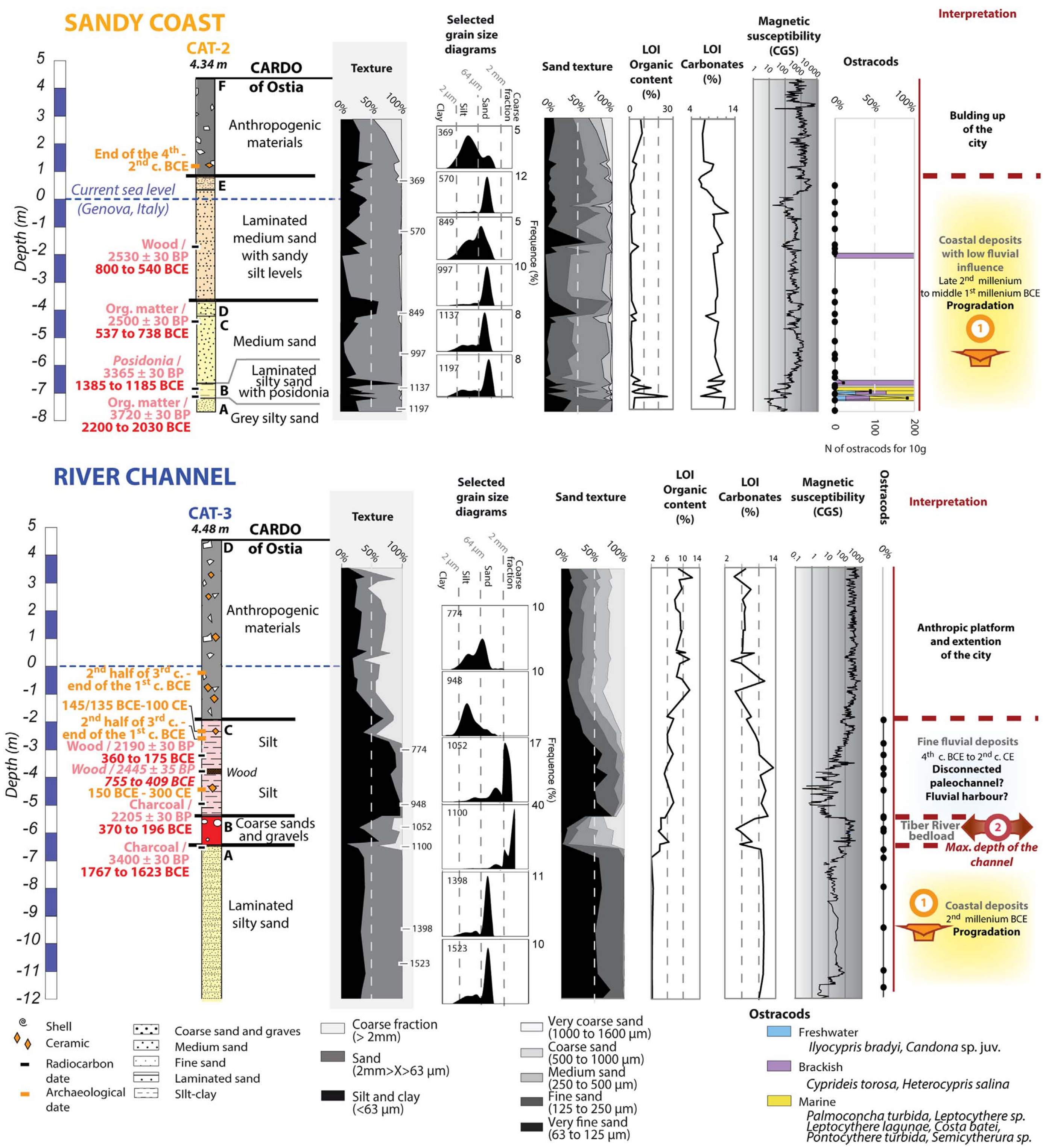

Fig. 3. Analysis and interpretation of the cores drilled in the northern cardo of Ostia (Cores CAT-3 and CAT-2).

reveals a singular type of environment, a mixed influence of coastal, brackish and freshwater environments (*Cyprideis torosa*, *Palmoconcha turbida*, *Leptocythere* sp., *Leptocythere lagunae*, *Costa batei*, *Pontocythere turbida*, *Ilyocypris bradyi*, *Heterocypris salina*, *Semicytherura* sp., *Candona* sp. juv.). The two most recent dates in this layer were dated between the end of the 3rd (3365 ± 30 BP/1385 to 1185 BCE/Lyon-11,781) and the end of the 2nd millennium BCE (3720 ± 30 BP/2200 to 2030 BCE/Lyon-11,780).

Higher values of magnetic susceptibility were measured (Median = 1351 CGS) for the sandy Unit C (75% to 90% of sand) (6.65 m to 4.17 b.s.l.). The sediments are very well sorted. *C. torosa* was recorded in some samples indicating a brackish environment (2.1 ostracods/g of dry and raw sediments). Lower energy is recorded in Unit D but still with a high magnetic susceptibility (Median = 1285 CGS) (4.17 to 3.65 m b.s.l.). More than 50% of the samples are composed by silts and clays. No bioindicators were found in this unit. Bedded silty sand similar to Unit C was recorded in Unit E (3.65 m b.s.l. to 0.8 m a.s.l.). The magnetic susceptibility is mostly lower with a median

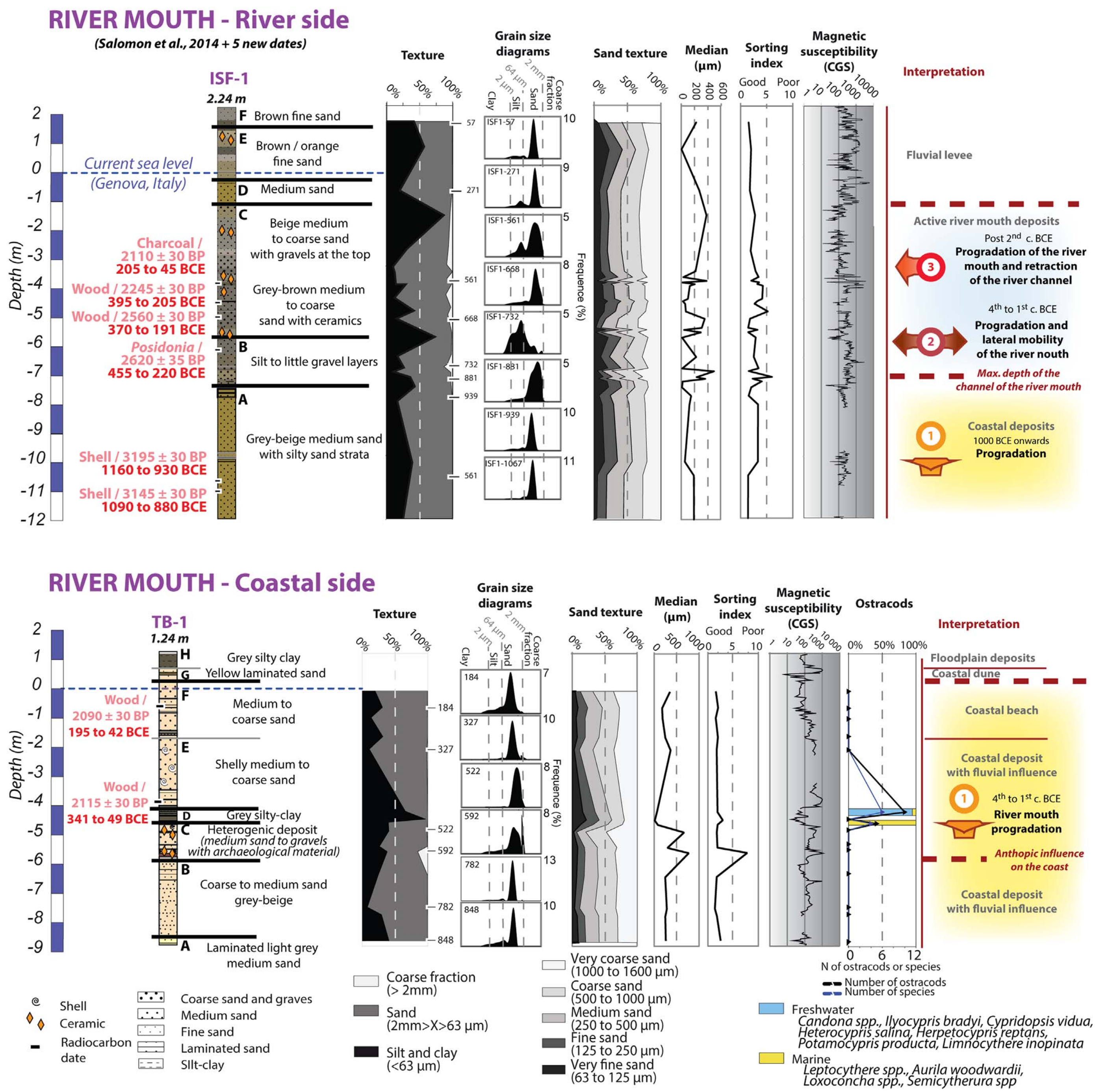

Fig. 4. Analysis and interpretation of the cores drilled near the Roman river mouth (Cores TB-1 and ISF-1).

at 860 CGS. The deposits from Units C, D and E are dated to the first part of the 1st millennium BCE (2500 ± 30 BP/738 to 537 BCE/Lyon-11,196; and 2530 ± 30 BP/800 to 540 BCE/Lyon-11,780).

Finally, the top most layer of Core CAT-2 has the highest magnetic susceptibility (Median = 2625CGS) (0.8 to 4.34 m a.s.l.). The texture is constituted of one third of coarse sediments, one third of sands and one third of silts and clays, resulting in a very poor sorting. No bioindicators were found in this unit. The ceramics provide a date for the bottom of this unit to the 4th–2nd c BCE (Table 1).

Core CAT-1 offers four stratigraphic units with mostly laminated well sorted medium to fine sands in Unit A, B and C similar to Units CAT-2/A to E. Unit B has many layers of organic matter. One of these has been dated by radiocarbon dating to 1690–1525 BCE (3325 ± 30 BP/Lyon-11,777). The top of Unit D has a very high magnetic susceptibility and many archaeological remains similar to Unit CAT-2/F.

4.2.2. River mouth deposits: analysis of Cores TB-1 and ISF-1

Cores TB-1 and ISF-1 come from opposite sides of the palaeo-river mouth of the Tiber (Figs. 4 and 5). Core TB-1 was collected on the external side of the river mouth which was mainly influenced by the coastal processes. Core ISF-1 records the river mouth deposits in the internal part dominated by fluvial processes.

Core TB-1 was composed of well sorted sand similar to the coastal cores CAT-1 and CAT-2, however the sands are generally coarser (coarse to very coarse sands). Eight units were observed. The two lower Units A and B (8.75 to 5.96 m b.s.l) were laminated medium coarse sand with a magnetic susceptibility with a median at 114 CGS with

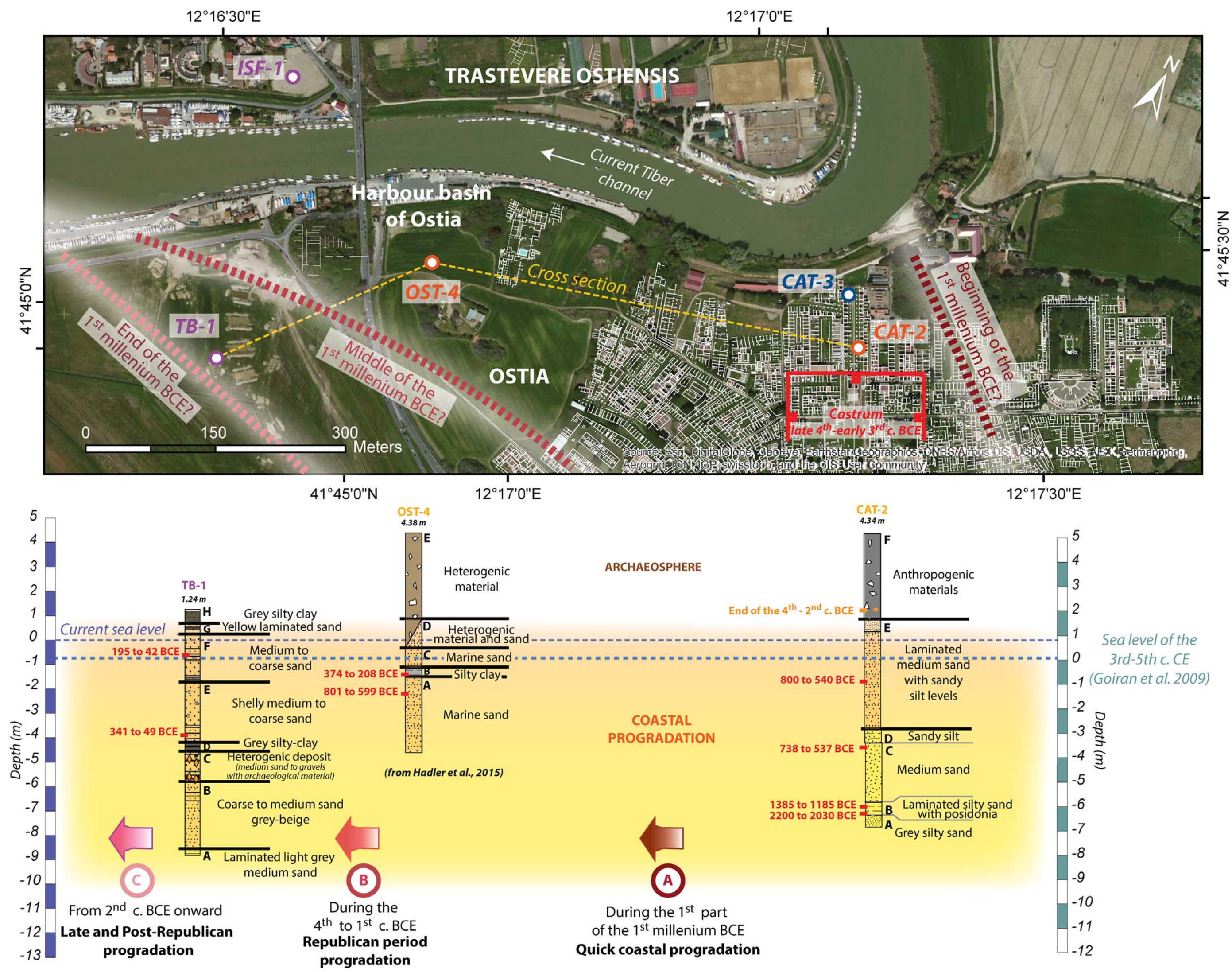

Fig. 5. Cross section of the coastal progradation of the river mouth promontory in the north of Ostia. The figure shows a quick progradation of the river mouth between the 8th and 5th c. BCE and a slower mobility of the coastline towards the west during the second part of the 1st millennium BCE.

values between 21 and 267 CGS. An important change occurs at 5.96 m b.s.l. as ceramics, bricks and stones are included in the sandy matrix in the Unit C. The median of the magnetic susceptibility of the matrix is a slightly higher compared to the underlying deposits (163 CGS) but in a much wider range of values (11 to 1154 CGS). Hydrodynamic conditions reduce considerably in Unit D (4.76 to 4 m b.s.l.) together with the magnetic susceptibility (55 CGS in a range of 17 to 254 CGS). Unit D is composed mostly of layered silts and silty sand deposited in a mixed environment. The ostracods reveal species characteristic of freshwater (*Candona* spp., *Ilyocypris bradyi*, *Cypridopsis vidua*, *Heterocypris salina*, *Herpetocypris reptans*, *Potamocypris producta*, *Limnocythere inopinata*) and a marine environments (*Leptocythere* spp., *Aurila woodwardii*, *Loxoconcha* spp., *Semicytherura* spp.), typical of a river mouth interface. Units E and F are mostly sands with a magnetic susceptibly median at 200 CGS (Range = 26 to 1015 CGS). These units were deposited between the 4th c. BCE and the 2nd/1st c. BCE (2115 ± 30 BP/341 to 49 BCE/Lyon-11,215; and 2090 ± 30 BP/195 to 42 BCE/Lyon-11,214). On top of Unit F, fine yellow laminated sand (Unit G) followed by grey silty clay (Unit H) were deposited above the current sea level.

Core ISF-1 offers many different facies (Salomon et al., 2014b). The facies are mainly sandy and several layers of silts were recorded, whilst coarse deposits over 2 mm were common. The characteristic of this sequence is the poor sorting index of the deposits. The bottom of Unit A is composed by medium sand with medium to good sorting dated from the end of the 2nd millennium BCE/beginning of the 1st millennium BCE (3145 ± 30 BP/1091 to 881 BCE/Lyon-11,222; and 3195 ± 30 BP/1160 to 930 BCE/Lyon-11,221). Magnetic susceptibility values were between 18 and 192 CGS for a median of 192 CGS. Poorly sorted sands and coarse deposits start at 7.50 m b.s.l. Some particles reached 8 mm (B-axis). Magnetic susceptibility from 7.50 m b.s.l. through to the top have a high variability between 12 and 6027 CGS with a median of 252 CGS. No ostracods were found in these high energy or unstable environments. Deposits in Unit B and C have been dated from the mid-5th c. to the mid-1st c. BCE (Lyon-11,216, 11,217, 11,218, with Lyon-9322 *in* Salomon et al., 2014b- Lyon-11,219, 11,220 have been removed).

4.2.3. Fluvial deposits: analysis of Core CAT-3

Core CAT-3 was drilled between the current River Tiber channel (80 m) and the northern wall of the *castrum* (100 m) in the northern *cardo* (Figs. 3 and 6). Four units were identified. At the bottom of the sedimentary core (Unit A: 12 to 6.51 m b.s.l.) were settled laminated silty sands light grey to grey-olive in colour. No coarse material (> 2 mm) was observed. Magnetic susceptibility was measured below 200 CGS with a median at 24 CGS. Fragments of pieces of unidentifiable marine shells were also observed. The top of this unit has been dated to

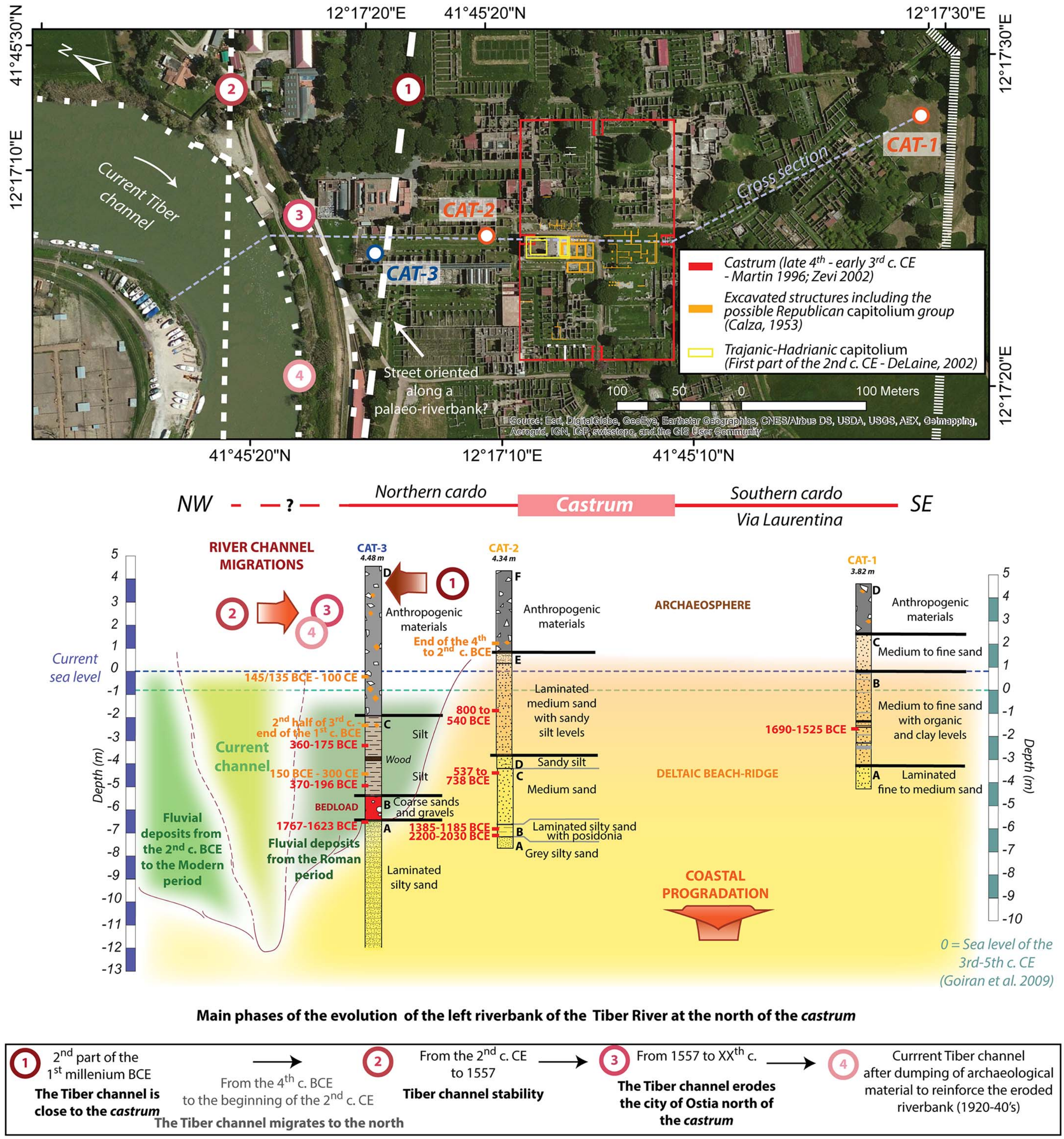

Fig. 6. Section following approximately the cardo of Ostia. It shows the location of the River Tiber channel close to the castrum in the c. late 4th–early 3rd c. BCE and the subsequent mobility of the river.

1767–1623 BCE (3400 ± 30 BP/Lyon-11,198).

A sharp discontinuity occurs at 6.51 m b.s.l. Unit B is 1 m thick, composed by 15% to 20% of coarse material, rising to 40% at the bottom of this unit. There is a sorting of the coarsest sediments to the finest from the bottom to the top of the unit. Pebbles were observed with a maximum A axis of 25 mm, but were mainly around 8–9 mm. Ceramics such as common fineware were found in the layer dated to the Roman period but without precise dates. Magnetic susceptibility is higher with a median at 165 CGS. This unit is abiotic.

On top of Unit B, Unit C is mainly composed of clay and silt (77%–96%). It contains a large piece of wood measuring 20 cm. The structure is not laminated and appears to be very homogeneous. The magnetic susceptibility is lower with a median at 23 CGS. In the upper part of the unit some coarse sediments were observed, characterizing a transition with the upper unit. An oyster shell was found around 2.98 m b.s.l. Two radiocarbon dates were taken on this unit. They provide a date between the 4th c. BCE and the 2nd c. CE by three AMS radiocarbon dates on wood and charcoal (2205 ± 30 BP/Lyon-11,783;

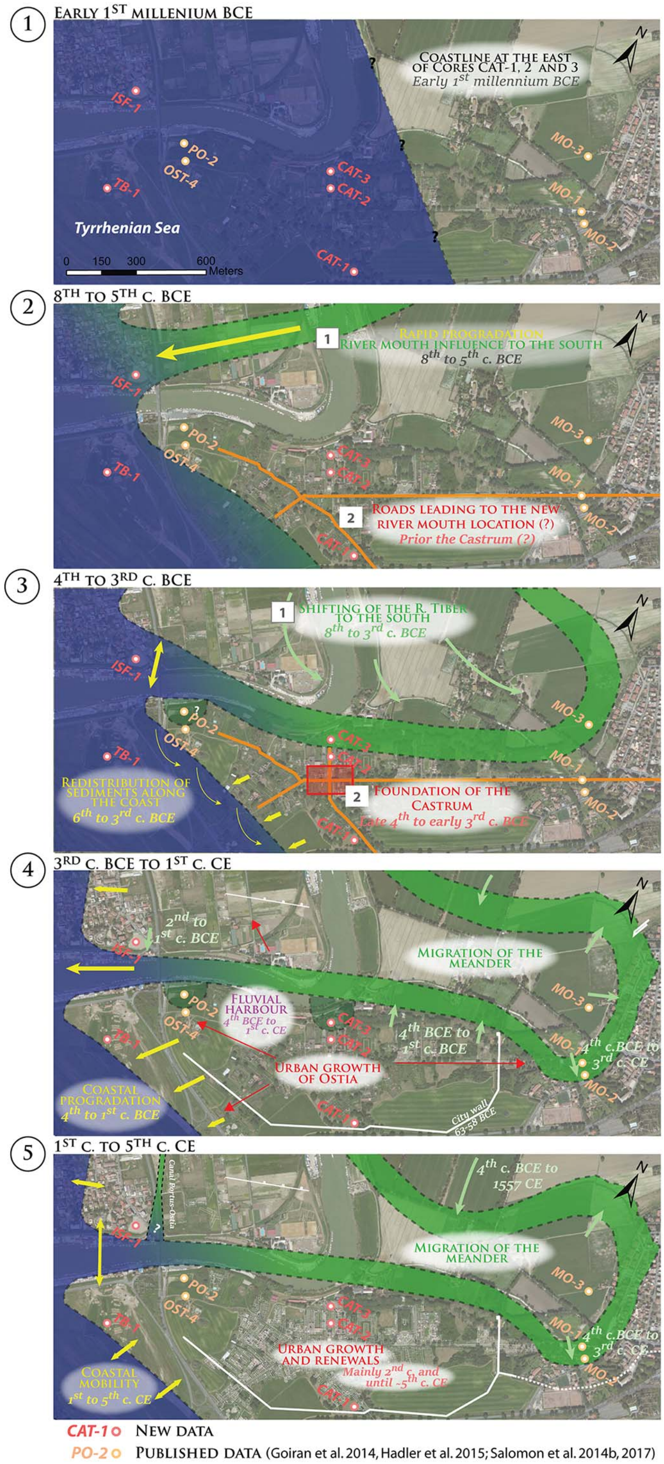

Fig. 7. Palaeoenvironmental reconstruction of the evolution of the river mouth of the Tiber during the Roman period.

2190 ± 30 BP/Lyon-11,782; and 2170 ± 30 BP/Lyon-11,778). The piece of wood of an unknown origin has been dated through standard radiocarbon dating to 754–409 BCE at − 3.82 b.s.l. (2445 ± 35 BP/Ly-16,569). Two identifiable ceramics at different depth give a more recent range of date from 2nd c. BCE to the 3rd c. CE.

The unit at the top contains a very coarse content (Unit D). The coarse fraction is composed of brick fragments, pozzolana and gravels. Its magnetic susceptibility is very unstable with a median at 312 CGS a maximum up to 700 CGS. A fragment of amphora, probably a Dressel 2–4, has been dated to between 70–60 BCE and 100 CE (Table 1).

5. Discussion

5.1. Fluvio-coastal environments at the mouth of the River Tiber between the 3rd millennium BCE and the end of the 1st millennium BCE

New Cores CAT-1, CAT-2, CAT-3 and TB-1, new dates from Core ISF-1 (Salomon et al., 2014b) but also published Core OST-4 (Hadler et al., 2015), provide reliable evidence for the evolution of the river mouth and the coastline mobility from the 3rd millennium BCE to the end of the Roman Republican period – 1st c. BCE (Figs. 5, 6 and 7). The cross section of Cores CAT-2/OST-4/TB-1 in Fig. 5 shows clearly the progradation of the coastline from east to west from the end of the 3rd millennium BCE to the end of the 1st millennium BCE. Beach ridges have been observed south of Ostia through aerial photography (Bellotti et al., 2011), but they have been covered by the archaeological remains in Ostia.

Below the archaeological layers (Units CAT-1/D and CAT-2/F), Cores CAT-1 and CAT-2 record shoreface deposits of well sorted laminated medium-fine sand and silty sand dating from the end of the 3rd millennium BCE to the middle of the 1st millennium BCE (Figs. 5 and 6). The bottom unit of Core CAT-3 (Unit A) shows well sorted silty sand corresponding to the same shoreface deposits. The top of Unit CAT-3/A can be dated to 1767–1623 BCE (Figs. 3 and 6) and matches the dates of Core CAT-2 at a similar level (Unit CAT-2/B dated at 2200–3030 BCE from organic matter and 1385–1185 BCE from *Posidonia*). Ostracods in Core CAT-2 show a mixed influence of fresh and marine water, especially in Unit B, suggesting a proximity of the mouth of the River Tiber. Similar environments have already been identified below the harbour of Ostia towards the east (Core PO-2/A in Goiran et al., 2014).

Consequently, the area of the *Castrum* of Ostia was still offshore at the end of the 2nd millennium BCE. However, the shoreline was nearby to the east since lower to upper shoreface deposits are dated between the end of the 3rd millennium BCE to the end of the 2nd millennium BCE (Units CAT-3/A, CAT-2/A and B, CAT-1/A and B). This new data allows us to adjust the model of progradation of the Tiber proposed by C.Giraudi (2004) and especially the extension of the progradational phase 4 (2140–1000 BCE). This period of coastal sedimentation starts with more human impact in the watersheds of Central Italy with the onset of the Bronze Age ar. 2300–2200 BCE, but this period corresponds also to a shift towards aridity dated around 2200 BCE (Drescher-Schneider et al., 2007; Magny et al., 2009; Mercuri and Sadori, 2012).

Radiocarbon dates from Units C to E in Core CAT-2 show that the area of the *castrum* was finally land between the 8th and the 6th c. BCE. Similar date range has been identified below the harbour of Ostia at − 8 b.s.l. with fluvio-coastal deposits dated to 837–734 BCE (Goiran et al., 2014). However, Core OST-4 located to the south of the harbour of Ostia show that the area of the harbour was prograded also between the 8th and the 6th c. BCE with coastal sand dated to 801–599 BCE at 1.30 m b.s.l. (Hadler et al., 2015) It can be established from the dates of the coastal deposits of Cores CAT-1 and CAT-2 that the coastline was further east before the 8th c. and the 6th c. BCE. Between the 8th c. and the 6th c. BCE, the coastline moved quickly from a point to the east of Cores CAT-1 and CAT-2 to one lying to the west of core OST-4. A similar progradation of the Tiber delta by almost 600 m has also been observed in historical times in the 16th c. CE, during the Little Ice Age (Le Gall, 1953; Salomon, 2013). This phase of quick progradation can be partly related to climatic factors. Between the 9th c. and the 6th c. BCE, a cool and wet period has been recorded in many part of Europe and the Mediterranean (Bond et al., 2001; Magny et al., 2007; van Geel, 2012; Groenman-van Waateringe and van Geel, 2016). At the same time, human impact increased in the watersheds of Central Italy (Di Giuseppe and Patterson, 2009) and many cultivated trees, cereals and weeds became widespread (Mercuri et al., 2002; Mercuri and Sadori, 2012).

Core TB-1 shows a more complex environment (Figs. 4 and 5). It is mainly composed of well sorted sand, coarse and very coarse sand which have been observed through the sequence (Units A to F) with a high content of anthropic material in Unit C. Units A to F are interpreted as shoreface deposits with a high influence from the river and from human activity. Unit D shows silty clay deposits with ostracods from freshwater and marine environments. The shoreface sequence is overlaid by very fine well sorted dune sand (Unit G) and silty clay floodplain deposits (Unit H). Finally, on top of the very well sorted coastal sand dated between 1160 and 880 BCE (ISF-1/Unit A), Core ISF-1 records also a river mouth environment with a high human impact but with a higher fluvial signal (Salomon et al., 2014b). These river mouth deposits show mostly poorly sorted medium to coarse sand dated between 455 and 220 BCE.

The progradation slows down after the 8th–6th c. BCE, and it was probably interrupted by an erosional phase (or several phases). The progradation estimated between Core OST-4 and TB-1 was only of 300 m between 6th c BCE and 2nd c. BCE/middle of the 1st c. CE. Climatic reconstructions provide less clear evidence for the understanding of this period (Berger and Bravard, 2012; McCormick et al., 2012). Archaeological excavations undertaken in 2011 next to core TB-1 confirm this chronological reconstruction (Fig. 1 - Raddi and Pellegrino, 2011)). Archaeological structures were discovered and dated between the end of the 1st c. BCE/1st c. CE and the beginning of the 3rd c. CE (Raddi and Pellegrino, 2011). Consequently, these structures were built after the progradational phase dated between 2nd and 1st c. BCE in Core TB-1. A higher fluvial activity is recorded in Ancient texts during the 1st c. BCE to the 2nd c. CE (Camuffo and Enzi, 1995; Le Gall, 1953), while coastal progradation is identified in the southern Tiber delta (Bicket et al., 2009). Upstream, the watershed of the Tiber River records its highest human impact between the 2nd c. BCE and the 2nd c. CE (Di Giuseppe and Patterson, 2009; Mercuri et al., 2002), combined with climatic variations (Camuffo and Enzi, 1995; Salomon, 2013) affecting the river mouth mobility.

5.2. The castrum of Ostia was originally closer to the Tiber and set back from the river mouth

The fast progradation phase between the 8th and the 6th c. BCE brings new elements to the discussion of the potential origin of Ostia during the reign of the legendary fourth king of Rome called Ancus Marcius (646–616 BCE). This foundation of Ostia is only attested in Roman tradition and no archaeological evidence supports such an early origin. In light of these new results, it is tempting to look for this early settlement towards the east following the hypothesis of Canina (1830). However, due to the uncertainty of the radiocarbon dates, any early settlement could have been established either on the east but also on the west, built on new prograded lands partly eroded in the second part of the 1st millennium BCE.

Important results are also provided by Core CAT-3 drilled in the *cardo* of Ostia, to the north of the *castrum/capitolium* (Fig. 6). The first interesting result comes from Unit B. Between − 6.50 and − 5.50 m b.s.l., Unit B is composed of coarse pebbles that corresponds to the bedload of the River Tiber. The coarsest sediments are rolled pebbles with an A-axis maximum at 2.5 cm. Similar facies with coarser pebbles were found in Cores MO-1, MO-2 and MO-3 published in Salomon et al. (2017). No similar deposits have been found in the north-south core cross section in Fig. 6. CAT-3/Unit B overlays a very well sorted silty sandy deposit interpreted as a shoreface deposit (CAT-3/Unit A), and a similar interpretation is proposed for sediments below the archaeological strata in Cores CAT-1 and CAT-2. Consequently, it is possible to establish that a palaeochannel of the River Tiber was flowing further south of where the current channel and the palaeochannel of 1557 lie (Shepherd, 2006; Salomon et al., 2017), and below what was to become the northern *cardo* of Ostia. The left riverbank of this palaeochannel migrated southward, up to a maximum location between cores CAT-3 and CAT-2. The date of this palaeochannel can be deducted from the dates of the under and overlying units. The palaeochannel eroded so therefore post-dates the coastal deposits of Unit A from the middle of the 2nd millennium BCE. It post-dates or is coeval to the coastal progradation of this area happening in the 8th–6th c. BCE (Cores CAT-1 and CAT-2). The bedload is covered by silts (Unit C) with a bottom part dated by radiocarbon technique between the 4th and the beginning of the 2nd c. BCE (370–196 BCE). It can therefore be proposed a date of the riverbed identified in Core CAT-3 between the middle of the 1st millennium BCE and the beginning of the 2nd c. BCE. Roman ceramics caught in the bedload reinforce this chronological framework.

The implications of these new results are crucial for our understanding of the palaeogeography at the mouth of the River Tiber during the foundation of the *castrum* between the late 4th and the early 3rd c. BCE. As hypothesised initially by Constans (1926), the *castrum* was a riverine fortress built close to the riverbank of the Tiber. However, the comment by Le Gall (1953) was also correct, as the Tiber riverbank was not directly at the foot of the northern wall of the *castrum* (CAT-2), but further north in an area now identified in between Cores CAT-2 and CAT-3.

At the time of its foundation, the fortress of Ostia was not located precisely at the mouth of the river. The *castrum* was closer to the River Tiber but set back from the promontory. The quick progradation identified in Cores CAT-1, CAT-2 and OST-4 (8th to 6th c. BCE) occurred before the foundation of the *castrum* (late 4th c. BCE to early 3rd c. BCE). These results match the archaeological observations suggesting that there was originally a curved road prior to the construction of the *castrum* which connected the *via Severiana* and the *via della Foce* in a single road parallel to the coast leading to the top of the river mouth promontory (Becatti, 1953; Mar, 1991; Zevi, 1996, 2002).

5.3. Evolution of the northern area of the castrum

On top of Unit CAT-3/B, composed of coarse pebbles and interpreted as a riverbed deposit, Unit CAT-3/C records 3 m of silts indicating a calm and protected environment (Fig. 6). This deposit has been precisely dated using both radiocarbon techniques and ceramics. The bottom is dated from the 4th–3rd c. BCE and the top between the 2nd c. BCE and the 1st c. CE. This unit is covered by 6 m of archaeological material dated at its base between 70/50 BCE and 100 CE by ceramics. This date matches the archaeological studies of the brickstamps of the *Capitolium* group and the structures built over this area dating from the beginning of the 2nd c. CE (DeLaine, 2002) – a *terminus ante quem* for the deposits of Core CAT-3, Unit C. This new planned urban area during the Hadrianic period corresponds to a major restructuring of the river side of Ostia. At this time the River Tiber was flowing at a location between the last archaeological structure identified north of the *Capitolium* and the course of the river before its cut-off in 1557 (Salomon et al., 2017). When considering this segment of the river, a displacement of the Tiber channel towards the north seems to have occurred between the 4th c. BCE and the first decade of the 2nd c. CE.

Further topographical and chronological indicators can be used if we consider a uniform migration of the river channel in Ostia towards the north. Firstly, when considering the city wall of Ostia was built between 63 BCE and 58 BCE (Zevi, 2001b), and in particular the wall built north of the *Porta Romana* and the *Torre sul Tevere* (Fig. 2), it can be argued that the migration of the River Tiber towards the north occurred between the 4th c. BCE and 62–58 BCE. On the opposite side of the river, the riverbank is fixed archaeologically to slightly later as several *cippus* delimitating the limit of the riverbank were set in placed in 23–41 CE (Le Gall, 1953).

Secondly, the urban area east of the original *castrum* and north of the *decumanus* can be related to the migration of the Tiber channel to the north during this period. It was hypothesised that this area was built over land deposited by the River Tiber (Constans, 1926; Zevi, 2001b). The interpretation of the data bedload identified in Core CAT-3/Unit-B in their archaeological context supports this hypothesis. Additionally, this migration of the river from south to north matches the dynamic of the palaeomeander of Ostia (Salomon et al., 2017). Following the theory of meander dynamics, the palaeomeander was effectively extending towards the east between the 4th c. BCE and the 1st c. CE (Salomon et al., 2017) and the neck of the palaeomeander narrowed during the same time span. This area north of the *decumanus* was delimited by a *cippus* established by the *praetor urbanus* C. Caninius that was dated to the 2nd c. BCE (Zevi, 2001b).

When bringing together the palaeoenvironmental and archaeological data, it is possible to reconstruct a migration of the River Tiber channel from a southern location closer to the *castrum* and the *decumanus* in the late 4th to the early-3rd c. BCE towards a course in the 2nd century BCE that was similar to that taken by the Tiber channel in 1557 CE, and which was stabilized by 63–58 BCE.

There remains the problem of the interpretation of Unit C in Core CAT-3 for two reasons: the nature of the deposit and the chronology. This silty unit marks a sudden change in the stratigraphy, from high (Unit CAT-3/B) to low energy. With the channel moving towards the north, Core CAT-3 was drilled in the inner bank of the river. Consequently, there should have been coarse deposits as high as the topographical surface, if this was the case. A similar sudden change has been observed in the palaeomeander of Ostia (Unit MO-2/C over MO-2/B in Salomon et al., 2017) and recently identified in similar river delta context (Pennington and Thomas, 2016). Several hypotheses can be suggested for this layer: (1) a harbour deposit similar to the facies described by Goiran et al. (2014) and Hadler et al. (2015) in the fluvial harbour of Ostia (concerning the harbour muds, see Marriner and Morhange, 2007; Marriner et al., 2010); (2) an abandoned secondary branch; (3) a deposit due to low energy in the channel and active flocculation processes related to the salt edge in the channel. Each of these hypotheses does not exclude the two others.

The second issue relates to the dates. Radiocarbon dating suggests a date between 370 and 175 BCE, and archaeological evidence indicates a date between 150 BCE (ceramics *in situ*) to the beginning of the 2nd c. CE (ceramics and the *terminus ante quem* of the building constructed on top of core CAT 3) (DeLaine, 2002). This complex chronology, typical of an operational harbour context, could imply dredging activity (Marriner and Morhange, 2006; Salomon et al., 2016), reinforcing the hypothesis of a harbour. The presence of an older thick piece of wood trapped in the deposits and many dated ceramics confirm a high human impact associated with this deposit. The dates suggest a long period of use possibly starting in a period coeval to the foundation of the *castrum* (late 4th–to early 3rd c. BCE) to a period after the migration of the Tiber channel to the north (1st c. BCE/1st c. CE). Further direct investigation by excavation would be necessary to test this hypothesis.

From at least the 2nd c. CE until the cut off of the palaeomander in 1557, the Tiber channel at Ostia remains more or less at the same location. This lateral stability was also identified for the secondary lobe of the palaeomeander of Ostia at least between the 3rd c. CE and 1557 (Salomon et al., 2017), while climate changes have been identified during this period (Camuffo and Enzi, 1995; McCormick et al., 2012). This stability is probably related to complex imbricated local factors. It can be related to upstream constraints on the palaeomeander dynamics (structures in the palaeochannel at the N-E of the palaeochannel), the reduction of the energy in the natural channel due to the diversion of water in the canals of Portus, or a possible reinforcing of the riverbanks in the Imperial period and its success to reduce lateral mobility (hypotheses discussed in Salomon et al., 2017). From the cut off of the palaeomeander in the 16th c. CE to the 20th c. the new Tiber channel migrated again towards the south and eroded the northern part of the archaeological site of Ostia. This erosion stopped in the first part of the 20th c. when the soil from the excavations was dumped into the concavity of the Tiber channel (Calza et al., 1953).

5.4. Fluvio-coastal dynamics influencing the urban fabric of the port-city of Ostia

The close interaction between Ostia and its fluvio-coastal environment can be assessed at the origin, but also later during the Republican and Imperial periods when Ostia became an important port-city in the port system of Rome (Keay, 2012).

Prior the construction of the *castrum*, a road system was probably established at the mouth of the River Tiber including the *via della Foce* possibly in continuity from the *via Laurentina* (Figs. 1 and 2) (Becatti, 1953; Mar, 1991, and Zevi, 2002). Following this hypothesis, this curved road might have tracked the coastline leading to a river mouth promontory. In this sense, it would be the first archaeological evidence suggesting the presence of a river mouth promontory in the vicinity. Typically, geomorphological features are used for palaeogeographical reconstructions in the Tiber delta (Bellotti et al., 1995; Giraudi, 2004; Keay and Paroli, 2011). The beginning of a change in the orientation of the beach ridges coming from the south is visible in aerial photography from the south of Ostia (Bellotti et al., 2011). It tends to support the presence of a river mouth promontory close to but without showing the last definitive clue somewhere to the north – the evidence for beach ridge features is hidden, now beneath the archaeological remains of the city of Ostia. However, this strong hypothesis brings many questions: was the road following the coastline all the way? How much does the road confirm the trace of the coastline? What was the distance between the road and the coastline? These questions relate finally to one main issue about the date of this road, or the dates of the different segments of this road. Bringing together archaeological and palaeoenvironmental data, this initial road system could have been built between the 8th–6th c. BCE (during the fast progradation phase), and the late 4th–early 3rd c. BCE (with the construction of the *castrum* at Ostia).

In the later periods the city of Ostia extended far beyond the limit of the *castrum*. Two archaeological features can provide fixed stages for the evolution of the coastline: the city wall built in 64–58 BCE (Zevi, 2001b) and the *via Severiana* (end of the 2nd c. CE). Two opposing interpretations can be suggested: either the orientations of these structures were controlled by internal factors (cadastral plan conformation, organic development of the city and auto-adjustment, *etc.*) or by an external factor, such as the presence of the coastline. It is also possible that the coastline influenced directly (road/wall following the coastline) or indirectly (road/wall flowing structures/cadaster following past coastlines) the orientations of the ancient roads and buildings. Supplementary cores would be necessary to reconstruct the evolution of the coastline during the Imperial period and especially in relation to the *via Severiana*, but some elements can already be proposed for the evolution of the shore of Ostia between the mid-1st millennium BCE and the 1st c. BCE.

In Fig. 2 it can be seen that almost all the districts south of the *via Laurentina*/*via della Foce* have the same range of orientation (mainly 3–32°/183–212° and 93–122°/273–302°). In more detail, there exists a gradient in the orientation from the east of the *via del Mare* (≈ 40° - SW-NE - brown/yellow), the *via del Mare* and associated structures (≈ 29° - SW-NE - red/orange), the buildings at the south of *via della Foce* (≈ 13° - SSW-NNE - red/orange), and the structures at the end of the *via della Foce* towards the river mouth (≈ 0° - S-N - purple). This would suggest a conformation of the development to the city to the initial curved road of the city being the *via Laurentina* and the *via della Foce*. However, the change in orientation of the *via della Foce* (93° down to 66° - WWS-EEN - Purple) and the southern segment of the city wall (98.5° - WN-ES - Orange) could be associated to a change in the orientation of the coastline between the mid-1st millennium BCE (possible date of the *via della Foce*) and the 1st c. BCE (construction of the city wall). Indeed, the rapid progradation during the 8th–6th c. BCE (rapid progradation between Core CAT-2 to OST-4) led to the formation of a promontory at the river mouth possibly fixed by the original *via Laurentina*/*via della Foce*. During the 6th and the 1st c. BCE, the mean sedimentary budget was reduced at the river mouth (Core OST-4 to TB-1) due possibly to (1) a reduced sedimentary input from the river not yet identified in the watershed (anthopo-climatic control); and (2) the partial erosion of the promontory. However, the sediments from the promontory were probably re-deposited on the northern and southern coasts by longshore drift, leading to a slight change in the orientation of the shoreline of Ostia.

The riverside of Ostia indicates a planned urbanism conforming to the orientation of the *cardo – 151.5*° - and the *decumanus – 61.5*° (*castrum* area, *capitolium* group, area delineated by C. Caninius along the river). However, in the *capitolium* group, between the *castrum* area and the River Tiber, dated by two different phases at the beginning of the 2nd c. BCE (DeLaine, 2002), the *via dei Misuratori* does not relate to the orientations of the *cardo-decumanus*, but is oriented at 71°, relating more to the orientation of the structures closer to the river mouth. Walls aligned with same orientation at 71° have been found to the east in the Insula IV. 5 (*Caseggiato dei Doli*), and the northern wall of Insula III. 6 (*Regio 1*, *Caseggiato*). Interestingly, cores CAT-2 and CAT-3 have been drilled on one side and another of this alignment of structures, showing the presence of the River Tiber north of these structures. Were these structures oriented to an urban district prior to the urban planning at the beginning of the 2nd c. BCE? Was this previous urban pattern conforming to the orientation of the left riverbank of a palaeochannel of the River Tiber? The results from Core CAT-3/Unit B seem to suggest such an interpretation, but further archaeological investigationon the substructures of Ostia would have to be undertaken.

The study of the urban fabric together with geoarchaeological cores therefore suggests a high potential for future research at Ostia and potentially for other extensively excavated Roman cities in similar geographical positions.

5.5. Fluvio-coastal changes and urban resilience of the port-city of Ostia

Located at the mouth of the River Tiber, Ostia was a key port-city in the port system of Republican and Imperial Rome (Keay, 2012). Indeed, Ostia became an even more important commercial focus after the foundation of Portus in the middle of the 1st c. CE (Meiggs, 1973; Keay, 2010). The *Piazzale delle Corporazioni* in the centre of Ostia was an important place that was frequented by merchants from across the Mediterranean, and was emblematic of the intense economic activity at Ostia in the 2nd c. CE. The warehouses built close to the river mouth in the 2nd c. CE, but also in other places in Ostia reveals the involvement of the city in port and trade activities (Heinzelmann, 2002; Bukowiecki and Rousse, 2007). Following recent geophysical surveys (Keay et al., 2014), there is now clear evidence that Ostia extended on the northern bank of the River Tiber suggesting that the whole of the Tiber channel inside Ostia was used as a linear harbour. Along the channel, at least one small harbour basin has been excavated near the so-called *Palazzo Imperiale* along the Tiber channel (Goiran et al., 2014; Hadler et al., 2015). It is possible that Unit CAT-3/C records another enclosed fluvial harbour established along the river channel.

Natural constraints might have affected the regular activity of the port-city. First, the formation of submerged river mouth bars is reported several times by ancient authors at the end of the 3rd c. BCE; (Livy, n.d.-a, -b, *Ab Urbe Condita*, XXIX, 24; Suetonius, n.d., *Tiberius*, 2) and the end of the 1st c. BCE/early 1st c. CE (Dionysius of Halicarnassus, n.d., *Ant. Rom.*, III, 44; Strabo, n.d., *Geography*, 5, 3, 5). These sediments relate partially to the sediment drilled in Core ISF-1 and dated between the 5th and 1st c. BCE. Two types of solution were considered by Romans: (1) the dredging of the river mouth (Plutarch, n.d., *Caesar*, 64, 58); and (2) the unloading of the big ships offshore onto smaller boats which then transported the goods to Ostia (To the shore? To the riverbanks? – Strabo, n.d., *Geography*, 5, 3, 5). These strategies reveal respectively the importance of the work that can be considered for such a problem and the flexibility of the Roman logistics. However, these solutions cannot alone resolve the problem of sedimentation in such a dynamic environment. The city of Ostia had to cope with these problems on a regular basis (each season, after each major event *etc.*).

This geoarchaeological study shows the importance of the river and coastal mobility during Roman period around the city of Ostia. Riverbanks and shores were the point of contact for loading and unloading ships and boats, and were consequently of primary importance for the city. Their mobility may have affected the infrastructures and the organization of the port of Ostia. However, Units B and C in Core CAT-3 attest that a district of shops and warehouse was built over a palaeochannel of the River Tiber and possibly an ancient silted-up harbour as well. The combined analysis of the urban fabric and the palaeoenvironmental analysis of Core CAT-2, OST-4 (Hadler et al., 2015) and TB-1, suggests that major coastal changes occurred between the time of the construction of the *castrum* and the Imperial period, together with intense construction along the seashore. Whilst further work should be undertaken to precisely define the palaeoenvironmental and archaeological chronologies, these results show a resilience of the city of Ostia during the Roman period.

Resilience is a polysemic concept and its use must be defined precisely (Reghezza-Zitt et al., 2012). In this paper, the resilience is related to Ostia as a city facing fluvio-coastal hazards. The definition of the resilience involves “the capacity of a system to integrate a disruption to its operation, without changing its qualitative structure” (Aschan-Leygonie, 2000). In other words the urban resilience of Ostia facing fluvial and coastal disruptions, would involve change in *form* but not in *structure* of the urban area. The *castrum* of Ostia corresponds to the initial structure from which the whole city was to develop from the 4th–3rd c. BCE onwards, and this urban centre was to be resilient for almost 1000 years with the capacity to adapt to fluvial and coastal dynamics. Its resilience decreases during Early Middle Ages and definitely ends with the construction of a new urban centre called *Gregoriopolis*, and the use of Ostia as a quarry (Pannuzi, 2009). Interestingly, the construction of another port a few kilometers north of Ostia in the middle of the 1st c. CE by the Emperor Claudius (Portus), did not affect the urban growth of Ostia, but reinforced its resilience for several centuries.

Additionally, resilience involves an effect of threshold related either to the society able to help an urban area to recover from a disruption, or to the intensity of the hazard confronting it. According to several authors, the legendary Palaeo-Ostia of Ancus Marcius (end of the 7th c. BCE) might have faced a major palaeogeographical change leading to its abandonment, revealing a low resilience for such hazard at this period. The resilience of the Republican and Imperial Ostia linked to the new fort of Ostia built at the end of the 4th- early 3rd c. BCE is mostly due to the development of Rome and its Empire but also to less intense fluvio-coastal changes.

Similarly resilient harbour cities have been identified in other areas and in other contexts for fluvial harbour structures along the Thames in London since Roman period (Bateman and Milne, 1983; Milne, 1985; Rogers, 2011) and for the early medieval wharves of Dorestad (Clarke and Ambrosiani, 1991), but the case of Ostia remains unique by its double side (coastal/river) and the importance of the work engaged.

6. Conclusions

While several ancient cities have been abandoned on account of important natural hazards, the decline of Ostia seems to be mostly related to the decline of Rome and the demands of its population for food. At the mouth of the Pelusiac branch in the Nile delta, Pelusium was probably abandoned in the 9th c. CE after the shifting of the Pelusiac channel to the east, and the progradation of the coastline towards the sea (Goodfriend and Stanley, 1999). To the west of the Nile delta, the cities of Canopus and Herakleion previously located at the mouth of the Canopic branch, lie today underwater due to the combination of different factors: lower fluvial inputs, coastal erosion, a rise in sea levels since antiquity, regional subsidence, and quick subsidence due to the destabilisation of the river mouth promontory after potential earthquakes in Medieval period (Stanley et al., 2004; Stanley, 2005; Stanley and Toscano, 2009; Flaux et al., 2017). A decline of the activity at the mouth of the Canopic branch had probably already begun in the early Medieval period due to changes of commercial routes, when a natural event brought an end to the two cities (Flaux et al., 2017). In Turkey, the Meanderes Delta shows the quickest coastline progradation since 4000 cal BP in the Mediterranean Sea, and reveals a regular displacement of the main city following the coastline (Brückner, 1997; Brückner et al., 2002). In this respect, the balance between the intensity of the hazard and the socio-economical potential of resilience of Ostia is not comparable. The coastal and river mobility identified in this study were manageable for a port-city controlling the access to the River Tiber, downstream of Rome.

This study emphasizes a very constrained environment and identifies evidence of a resilient ancient city in such a context. River mouths are affected by very active coastal and channel mobility making this environment difficult to urbanize. However, despite the problem of the mouth bars regularly affecting the access of larger vessels, the floods, the coastal mobility, and the river mobility, Ostia maintained a dynamic urban development for several centuries from the late 4th- early 3rd c. BCE to the 5th c. CE. It was a key port-city in the harbour system of Rome, and connected the capital of the Roman world to the Mediterranean Sea. As such, Ostia was sustained as an active focus of population and commercial activity. The establishment of Portus in the middle of the 1st c. CE was the most significant adjustment made by the Romans to solve the natural constraints of Ostia and to provide better harbour facilities. Within Ostia itself, the urbanism shows adjustments and resilience to fluvio-coastal mobility. These results were obtained by combining the analysis of the urban fabric analysis and its palaeoenvironmental records, and this method provides a new avenue of research into the archaeology of Ostia, providing us with a tool for the analysis of the risks and resilience of cities in a long term perspective.

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