The geoarchaeology of ancient Mediterranean harbours in a deltaic context

Methodological approaches highlighted by three study cases from the Nile (Egypt) and Tiber (Italy) deltas

Introduction

In geoarchaeology, an ancient harbour is defined and studied in terms of its outer structure and its content (Fig. 1). The outer structure corresponds to the harbour structures of breakwaters and wharves. The content consists of a volume of sediments accumulated at the bottom of the basin and a volume of water when the basin is in use. Viewed as a geological container the harbour consists either of a hard substratum, when the harbour is carved into the rock, as with the cothons or artificial harbours attributed to the Phoenicians, or of soft sediments, when the harbour is dug out of sand or the mud, such as the basin at Ephesus. In other situations, when the natural depth allows it, the structures stand directly on the subsurface. This is the case for the harbours built in offshore areas, such as the encircling breakwaters of Claudius (1st c. AD, Tiber delta). Quite often, the construction of the harbours is mixed such as *Portus*. The inner part is dug into a soft geological base (the harbour of Trajan, 2nd c. AD, Tiber delta) while the outer part is reclaimed from the sea, such as the offshore harbour of Claudius. The study of an archaeological harbour sites is generally rendered difficult by the presence of the water table. The use of pumps does not enable deep stratigraphic sections to be cleared. The construction of cast or revetted walls

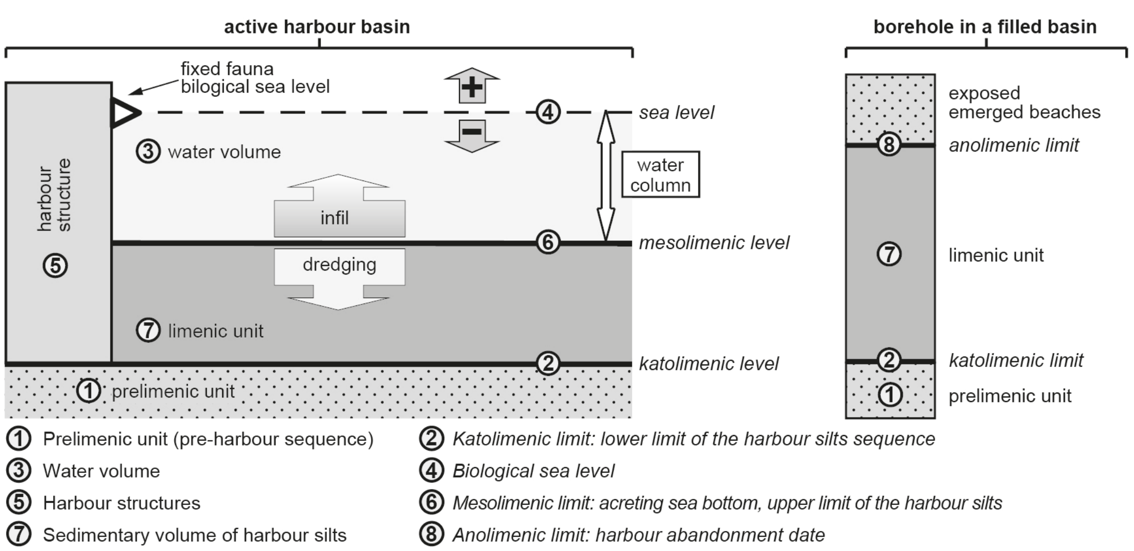

Fig. 1. Comparative stratigraphy of the harbour basins in marine and deltaic contexts and their immediate environment.

is the ideal technique for carrying out harbour excavations, but they are costly to build. However, the use of a core drill enables a complete stratigraphy of the sediments of satisfactory quality, to be obtained (Goiran and Morhange, 2003). Most harbour basins contain a dark muddy sediment characteristic of a protected environment, the 'limenic facies'. The palaeoenvironmental indicators are well preserved (fauna, pollen, charcoal, plant macro-remains, seeds...) and the radiocarbon dates can be reliable as they can be obtained from different materials. The geoarchaeological study of an ancient harbour relies on the evidence provided by three stratigraphic units (sedimentary facies): the pre-harbour unit, the harbour or limenic (from the Greek *limenos*, harbour) unit, and the post-harbour unit, and by the study of the contacts between these unit. The question of the biological marine level and the bio-indicators will be discussed. This outline of the theoretical evolution is illustrated by three field studies: Alexandria, in a maritime context (Egypt), *Portus* (*Ostia*, Rome), in a fluvio-marine context, and Avaris (Egypy), in a fluvio-deltaic context.

Elements of terminology and methodological approach

Terminology of the sedimentary facies

The study of the pre-limenic (or pre-harbour) unit enables the type of environment that existed before the harbour to be understood. Two situations can occur when the bedrock consists of soft sediments. (i) The top part of this unit is missing, which reveals the excavation operations that created the basin, or (ii) a stratigraphic continuum exists between the pre-limenic and the limenic units. This indicates that the environment was deep enough for the ships. If the pre-limenic sediments are preserved, it becomes possible to study the chronology of human occupation (geochemistry of lead, pollen) and to characterise the landscape that existed before the harbour was built (lagoon, meander, etc.). The limenic (or harbour) unit corresponds to sediments that accumulate in the basin. In the case of a protected harbour, the unit is characterised by compact mud ('plastic' mud) of a dark grey to blackish colour. This facies is typical of calm, confined, almost anoxic environments. The average rate of sedimentation (or ARS) is often rapid, approximately 1 cm yr^{1}. In the case of an open harbour or pre-harbour, the unit is organised in banks of fine to average sand. It is thus not rare to find gaps in the sedimentation, which may correspond to phases of re-excavation, cleaning or dredging (Marriner *et al.*, 2010). The meta-limenic (or post-harbour) unit, situated above the limenic unit, is formed after the abandonment of the harbour. Depending on the situation, the transition between facies (dune sands, alluvia) can be clear or progressive. The study of the stratigraphy thus provides new information on the nature and temporality of the harbour's decline.

The terminology of sedimentary boundaries

Four boundaries provide a framework for these three sedimentary units (Fig. 1). Their recognition enables the history of the basin when it functioned as a harbour to be better understood:

- The kato-limenic boundary indicates the foundation of the harbour. It corresponds to the contact point of the pre-limenic and the limenic units. It is often characterised by an abrupt variation in the facies (change in texture and/or colour).
- The ano-limenic boundary corresponds to the date of abandonment of the harbour. In the case of a progressive abandonment of the harbour basin, this boundary is more apparent in the stratigraphy as a sedimentary unit of transition between limenic (harbour) and meta-limenic (post-harbour).
- The meso-limenic boundary characterises the bed of the harbour basin (called marine bottom or channel bottom).

When the basin began to function, the meso-limenic and kato-limenic boundaries are the same. With the progressive accumulation of the sediments in the basin, the meso-limenic boundary follows the accretion of the bed of the harbour. Finally, the latter joins the marine or fluvial level, and the basin is thus definitively filled. Whilst the basin is in use, the altimetric difference between sea level and the meso-limenic boundary provides the height of the water column (or accommodation space). This figure can then be compared with the draughts of ships (Boetto, 2010).

Finally, sea level or fluvial level must be determined or estimated by four indicators. (i) Biological indicators: this is indicated on the quays (harbour structures) by the fixed marine fauna. Measurement of the highest level of the presence of these organisms gives the position of the average sea level for a given period. The following paragraph develops this aspect. In a context of a weak tide, the measurement is in terms of centimetres. (ii) Morphological indicators: the quays are cut into by erosion (notch), measurement being in terms of decimetres. (iii) Archaeological indicators: points of mooring, wharf paving, here measurement resolution is in terms of decimetres or metres. (iv) Textual indicators: use of devices for measuring the ancient high-water levels.

Contribution of marine fauna to the study of an ancient harbour

Macrofauna

By applying an updated approach to the study of sessile (fixed fauna) and vagile (un-fixed fauna) malacofauna assemblages, it is possible to analyse the biocoenoses that were present in ancient harbour environments as well as those peripheral to the harbour structures (Fig. 2). The biocoenoses organise themselves in belts or bands of which there are three levels or stages:

(i) The supra-littoral stage, as touched by the sea spray, does not provide much geoarchaeological information.

(ii) The medio-littoral stage corresponds to the tidal range (40 cm at the sites of Alexandria and *Portus*) and the play of the waves. Its lower sub-stage is either submerged (high tide) or drenched by the waves (low tide). Its lower edge corresponds to a level in which the populations are always submerged (Peres, 1967). The sessile marine macrofauna (fixed fauna and those that bore) colonise the harbour structures and leave traces, which become useful indicators in geoarchaeology (Pirazzoli and Thommerert, 1973; Morhange *et al.*, 2001). Thus the average biological sea level corresponds to the border between the medio-littoral biocoenosis and the infra-littoral biocoenosis (Laborel and Laborel-Deguen, 1994). In a harbour basin, where the waters are relatively calm, a narrowing of the stages of the fauna may be observed and the average biological sea level may thus be measured with a margin of accuracy of less than a decimetre (±5-10 cm). However, on a breakwater that is more exposed to the swell, the medio-littoral stage is more developed and higher in comparison to the fauna of the interior of the basin. In conclusion, to obtain the biological sea level of an ancient quay it is necessary: (i) to measure the upper band of the fixed fauna, (ii) to define the species or genus observed (barnacles, fixed molluscs, oysters), (iii) to record the exposure (battered or calm), and (iv) to take samples of these organisms for radiocarbon dating. Finally, comparison with the biological sea level observed in the present harbour or on the littoral is necessary to calculate the speed of the relative variation of the sea level. Deltas subside down under their own weight and so some harbour sites are thus subject to subsidence such as at *Portus*. In certain cases abrupt collapse occurred as at Alexandria. The use of the word 'relative' signals estimates of only the difference in height between the ancient sea level and the present one, without taking into account complex factors that are part of the subsidence phenomenon (isotasy, eustasy, etc.).

(iii) The infra-littoral stage, permanently submerged and whose lower edge corresponds to the depth of light penetration, also provides information on palaeoenvironments and can reveal the impact of the construction of harbour structures on their biotope. For these organisms, it is possible to outline zones (Peres and Picard, 1964; Peres, 1967). The biocenosis of superficial Muddy Sands in Sheltered Waters (MSSW) presents muddy sand. It is usually found at a depth of less than 4.5 m in the zones protected by a barrier that is natural (mass of *Posidonia* or seagrasses) or artificial (dyke, breakwater). This is the biocoenosis typical of calm harbour basins. It is often associated with a lagoonal, euryhaline and eurythermal biocoenosis (LEE), which is found in river mouth zones and near coastal ponds and lagoons. The organisms of this biocoenosis develop in sandy and muddy environments. Fine Sands in Shallow Waters (FSSW) constitutes the 'upper beach' and extends from the highest point of the infra-littoral stage to a depth from 2.5 m to 3 m; it relates to large beaches of submerged fine sand. The biocoenosis of coarse sand and fine gravel under bottom currents (SGBC) develops in an environment of high hydrodynamic activity. The currents allow the development of this biocoenosis, also found in the channels between the Posidonia.

The construction of a harbour basin in antiquity causes, depending on the particular site, (i) the disappearance of the LEE biocoenosis when the harbour is created in a lagoon or a swamp, (ii) the disappearance of the FSSW biocoenosis when the harbour is built offshore, (iii) the sudden widespread appearance of the MSSW biocoenosis, (iv) the appearance of a bioaccumulation of shells of species that develop on a hard substratum and reveal the presence of breakwaters, and (v) a reinforcement of currents on the external marine face of the harbour structures that causes a development of the SFBC biocoenosis and an erosion of the *Posidonia* meadow (Bellan-Santini, 1996). To this can be added the information provided by freshwater species sometimes found in the samples. In the case of rivers, the fauna is distributed according to the speed of the current, the granulometry of the sediment, the quantity of incidental light, the transparency of the water, and the richness of nutrients.

Ostracofauna

Micropalaeontology is used as a method of investigation in archaeology principally using groups such as the benthic Foraminifera, and especially the

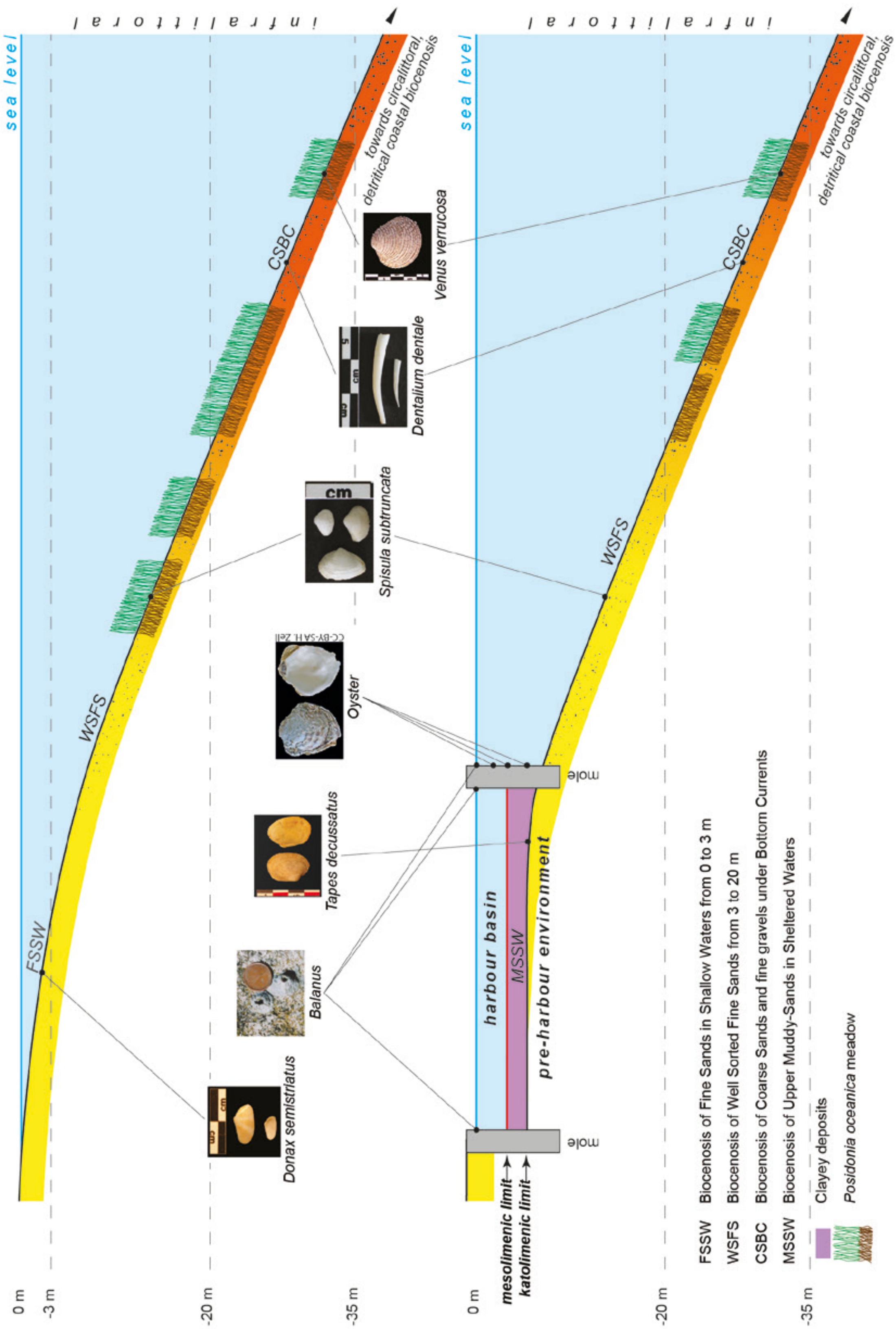

Fig. 2. Impact of the harbour structures on the marine biocoenoses (before/after).

Ostracoda, which are used in this case. These are small crustaceans that live in all environments where water is present. Their bivalve carapace, composed of magnesian calcite, fossilises very easily. Their ubiquity, small size (<1 mm), their diversity and species composition, which varies qualitatively and quantitatively depending on the physical-chemical, biological and trophic parameters of the environment, all make them excellent indicators of the variations in these parameters. Their use in the study of historical sequences appears thus to be a valuable element in characterising human impact, particularly in the coastal zones where harbours were constructed, modifying the natural landscape. The small size of the ostrocods permits a statistical validation that is comparable to that of pollen. The study of many samples taken in present-day environments as well as that of several dozen borehole-samples taken from archaeological sites has enabled determination of the fauna typical for different biotopes. Depending upon their quantitative and qualitative characteristics, the ostracofauna provide six types of information: (i) the number of individuals provides information on the trophic character of the environment and on hydrodynamics; (ii) the diversity of species is characteristic of the chemical stability of the environment (salinity, ionic stability). Thus, in freshwater or seawater the diversity is maximal, whereas it is dramatically reduced in euryhaline water (a proportion of 30 to 2). Stable brackish waters (the Caspian, for example) show a reduction of genera; (iii) the composition of communities of species is a function of the salinity, and then of water mass parameters (depth, freshwater present…); (iv) the size of the faunas is an indication of transport and of sorting: a fauna containing both adults and juveniles of one species is very probably 'in place'; (v) the analysis of stable isotopes (O and C) in the lagoonal and coastal environments provides information on the precipitation-evaporation equilibrium. Analysis of the stable isotope composition can provide valuable information from faunas *in situ*.

The contribution of granulometry

In a geoarchaeological context, the size and sorting of sedimentary particles provide information on the processes of transport and deposition, for marine, fluvial as well as deltaic environments. After analysis using laser micro-granulometry, statistical indications were used (Trask, 1932; Folk and Ward, 1957; Folk, 1966) on all the stratigraphy in order to reconstruct palaeoenvironmental evolution. The pre-limenic unit is often composed of sediments regarded as natural, in which the anthropogenic influence is minimal. The environment is generally 'open' and crossed by currents, which result in histograms of unimodal frequencies, a relatively large median diameter and high sorting. During the harbour sedimentation sequence, the granulometric histogram, can be multimodal (heterometric), due to enrichment in fine sediments related to artificial protections. Finally, the meta-limenic (or post-harbour) unit belongs to a return to natural dynamics: the histograms are again unimodal and sorting becomes higher again, even very high in certain cases, due to aeolian activity.

The maritime harbour of Alexandria (western edge of the Nile delta, Egypt)

Alexandria, founded in the 4th c. BC, had two basins, one on each side of the Heptastade, a causeway linking the island of Pharos to the town. A third basin has been reported in the western harbour, called *Kibotos*.

In the eastern harbour of Alexandria (the *Magnus Portus*), the pre-limenic phase corresponds to a marine bay filled with fine whitish sediments dating to between the 11th and 9th c. BC. This environment, calm yet open to the sea (lagoonal marine ostracofauna), was related to both the morphogenesis of a tombolo, which acts as an obstacle and the presence of two capes and some reefs, which reduce the strength of the currents. The Hepastade was built on the top part of this tombolo (Goiran, 2001). In the eastern bay, the limenic facies corresponds to a muddy facies, rich in gypsum and in the fauna of a confined environment. This homogenous harbour unit shows a high ARS (1 cm yr^{-1}; Stanley and Bernasconi, 2006). The harbour basins of the periphery of the eastern bay of Alexandria are 8 m below the ancient sea level. The latter was positioned (for the eastern bay) at about 6.5 m below the present sea level (Goddio *et al.,* 1998; Goiran, 2001). At the end of the Byzantine period, the depth of certain basins at Alexandria was no more than 2 to 3 m at the most. The post-harbour unit consists of very rough sediments, including branches of coral and fragments of shell debris. It belongs to a particularly violent stormy episode or an event of tsunami type that occurred between the 8th and the 11th c. AD.

A comparison with the western harbour of Alexandria (the harbour of *Eunostos*) reveals some differences in the sedimentary facies, and therefore in the exposure and in the development of the harbour. Before the construction of the harbour, the bay was

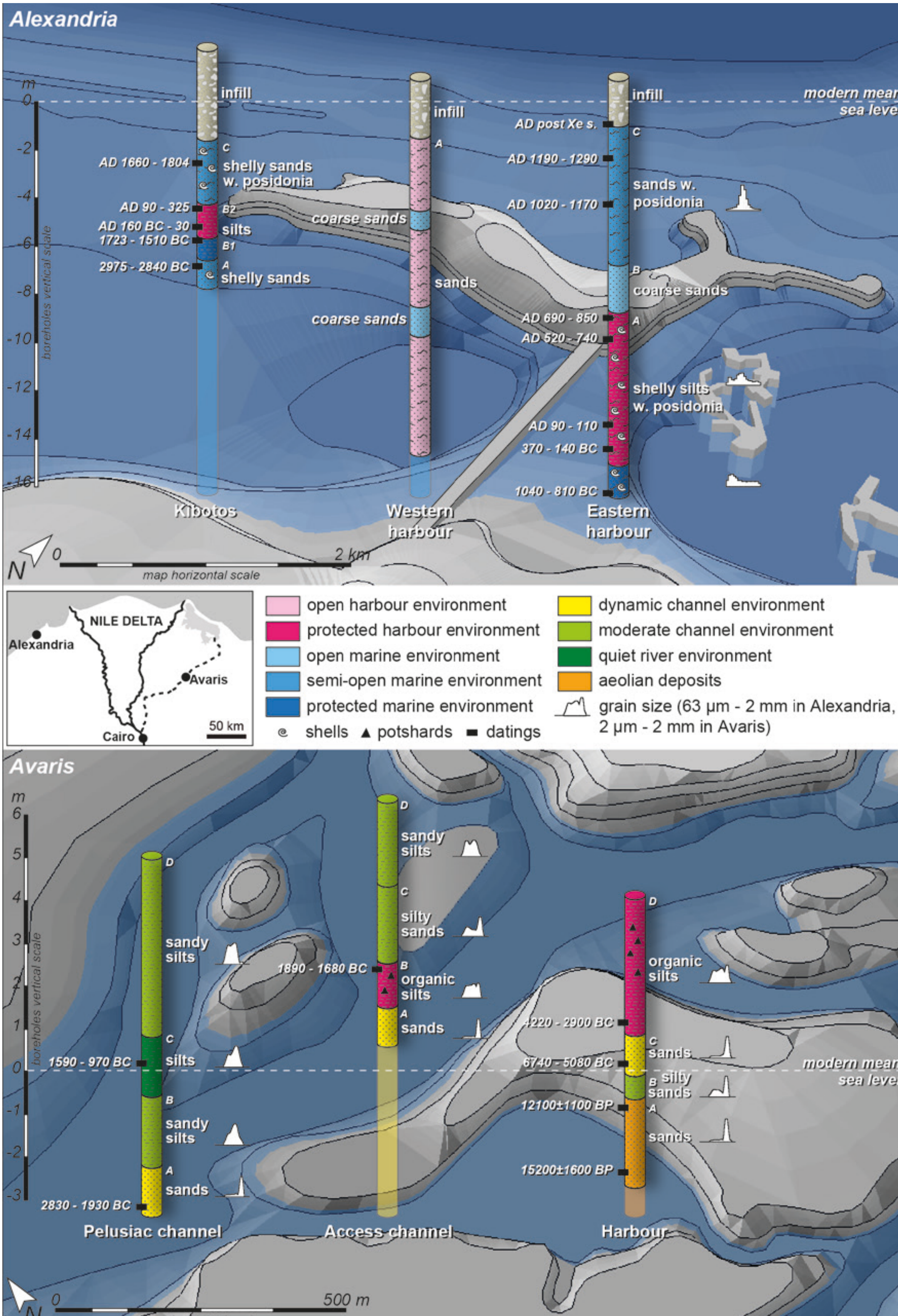
Alexandria
m
0
-2
-4
-6
-8
-10
-12
-14
-16
boreholes vertical scale
infill
shelly sands w. posidonia
silts
shelly sands
AD 1660 - 1804
AD 90 - 325
AD 160 BC - 30
1723 - 1510 BC
2975 - 2840 BC
C
B2
B1
A
coarse sands
sands
coarse sands
infill
AD post Xe s.
AD 1190 - 1290
AD 1020 - 1170
sands w. posidonia
coarse sands
AD 690 - 850
AD 520 - 740
shelly silts w. posidonia
AD 90 - 110
370 - 140 BC
1040 - 810 BC
modern mean sea level
Kibotos
Western harbour
Eastern harbour
N
0
2 km
map horizontal scale
NILE DELTA
Alexandria
Avaris
Cairo
50 km
open harbour environment
protected harbour environment
open marine environment
semi-open marine environment
protected marine environment
shells
potshards
datings
dynamic channel environment
moderate channel environment
quiet river environment
aeolian deposits
grain size (63 µm - 2 mm in Alexandria, 2 µm - 2 mm in Avaris)
Avaris
m
6
5
4
3
2
1
0
-1
-2
-3
boreholes vertical scale
sandy silts
silts
sandy silts
sands
1590 - 970 BC
2830 - 1930 BC
D
C
B
A
sandy silts
silty sands
organic silts
sands
1890 - 1680 BC
organic silts
4220 - 2900 BC
sands
silty sands
sands
6740 - 5080 BC
12100±1100 BP
15200±1600 BP
modern mean sea level
Pelusiac channel
Access channel
Harbour
N
0
500 m
map horizontal scale

Fig. 3. Stratigraphy of the harbours of Alexandria and Avaris, Egypt.

more open to the sea and received sand. The limenic unit consists only of fine sand, not mud. This sedimentary composition can explain the engineers' decision to construct, at the heart of the harbour of *Eunostos*, a true protected harbour, the *Kibotos*, which has never been precisely located. However, a borehole sample appears to have been taken through this interior basin (or in its immediate proximity). In fact, a sequence of dark grey mud appears between the 2nd and 1st c. BC (Hellenistic period) and ends between the 3rd and 4th c. AD. This protected environment shows an ARS (0.5 cm yr^{-1}) two times less than in the eastern bay, which suggests either less sedimentary deposits or more frequent dredging of the sediments. Let us now compare the harbour complex of Alexandria with that of *Portus*.

The fluvio-maritime harbour of *Portus* (*Ostia*, the Tiber delta)

Portus consists of two coalescent harbours (Fig. 4). The first, the harbours of Claudius, was founded in the 1st c. AD. Its vast basin (about 200 ha) was subject to storms and to silting-up. Claudius then provided his harbour with a *darsena,* a highly protected basin. A second harbour, hexagonal in shape, was then built in the 2nd c. AD under Trajan's rule. The borehole samples recovered in the basins show sedimentary stratigraphy that confirms certain elements but invalidates others.

The borehole samples reveal that the basin of Claudius did not fill up with mud but rather with light grey sand (SFBC). It thus corresponds to a pre-harbour and not a protected harbour. In its central part, the basin of Claudius attained a depth of approximately 7.5 m below the ancient sea level. The radiocarbon dates obtained show a relatively low TSMA, 0.5 to 0.7 cm yr^{-1}. However, the borehole samples obtained in the access channel and at the entrance to the hexagon reveal a homogenous dark grey clay-silt stratigraphy, which is typical of a calm and well-protected environment (SVMC). From west to east, the depth of the channel decreases, from a depth of -8 m and -7.5 m

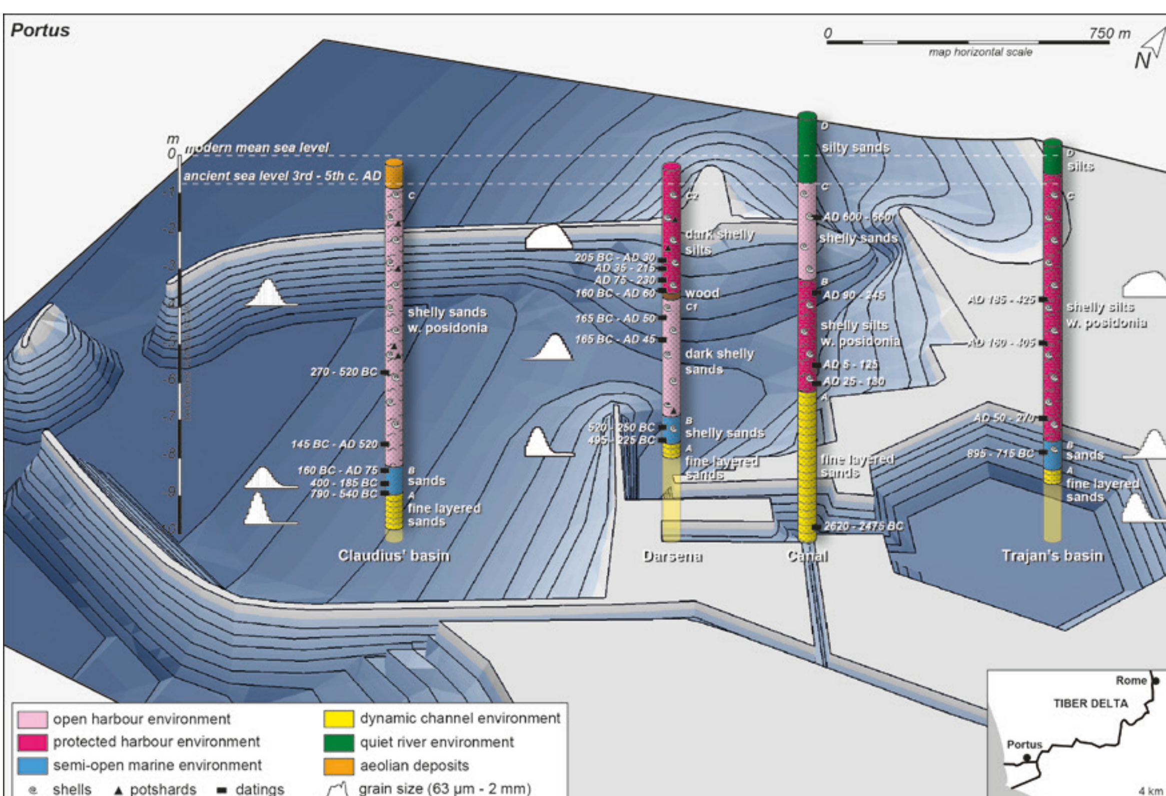

Fig. 4. Stratigraphy of the harbours of *Portus*, Tiber delta, Italy.

to -7 m and -6.5 m at the entrance to the hexagon. The ARS is approximately 1.5 cm yr^{-1}, that is, twice that measured in the offshore harbour of Claudius. The construction of a second basin, more inland, by Trajan's engineers, is therefore more related to a problem of the sustainanbility and design of the first basin, which was too open to the marine influences of the open sea (storms, swells, etc.). The study of the filling in of the *darsena* reveals two facies. In the lower part, a sandy marine unit developed (SFBC), typical of a sandy limenic facies of an open harbour with a depth of 6 m. The second unit consists of mud typical of a muddy limenic facies (SVMC) that is contemporary to (or slightly later than) the period that the Claudian harbour functioned. This evidence enables the *darsena* to qualify as a "true" harbour basin *stricto sensu* but one with little depth, not more than 3 m below the ancient sea level. Finally, the canal *di collegamento* between *Portus* and the *fossa traiana* (rich in freshwater ostracods) has a depth of 5.5 m below the ancient sea level (Salomon *et al.*, 2012). For the first time, a bathymetric map of *Portus* has been made (Fig. 2) by compiling all the data from the different borehole samples (Arnoldus-Huyzendveld, 2005; Bellotti *et al.*, 2007; Giraudi *et al.*, 2009; Goiran *et al.*, 2010; Keay and Paoli, 2011; Morelli, 2011). The pre-limenic unit corresponds to a fluvio-deltaic environment (alternation of sandy alluvial and sterile alluvial deposits yellow-gray in colour). This environment dates to the 8th and 10th c. BC and is truncated by the harbour sequence (limenic unit). During the digging operations, the engineers destroyed the upper part of the pre-limenic stratigraphy in making their harbour 7 m below the ancient level of the marine floor.

The fluvio-deltaic harbour of Avaris (Nile delta, Egypt)

The city of Avaris, situated on the Pelusian palaeobranch of the Nile River, which had been flowing since 4500 BC (Sneh *et al.*, 1986; Stanley and Warne, 1998), accommodated the main harbour of the Hyksos (Bietak 1975), who reigned over Egypt between 1674 and 1548 BC. Two environments can be differentiated (Fig. 3): (i) the main channel, forming a wide meander north-west of the site, and (ii) the harbour environment, composed of the basin itself, at the heart of the city, and the short channel linking it to the Pelusian branch (Forstner-Müller, 2009; Tronchère *et al.*, 2012).

The fluvial energy of the branch appears to have continually decrease over time. Unit A (2830-1930 BC; the dates were obtained by OSL) reveals a high-energy (sand, gravel) environment. A first lowering of energy is indicated by an increase in the alluvium-clay fraction (unit B). A third unit with finer deposits (C), dated to 1590-970 BC, posterior to the Hyksos occupation, indicates the end of activity in the Pelusian branch at Avaris. The apparent average rate of sedimentation is about 30 cm yr^{-1}. Unit D consists of fine deposits of the flood plain (about 1-3 m). Knowledge of the natural fluvial facies was a crucial element in the discrimination of the harbour facies described.

The pre-limenic stratigraphy consists of three units: (i) the Pleistocene substratum (Unit A of the future harbour zone), dated to 15200-12000 BP (Tronchère *et al.*, 2012), and a vestige of a natural depression created by aeolian deflation, and (ii) a sedimentary unit of fluvial origin in which two stages of sedimentation may be distinguished. The oldest (Unit B), composed of alluvial sand, indicates the beginning of outflow. The youngest (C for the 'harbour' borehole sample and A in the segment linking the depression to the main channel), dated to 6740-2900 BC, presents a higher level of fluvial energy. The accumulation in the enlarged channel began before that of the main channel, a frequent asynchrony in anastomosed systems (Makaske 2001), and could have been locally accentuated by the large width of the pre-limenic channel. (iii) The third unit is characterised by a blackish silty-clayey texture, rich in organic material and plant debris which was deposited about 4220-2900 BC (Unit D in the harbour itself, Unit B in the access channel). The low energy of the channel related to the morphology of the depression created a protected zone favourable to the creation of a harbour.

The limenic facies, composed of blackish mud, corresponds to Unit E (of the 'harbour' borehole sample and B of the 'access channel' borehole sample). The unit is rich in sherds of the Hyksos period. The geomagnetic survey shows a series of warehouses, aligned and open towards the harbour basin. In other words, a calm environment of a muddy type was in place here before the foundation of the harbour and guided the building of the latter. The thickness of the limenic deposits is indicative of anthropogenic maintenance, which prevented obstruction of the channel and ensured a flow of water that was enough for embarkations. A date taken at the top of the limenic sequence of the access channel confirms the archaeological observations and validates the existence of this manner of access to the harbour during its period of activity: 1890-1680 BC, which is contemporary to the Hyksos reign.

There is not, properly speaking, a meta-limenic unit in the port zone itself, the muddy deposits being still present today. However, in the access channel, the limenic facies is covered by alluvia from flooding, probably from the main channel (Unit C), which were then shifted by modern agricultural activity (Unit D).

Conclusions

These examples of harbours built in differing deltaic environments illustrates both the similarities and the differences found in palaeoenvironmental contexts of harbour construction. The developing outline presented in the introduction will thus continue to be clarified (Fig. 1) and this palaeoenvironmental approach has the value of illustrating the main environmental elements the study of a maritime or fluvial harbour complexes in antiquity.

In a maritime context, the interior basin is often dug into the Holocene geological base and a hiatus is observed in the sedimentation (Fig. 2). The kato-limenic limit/boundary then corresponds to a gap and cannot be considered to be the surface of the foundation of the port. The altimetric difference between sea level and the kato-limenic limit is optimal, as it is in calm mode, and the medio-littoral stage corresponds to the tidal range. The filling-in is rapid (1-1.5 cm yr^{-1}) and prompts investigation of the cleaning or dredging phases in the history of the basin.

For an offshore basin, a stratigraphic continuum is generally observed between the pre-limenic and the limenic units (Fig. 3). The kato-limenic limit thus appears more as a break in the sedimentation and not as a gap. The ARS of the grey sands approaches 0.5 cm yr^{-1}. This slower rate in the basin can be explained by the low potential of compaction of the sand, by equilibrium of the sediment quantities, and/or by more frequent dredging. In all cases, the offshore basin retained a consistent depth. Finally, the offshore basin is indicated by both the presence of notches caused by marine erosion and by an altimetric increase in the presence of medio-littoral populations of organisms.

In a fluvial context (Fig. 4), the water column is subject not to the tidal range but to the variation in depth between low tide and the flow level of the river, a factor that is difficult to determine in an archaeological context. Differentiation between the harbour deposits, poor in bio-indicators, and natural deposits is furthermore made more complex by the stage of sedimentary accretion of the river and the neighbouring presence of the alluvial plain with its fine sands. When the channels are active (high energy), the coarse deposits (sand, gravels, even pebbles) of the river are clearly differentiated from the fine sediments of the protected harbour basin. However, the general decrease of channel flow leads to fine sedimentation comparable to harbour deposits, which tends to make the facies in the flood plain uniform.

Acknowledgements

ANR GEZIRA n° BLAN08-1_308860, ANR POLTEVERE n° JSHS3-002 01, Austrian Archaeological Institute of Cairo, Cealex USR 3134, University of Alexandria, IFAO, Archaeological Service of Ostia, Ecole Française de Rome, British School at Rome. We thank D. Laisney (CNRS MOM) for his help with the figures and E. Willcox for translation from the French.

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