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Taken from the sea, reclaimed by the sea: The fate of the closed harbour of Elaia, the maritime satellite city of Pergamum (Turkey)

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ABSTRACT

During Hellenistic times, when the Pergamenian kingdom was prospering, Pergamum was operating an important harbour, used by merchants and military at the city of Elaia. This paper focuses on the development, utilisation and decay of the closed harbour of Elaia, which is discussed in the context of the landscape evolution of the environs of the ancient settlement. Based on geoarchaeological, archaeological and literary evidence, the construction of two harbour moles in order to provide shelter against wave action and enemies can be attributed to the early Hellenistic period. Geoelectric measurements revealed the construction profile of the moles. Coring evidence indicated that together with mole construction, a greater area of the formerly shallow marine and sublittoral terrain was consolidated, most probably to create space for harbour installations. The closed harbour basin was used intensely during Hellenistic and Roman times. Later, continued siltation hindered further usage. In combination with the decline of the city of Elaia in Late Antiquity, this was the reason why the harbour was abandoned. Scenarios for the time of the maximum transgression of the sea around 2500 BC, the early Hellenistic times around 300 BC, and Late Antiquity AD 500, are presented.

1. Introduction

Many multidisciplinary studies have focused on ancient harbours along the Mediterranean coasts throughout the last decade: the Great Harbour of Ephesus (Kraft et al., 2000, 2007), the harbour of Tyre (Marriner and Morhange, 2006b; Marriner et al., 2007; Morhange et al., 2012), the seaport of Oiniadai (Vött et al., 2007), the harbour of Luni (Bini et al., 2009), the western harbour of Corinth (Morhange et al., 2012), Herod the Great's harbour at Caesarea (Reinhardt and Raban, 1999), and the harbour of Carthage (Gifford et al., 1992), just to mention a few. The importance of the topic is underlined by the fact that in August 2012 the German Research Foundation launched a priority programme to further investigate ancient harbours from Roman Imperial to Medieval times (DFG-SPP 1630).

This paper presents the results of the first geomorphological, geoarchaeological, geophysical, and geochronological research on the closed harbour of the ancient city of Elaia, which was also Pergamum's principal marine harbour. Its basin is situated at the foot of the city hill in the central northern part of the Gulf of Elaia (Figs. 1 and 2). The harbour was built during Hellenistic times according to historical sources and archaeological evidence. It is the only still visible ruin of Elaia, although it has almost completely been silted up with marine, alluvial and colluvial deposits (Fig. 3). The main objectives of this study are: (i) to investigate the siltation process of the closed harbour of Elaia in space and time; (ii) to compare this process within and around the harbour basin; and (iii) to provide a chronological framework for the construction of the moles from a geoarchaeological point of view.

2. Study area

2.1. Physical setting

The Bay of Elaia is the innermost part of the Gulf of Elaia (modern name: Gulf of Çandarlı). It is located between the Yuntdağ mountain complex to the east and the Karadağ mountain complex

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Fig. 1. Research area at the Aegean coast of Turkey. (a) Overview based on Landsat ETM+ 2005 with locations mentioned in the text; (b) General map of western Turkey with a selection of ancient and modern settlements.

on Kane Peninsula to the west (Figs. 1a and 2). The Kaikos River (modern Bakır Çay) debouches into the Aegean Sea between the Kane Peninsula and the Bay of Elaia by forming a cuspate delta. The slopes of the Yuntdağ Mountains border the swampy coastal plain to the east and to the north. The latter and the Bay of Elaia are very flat with a seafloor gradient approximating 0.5% (Aksu et al., 1987). A mean tidal range of ~20 cm was inferred for the Bay of Elaia by DGPS. This value is in good agreement with studies from similar embayments in the Eastern Mediterranean (Flemming, 1978; Anzidei et al., 2011). The innermost part of the gulf is protected from stronger wave action, even during winter storms, due to its sheltered position.

The Yuntdağ and Kozak mountain ranges consist of Palaeozoic–Mesozoic granites. The Bay of Elaia is part of the Aegean-Anatolian microplate. With the westward drift of the Anatolian Plate, several E–W oriented rift structures were formed in the late Miocene, such as the Bergama graben, and its tributary, the Zeytindağ graben (Fig. 2). This tectonic ensemble represents a fractured zone which was favourable for the evolution of the Kaikos valley (Vita-Finzi, 1969; Brinkmann, 1976; Aksu et al., 1987; McHugh et al., 2006). The ongoing subsidence is evident from drowned archaeological remains: (i) a Roman thermal bath complex on Kane Peninsula (Fig. 1a); and (ii) underwater wall structures in the south-western Bay of Elaia, probably dating to Late Roman times (Fig. 4a) (Seeliger et al., 2012).

2.2. Historical and archaeological background

The Pergamenian kingdom was highly influential in Asia Minor during Antiquity. Pergamum, its capital city, is often mentioned in contemporary sources together with other important cities including Troy (Troia) and Miletus (Fig. 1b). To date, the city is known for its unique archaeological finds, among others the Pergamum Altar, and for Aelius Galenus, one of the most famous physicians of ancient times (Radt, 1999; Cimak, 2009).

Following the Wars of the Diadochi after Alexander the Great's death in 323 BC, the House of the Attalids came to power in the Kaikos region until 133 BC. Under the reign of Eumenes II (197–159 BC), the Attalids governed the whole western part of modern Turkey (Hansen, 1971; Radt, 1999; Cartledge, 2004; Pirson, 2008; Cimak, 2009).

The 330 m high city hill of Pergamum dominating the surrounding Kaikos plain provided a strategic location for the foundation of a new city. Access to the Mediterranean Sea for traffic and

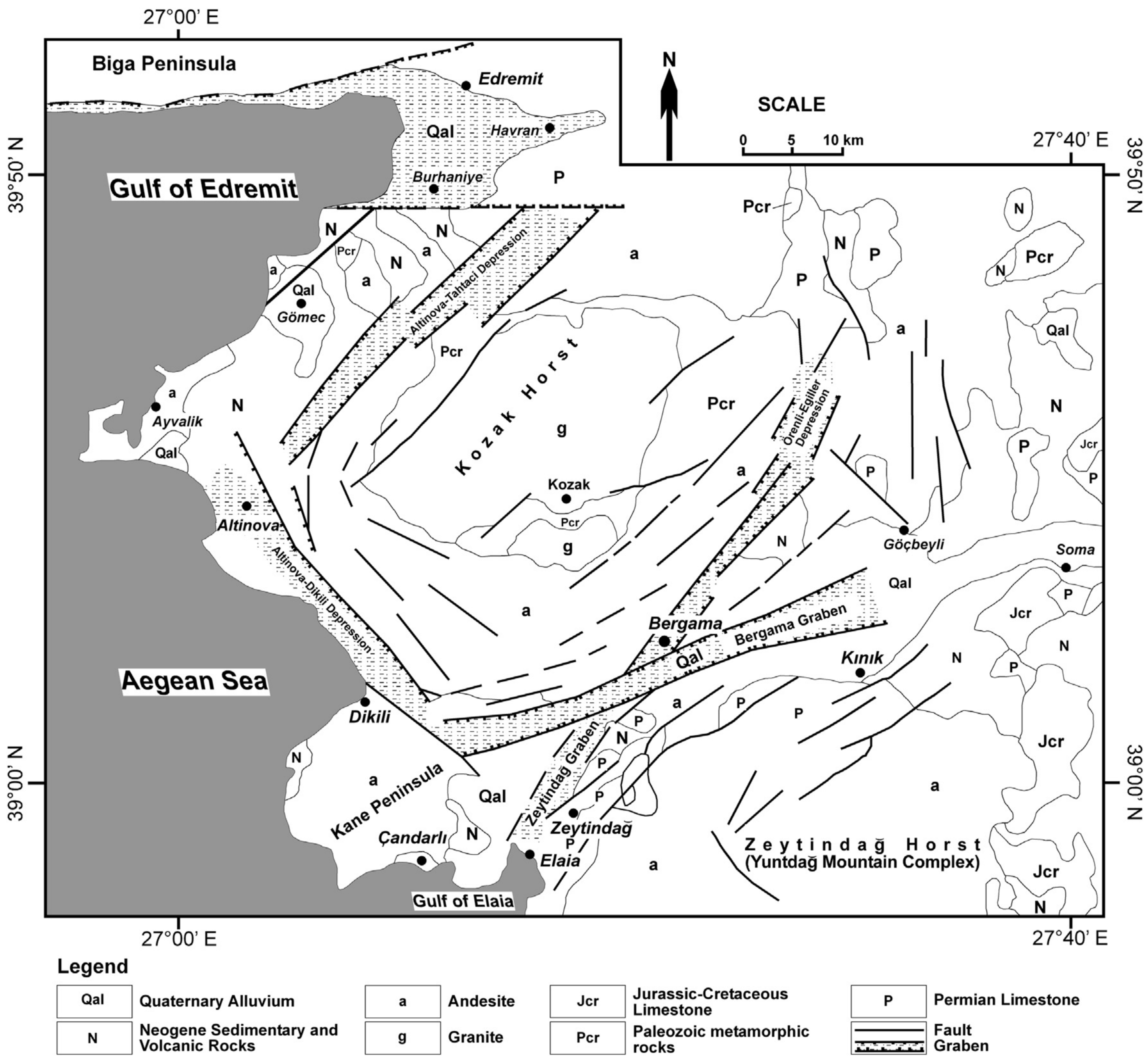

Fig. 2. Structural map of the research area and the surrounding mountain ranges. Source: Altunkaynak and Yılmaz (1998), slightly modified.

trade was provided through the acquisition of nearby Elaia, situated at the Aegean coast 26 km southwest of Pergamum, under Eumenes I (reign: 263–241 BC) (Radt, 1999; Pirson, 2004; Cimak, 2009). Strabo identified Elaia as the commercial harbour of the Pergamenians and as the military base of the Attalids (Strabo (2005), Geographica XIII, 1, 67 and XIII, 3, 5). Further literary evidence as well as archaeological findings confirm the relations between Elaia and Pergamum (Pirson, 2004, 2009).

Thus, Elaia was Pergamum's key portal to the Aegean Sea with regards to traffic, trading, and military actions, although also other naval bases existed, e.g. on the Island of Aegina. By the end of the 3rd century BC, Pergamum's navy encompassed at least 35 warships in the category of the so-called "fives" (*quinqueremes*) (Pirson, 2004). This is quite a small fleet as compared to coexisting naval bases of other poleis, e.g. on the Island of Rhodes or in Piraeus; it explains Pergamum's need for other bases (Pirson, 2004).

In the Archaic and Classical period, Elaia was of only minor importance: Herodotus does not mention the city in his list of the twelve Aeolian cities (Herodotus (2001), Historia I, 149). In the tributary lists of the Attic Delian League between 454 and 425 BC, it is quoted with a very low toll of 1/6 talent. Pergamum, and as a consequence Elaia as well, gradually lost their significance when Ephesus was nominated the capital of the Roman province of Asia in the 1st century BC (Pirson, 2004, 2008). Thus, Elaia's most prosperous time was clearly confined to the Hellenistic era when the city was under the rule of Pergamum (Pirson, 2008; Cimak, 2009).

A major outcome of the ongoing large-scale ceramic survey was that during Archaic and Classical times the settlement of Elaia was restricted to the central city hill, which is located northeast of the closed harbour (Figs. 3 and 4), and had continuously been settled since the Bronze Age (Pirson, 2010). The situation changed during Hellenistic and Roman times, when many areas surrounding the city hill were settled as well. The fortification wall and an internal wall (*diateichisma*) were erected in the Hellenistic period. The *diateichisma* divided the city into a densely populated area in the northwest around the central city hill and the closed harbour, and a sparsely inhabited area in the southeast. During Late Antiquity, the population of Elaia shrank and was contained within the boundaries of the city hill. Finally, the city was abandoned between the 6th and the 7th century AD (Pirson, 2010).

In addition to its maritime and economic relevance, Elaia played an important strategic role in securing the southern entrance to the Kaikos plain which was the main land of the Pergamenian kingdom. As the foothills of the Yuntdağ mountains reach the sea by creating a steep slope, there is only a narrow passage north of Yeni Şakran (Fig. 1a) that could easily be controlled by the Pergamenian forces based in Elaia (Pirson, 2004). The topographic

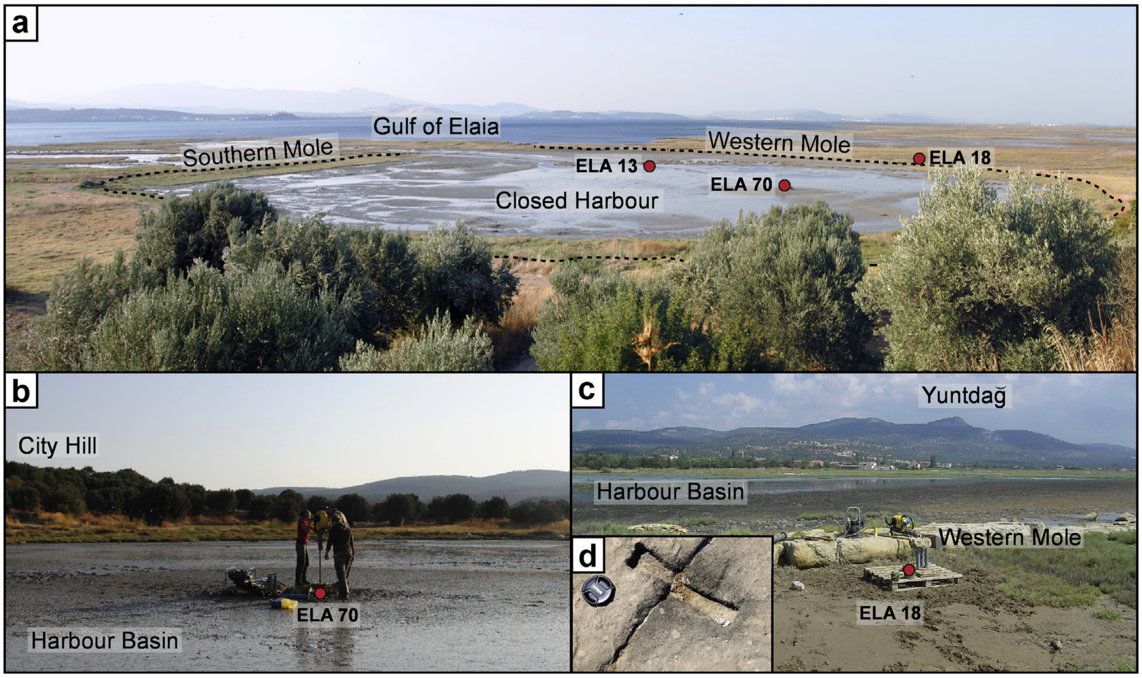

Fig. 3. The closed harbour of Elaia. (a) Overview from the top of the city hill; (b) Location of coring site ELA 70 inside the harbour basin; (c) Western mole with location of coring site ELA 18 outside the harbour basin; (d) Recess for the former wooden dovetail cramp on top of the mole. Photographs: Bartz and Seeliger (2010, 2011).

situation is slightly comparable to that at Thermopylae in Greece (Kraft et al., 1987): a narrow passage flanked by high mountains on the one side and the sea on the other.

Located 18 m higher than the coastal plain, the city hill of Elaia played an important role, at least from the archaeological point of view, as it hosted the major settlement centre from the Bronze Age up to the abandonment of the city in the 6th/7th century AD. The closed harbour basin is located to the southwest of this hill (Figs. 3b and 4a). This harbour was protected against wave action by two moles, a southern one and a western one. The upper section of the western mole can still be seen above the ground. It is constructed from ashlar masonry made of yellowish calcareous sandstone blocks up to 1.70 m × 0.80 m × 0.40 m each. Only the cap of the mole which was always above sea level is visible. Its basement most likely consists of an embankment of dumped rubble and rocks. As soon as this artificial structure had reached the sea surface, the ashlar wall was built on top of it, up to an original height of at least 2 m above the palaeo-sea level. The second mole in the southeast of the harbour basin was detected in the geophysical survey, and its construction style must have been of the same kind (Pirson, 2004, 2010).

The closed harbour was most likely incorporated into the fortification wall of Elaia. The basin had a length of about 200 m from east to west and about 250 m from north to the south; it encompassed an area of approximately 4.8 ha. The seaward entrance was some 45 m wide, and located in the south of the harbour basin, protected from the prevailing western winds (Pirson, 2004, 2008).

The building techniques of the western mole with ashlars joint together by wooden dovetail cramps (Fig. 3d) as well as lack of *opus caementitium* (Roman concrete) as building material date the mole to pre-Roman times. *Opus caementitium* was introduced to Asia Minor not before the middle of the 1st century BC (Ganzert et al., 1984; Waelkens, 1987). As written sources state, Elaia was only of minor importance in the Archaic and Classical periods, as confirmed by the archaeological survey (Pirson, 2010). Therefore, Elaia could not have implemented such a building programme during those centuries. This leads to the conclusion that the harbour basin with its two moles was most probably constructed in Hellenistic times.

3. Methods

The detailed study of lateral and vertical changes of sedimentary facies from nearshore sediments is a well-established approach to reconstruct palaeoenvironmental variations during the Holocene. To date, 78 terrestrial and semi-aquatic cores have been taken in the area since 2008 to decipher the palaeogeographic evolution and, in particular, to detect coastline changes. This article focuses on three vibracores drilled inside and adjacent to the closed harbour basin of Elaia.

Drilling was done with an Atlas Copco Cobra mk1 vibracorer (Fig. 3b). Closed steel auger heads with 1 m PVC inliner tubes (external diameter: 50 mm) were used for coring ELA 70, while cores ELA 13 and ELA 18 were performed with open steel auger heads (diameters of 60 and 50 mm, respectively). Preliminary sedimentological studies were carried out directly in the field, including grain size, colour (Munsell Soil Color Charts), texture, roundness, and carbonate content (10% HCl) (AG Boden, 2005). Bulk samples for laboratory analyses, as well as macrofossils and ceramic fragments for a later determination were taken from open sediment cores. All coring sites were levelled with DGPS (Leica GPS System 530; lateral and vertical resolution of $\leq$2 cm). The altitude above sea level is based on the local reference system PergSys05, established by the German excavation team of Pergamum in 2005; the values have to be height-corrected by −0.875 m due to an inaccuracy of the reference system (Seeliger et al., 2012).

In the laboratory the sediment samples were air-dried, ground, and sieved to separate the matrix material <2 mm for further analyses. The granulometry was measured with a laser particle sizer (Beckman Coulter LS13320) after the removal of the organic content with H_2O_2. For the calculation of grain-size parameters after Folk and Ward (1957), the GRADISTAT software (Blott and

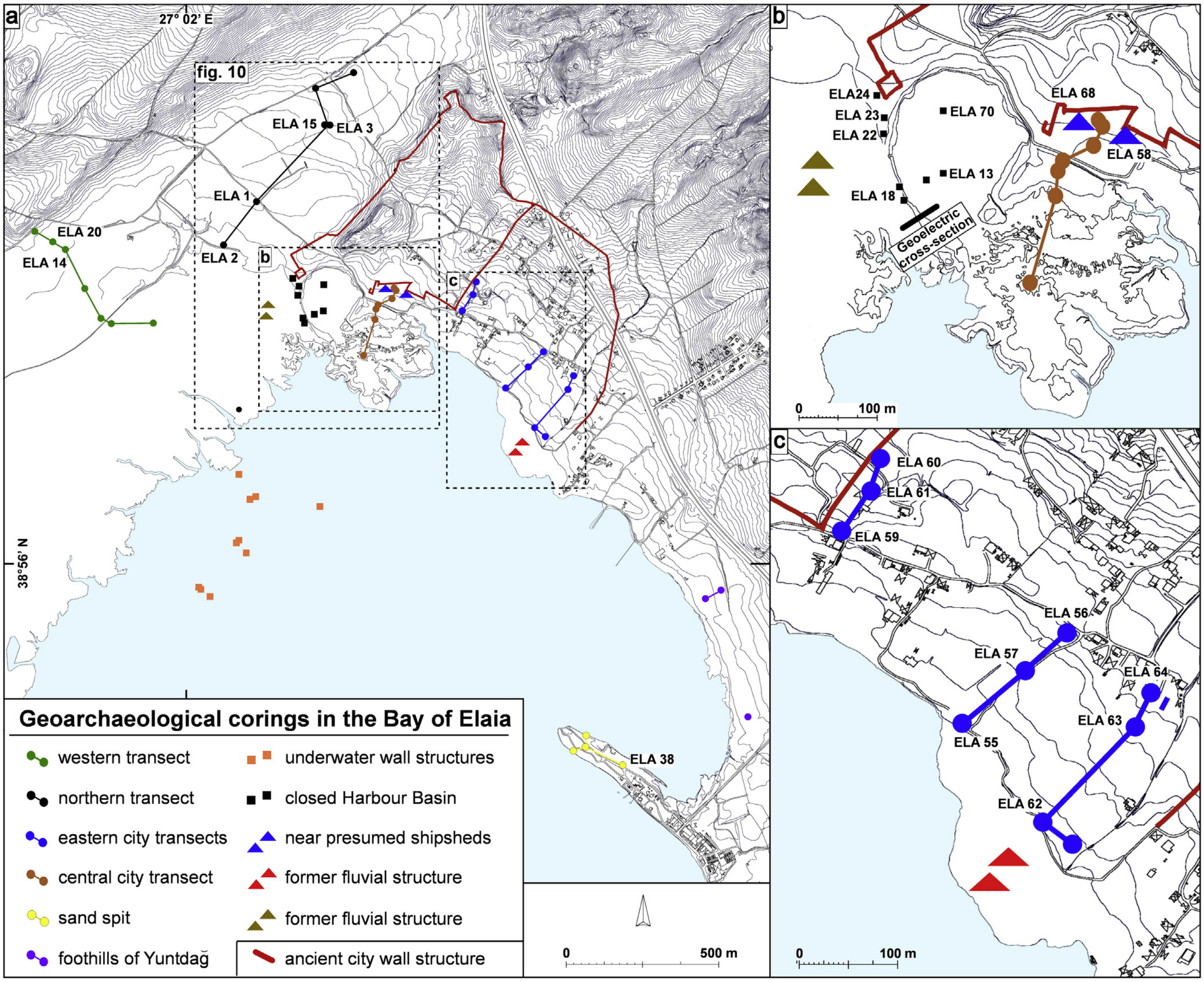

Fig. 4. Location of vibracores carried out in the Bay of Elaia 2008–2011. The maps are based on DGPS data levelled by the Pergamum excavation. (a) Synoptic view with the area of the city of Elaia; (b) Cores in the area of the so-called closed harbour; (c) Cores in the eastern part of Elaia.

Pye, 2001) was applied. Carbonate content was measured by a Scheibler device. The loss on ignition (LOI) was determined by oven-drying the samples at 105 °C for 12 h, and ignition in an annealing furnace at 550 °C for 4 h (Beck et al., 1995). The accuracy of the LOI parameter is widely discussed because two chemical processes may cause errors (Mook and Hosin, 1982; Heiri et al., 2001; Barillé-Boyer et al., 2003): the possible loss of CO_2 from carbonates consisting of inorganic material (Salehi et al., 2011), and the loss of structural water from clay minerals (Dankers and Laane, 1983). Both result in weight reduction not caused by loss of organic matter. A subsequent correction of the LOI values was not done in this study.

Measurements of the electrical conductivity were performed in an aqueous solution consisting of 15 g of sediment and 75 ml distilled water with a glass electrode (Mettler Toledo InLab®731-2m) (Beck et al., 1995).

A portable XRF spectrometer (Niton Xl3t 900 GOLDD) was used to determine total amounts of 25 elements with a vertical resolution of several decimetres (in cases of ELA 13 and 18) and 5 cm (ELA 70), respectively. Sodium (Na), an indicator for marine environments, is not detected with this XRF technique; it was measured by using atomic absorption spectrometry (AAS; A-Analyst 300 by Perkin Elmer).

These multi-proxy geochemical and granulometric analyses were primarily carried out in order to support the facies determination (cf. Ernst, 1970; Vött et al., 2002, 2004; Brückner et al., 2005, 2006, 2010a; Engel et al., 2009; Niwa et al., 2011).

Earth's electrical resistivity was determined with the RESECS multi-electrode system in order to detect the thickness and shape of the central harbour pier of Elaia. On profiles with a length of 47 m and an electrode spacing of 1 m, measurements with several electrode configurations such as Dipole–Dipole, Wenner and Schlumberger were done. The apparent electrical resistivity was determined as a function of the electrode geometry by the measuring instrument. Using the inversion software RESINV2D (Loke and Barker, 1995), the resistivity-depth distribution for each profile was inverted from the field data.

^{14}C-AMS age estimates based on wood, charcoal, seagrass, and marine gastropods were performed in the Center for Applied Isotope Studies (CAIS) of the University of Georgia at Athens (USA). For calibration, the Calib 6.1.1 software was applied with a marine reservoir effect of 390 ± 85 years and a ΔR of 35 ± 70 years (Siani et al., 2000). These ages are stated in calibrated years BC, AD, or BP, with a 2σ-standard deviation (Table 1). As the spatio-temporal variation of the marine reservoir effect for the Aegean Sea is still not known, the ^{14}C-ages of marine carbonates are estimates only. Diagnostic ceramics helped to improve the local chronology.

Table 1
Radiocarbon data set. AMS-^{14}C measurements were carried out at the Center for Applied Isotope Studies (CAIS) of the University of Georgia at Athens (USA).

Sample ID	Lab no. (UGAMS)	Material	δ^{13}C (‰)	Libby-age	Cal BC/AD (2σ)	Cal BP (2σ)
ELA 13/10HK	6038	Charcoal	−26.4	1640 ± 25	340–532 AD	1418–1610 cal BP
ELA 13/13HK	6037	Charcoal	−27.5	1750 ± 25	283–381 AD	1569–1719 cal BP
ELA 13/22H	6036	Wood	−27.4	2250 ± 25	391–209 BC	2158–2340 cal BP
ELA 18/7HK	6031	Charcoal	−24.5	1740 ± 25	240–381 AD	1569–1710 cal BP
ELA 18/9HK	6030	Charcoal	−25.0	1730 ± 25	245–384 AD	1566–1705 cal BP
ELA 70/66HK	11,130	Charcoal	−27.0	1960 ± 30	39 BC–121 AD	1829–1988 cal BP
ELA 70/80H	11,131	Seagrass	−18.2	2680 ± 30	647–178 BC	2127–2596 cal BP
ELA 70/122H	11,132	Seagrass	−17.7	5920 ± 30	4530–4204 BC	6153–6479 cal BP
ELA 70/144F	11,133	Marine gastropod	−0.7	7040 ± 30	5692–5422 BC	7371–7641 cal BP

4. Results

The coring in and around the closed harbour of Elaia was carried out in order to contribute its history with geoarchaeological evidence. In this context, the timing of the construction of the moles and the later siltation process were of particular interest. Here, cores ELA 70 and ELA 13, both from inside the harbour basin, and ELA 18 directly outside the western mole are described (Figs. 3 and 4).

4.1. Sediment core ELA 70 from inside the harbour basin

ELA 70 was cored inside the harbour basin, in the direct vicinity of the ancient city (38°56′35.34″ N; 27°02′19.04″ E; total depth: 9 m; elevation: 0.12 m b.s.l. [below present mean sea level]; for location see Figs. 3a,b and 4; for profile see Fig. 5). Neogene bedrock, compact yellowish calcareous sandstone, was reached at 8.03 m b.s. (below surface) (unit 1).

Between 8.03 m and 4.38 m b.s., unit 2 occurs, a dark to olive grey silty sand with graded bedding of pebbles at the base. The electrical conductivity shows strong variations between 4 and 27 mS; the values increase upwards to 5.08 m b.s. The Ca/Fe ratio shows remarkable fluctuations as well, with a decreasing upwards trend. The whole section is interspersed with seagrass (*Posidonia oceanica*) as well as broken shells, e.g. *Dosinia lupinus*, and gastropods. Three radiocarbon ages provide a chronological frame for this part of the core: a marine gastropod at 7.82 m b.s. yielded an age of 5692–5422 cal BC (7371–7641 cal BP; sample ELA 70/144F), *P. oceanica* at 6.72 m b.s. an age of 4530–4204 cal BC (6153–6479 cal BP; ELA 70/122H), and *P. oceanica* at 4.57 m b.s. was dated to 647–178 cal BC (2127–2596 cal BP; ELA 70/80H). The wide dating range of the latter sample is due to two facts: (i) The 2 sigma standard deviation is given which renders a confidence interval of 95.4%; and (ii) unfortunately, in this age range the ^{14}C-calibration curve has a plateau.

Between 4.38 m b.s. and the surface light grey clayey silts form unit 3. The mean grain size decreases to 30 μm. The Ca/Fe ratio drops to very low values as well, showing less variation than below. The electrical conductivity starts at high levels (30 mS), but decreases to 5 mS. A piece of charcoal at 3.77 m b.s. was ^{14}C-dated to 39 cal BC–121 cal AD (1829–1988 cal BP; ELA 70/66HK).

4.2. Sediment core ELA 13 from inside the harbour basin

Coring ELA 13 was carried out inside the harbour basin, 37 m to the east of the western mole and not far from the 45 m wide harbour entrance (38°56′32.18″ N, 27°02′17.76″ E; total depth: 10 m; elevation: 0.18 m b.s.l.; Figs. 3a, 4b and 6). In contrast to ELA 70, the lower units 1 (bedrock) and 2 (open marine environment) were not reached at this site. The lower 5 m of ELA 13 (very homogeneous clayey silts) are not shown in Fig. 6. Between 10 m and 3.10 m b.s., green to grey clayey silts form unit 3a. Numerous plant remains occur, with a clustering of seagrass (*P. oceanica*) at 6.75 m and 5.65 m b.s. This is reflected in the high LOI (12–13%). A piece of wood at 6.75 m b.s. dates to 391–209 cal BC (2158–2340 cal BP; ELA 13/22H). The appearance of habitat-specific bivalve and gastropod species (e.g., *Cerastoderma glaucum*) indicates a lagoonal environment.

Unit 3b (3.10 m and 1.80 m b.s.) consists of silty fine sand. The decreasing Na/Fe ratio correlates with decreasing LOI. Two pieces of charcoal at 2.55 m b.s. (283–381 cal AD, 1569–1719 BP; ELA 13/13HK) and at 1.92 m b.s. (340–532 cal AD, 1418–1610 cal BP; ELA 13/10HK) give a chronological framework.

The top of the section (unit 3c) is grey to greenish grey clayey silt and silty clay. In contrast to unit 3b, LOI increases (10–18%). The Na/Fe ratio shows remarkable alterations (0.6–1.2). The sedimentation pattern corresponds to the modern nearshore conditions in the basin of the closed harbour.

4.3. Sediment core ELA 18 from outside the harbour basin

ELA 18 was drilled outside the closed harbour basin, 2 m next to the western mole (38°56′31.45″ N; 27°02′16.66″ E; total depth: 3 m; elevation: 0.18 m a.s.l.; Figs. 3a, c, 4b, 7). It was performed to render particular information about the characteristics of the mole's construction and foundation.

Unit 4 (3.00–1.85 m b.s.) is remarkably inhomogeneous: angular and rounded stones of up to 5 cm, rounded and weathered ceramic fragments, with almost no fine-grained matrix material. The macroflora is composed of *P. oceanica*, the macrofauna of shell debris of different marine mollusc species.

From 1.85 to 1.36 m b.s. is a dark grey, slightly silty sand (unit 5). The amount of plant remains, shell debris and other organic matter decreases towards the top. Pieces of charcoal at 1.75 m b.s. date to 245–384 cal AD (1566–1705 cal BP; ELA 18/9HK), and at 1.38 m b.s. to 240–381 cal AD (1569–1710 cal BP; ELA 18/7HK).

Above 1.36 m b.s., the mean grain size drops to 6–9 μm. This sequence of clayey silt is in parts intercalated with lenses of slightly clayey sand. Low Na/Fe ratios and relatively high values of LOI (6–7%) characterise unit 6.

5. Geoelectric cross-section of the western harbour mole

Geoelectric cross-sections were measured to detect the thickness and the shape of the mole's basement. One is presented in Fig. 8 (length: 47 m, max. depth of penetration: approx.

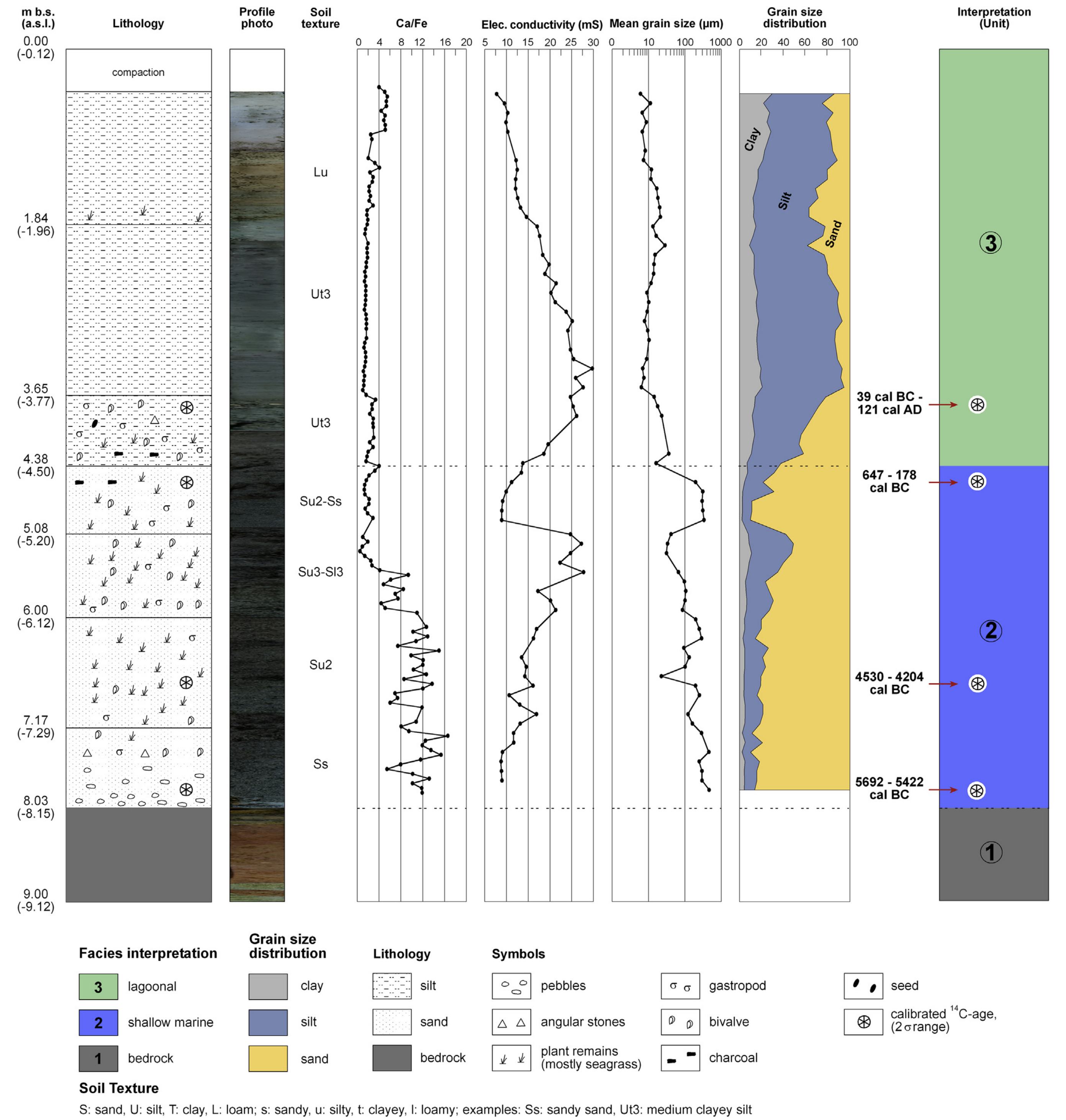

Fig. 5. Stratigraphical record and facies distribution of ELA 70, a vibracore inside the basin of the closed harbour (27°02′19.04″ E, 38°56′35.34″ N; ground level: 0.12 m below sea level). Facies: 1 = bedrock; 2 = shallow marine; 3 = lagoonal. For location see Figs. 3a,b and 4b.

9 m b.s.). The blocks of the mole are located in the central position of the profile. The calculated electrical resistivity has a bandwidth of less than 0.1–2 Ωm. Low resistivity (<0.256 Ωm) occurs at the outer parts of the cross-section near the surface. The highest resistivity (>1.58 Ωm) is found in the centre creating a zone of nearly 8 m lateral and 2 m vertical extension between approx. 2 m and 4 m b.s.. The measured resistivity values are very low compared with land measurements because the electrical resistivity is strongly influenced by the salty pore water.

6. Discussion

6.1. Coring ELA 70 from the centre of the harbour basin

Neogene bedrock encountered in ELA 70 at 8.03 m b.s. (unit 1; Fig. 5) forms the base of numerous cores in the study area, e.g. ELA 20, 58 and 63 (Fig. 4). It is calcareous sandstone which was used for the construction of the harbour moles (Figs. 3c and 8a). The overlying unit 2 represents a shallow marine facies with wave

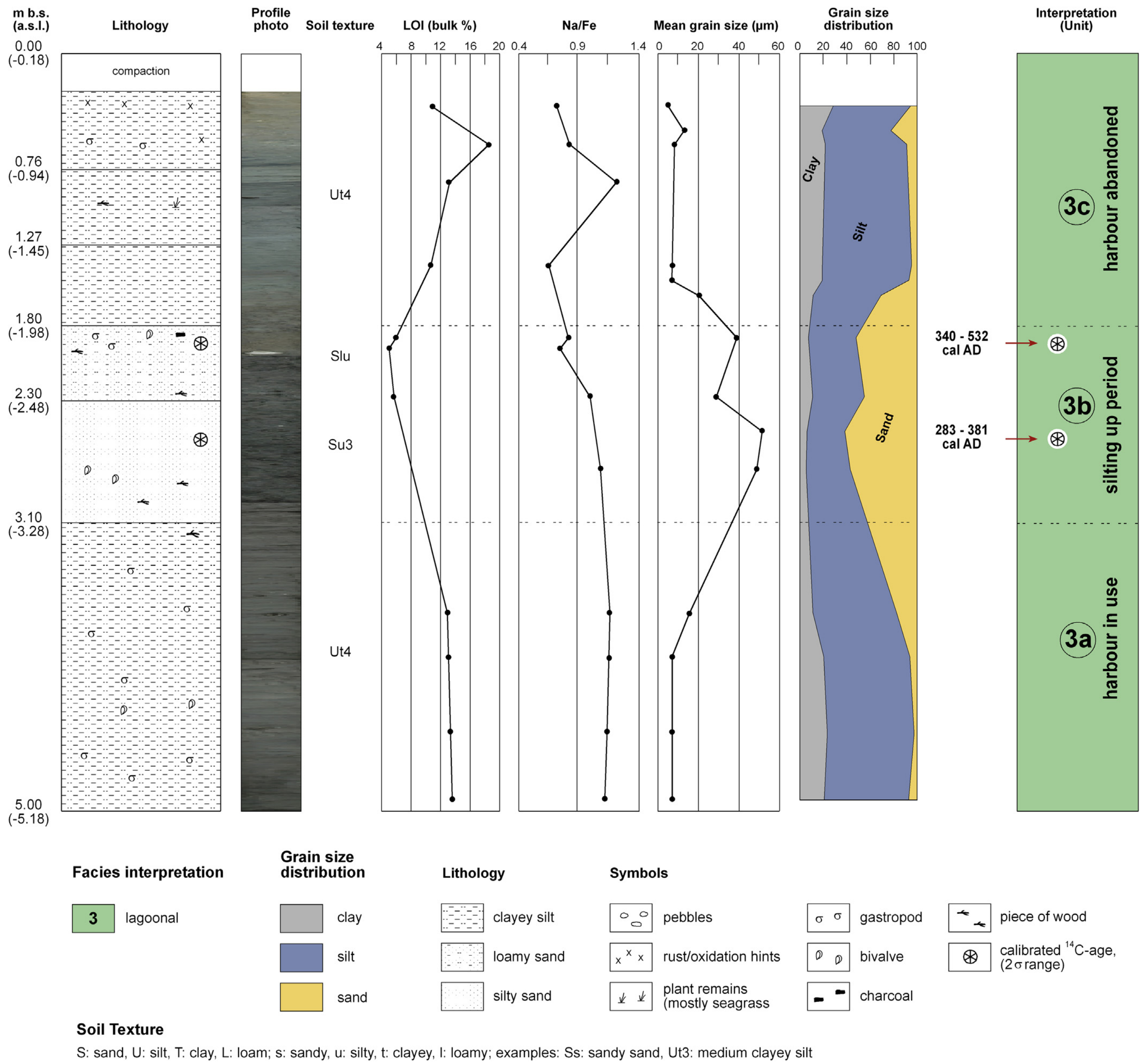

Fig. 6. Stratigraphical record and facies distribution of ELA 13, a vibracore inside the basin of the closed harbour, near the entrance (27°02′17.76″ E, 38°56′32.19″ N, 0.18 m b.s.l.). Facies: 3a = lagoonal (harbour in use); 3b = lagoonal (siltation period); 3c lagoonal (silted-up, present situation). ELA 13 was cored down to 10 m b.s.; here only the upper 5 m are shown. For location see Figs. 3a and 4b.

action, based on the comparatively coarse grain size and the abundant occurrence of seagrass (*P. oceanica*) which is also reflected in LOI peaks (organic contents of >20%; cf. Short and Wyllie-Echeverria, 1996; Montefalcone, 2009). As in this context, Ca is more indicative of marine and Fe of terrestrial environments (Vött et al., 2002), high Ca/Fe values support the marine origin of this sedimentary unit. Fluctuating values of the electrical conductivity reflect minor grain size variations and point to local changes of the sublittoral environment. The post-glacial sea-level rise, represented by the base of unit 2, dates to 5692–5422 cal BC (7371–7641 cal BP). This age gives an index point for the palaeo-sea level: around the middle of the 6th millennium BC it was at ~8 m b.s.l., which is roughly in agreement with other sea-level curves of the eastern Mediterranean (Brückner et al., 2006, 2010b).

With continued transgression and increasing water depth, the littoral environment turned into a shallow marine one. This milieu of deposition prevailed at least until the 7th century BC, most likely even longer.

A definite facies change occurs at the contact between units 2 and 3, 4.38 m b.s. (4.50 m b.s.l.): the remarkable decrease in the mean grain size indicates the abrupt change to a low-energy wave climate. In addition, decreased Ca/Fe ratios document the increased terrestrial influence. For grain sizes of <30 µm, the total amount of the particle surface area is enlarged, which results in high values of electrical conductivity (Niwa et al., 2011).

The abrupt transition from unit 2 to unit 3 reflects the change from open marine to harbour-associated lagoonal conditions. It dates to 647–178 cal BC (2127–2596 cal BP). The wide dating range is due to a plateau of the radiocarbon calibration curve. However, the given

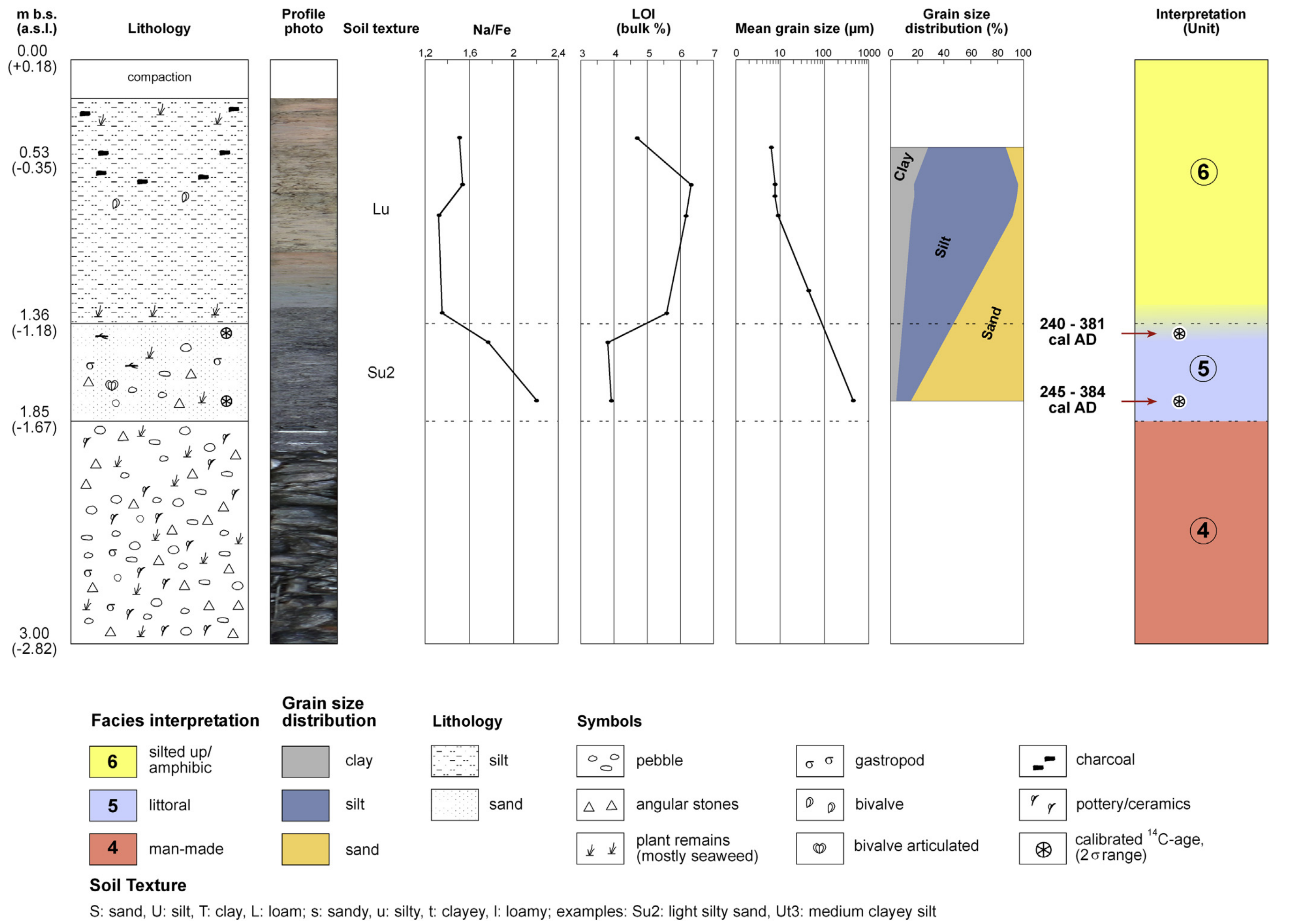

Fig. 7. Stratigraphical record and facies distribution of ELA 18, a vibracore outside the basin of the closed harbour, directly at the western mole (27°02′16.66″ E, 38°56′31.45″ N, 0.18 m a.s.l.). Facies: 4 = human-made basement of the mole; 5 = littoral; 6 = nearshore. For location see Figs. 3a,c and 4b.

interval does include the early Hellenistic period, which (for archaeological reasons) was the time of the construction of the mole.

The sedimentary facies sequence of ELA 70 fits well to the Ancient Harbour Parasequence (AHP) postulated by Marriner and Morhange (2006a) derived from a summary of different harbour locations, most of them situated in the southern Mediterranean, especially in Tyre's northern harbour (Marriner and Morhange, 2006b). In contrast to Marriner and Morhange (2006a, 2006b) the onset of the postulated "transgressive contact" is 1500 years earlier in Elaia; this might be explained by the contrast between the southern Mediterranean sites and the more northern ones such as ancient Elaia.

6.2. *Coring ELA 13 from inside the harbour basin*

In contrast to ELA 70, the entire facies of profile ELA 13 can be classified as lagoonal (Fig. 6). Internal changes of the geochemistry and granulometry allow for the differentiation of three subunits.

The grain size and the homogeneity of unit 3a are hints of a quiescent sedimentary environment. The interpretation of a lagoonal environment is supported by the presence of indicative fauna, such as *C. glaucum*, a euryhaline cockle colonizing muddy to sandy grounds in brackish lagoons and estuaries up to water depths of 10 m (Dance, 1977; Poppe and Goto, 2000; Nikula and Väinölä, 2003). The generally low Na/Fe ratio can be interpreted as terrestrial influence from the drainage area of the harbour basin. According to the ^{14}C age at 6.75 m b.s., the middle part of this unit was deposited in late Classical to early Hellenistic times (391–209 cal BC, 2158–2340 cal BP).

In unit 3b, still a lagoonal facies, siltation was accelerated as compared to unit 3a. Low Na/Fe ratio values, in particular towards the top, point to an increased terrestrial influence. The coarser average grain size is evidence of (a) stronger wave action due to the shallower water depth, and/or (b) the input of coarser sediment.

The uppermost silty to clayey layer (unit 3c) represents a semi-terrestrial environment; the sedimentation pattern corresponds to the modern nearshore conditions. Nowadays, the basin is periodically flooded during high tides and storms; it may, however, nearly run dry during low tides and phases of high insolation. Due to its extreme flatness, the silted-up harbour of Elaia is one of the rare locations along the shores of the Mediterranean where the effects of the tides, although only 20–30 cm, can be observed daily. Occasionally, it receives terrestrial/alluvial input, especially during the rainy season in winter.

6.3. *Western harbour mole – ELA 18 and the geoelectric cross-section*

Due to its characteristics, unit 4 (Fig. 7) is assumed to be an anthropogenic infill related to the western harbour mole. It was built in order to protect ships against wave action and attacks by enemies, and to facilitate an easier handling of trade goods.

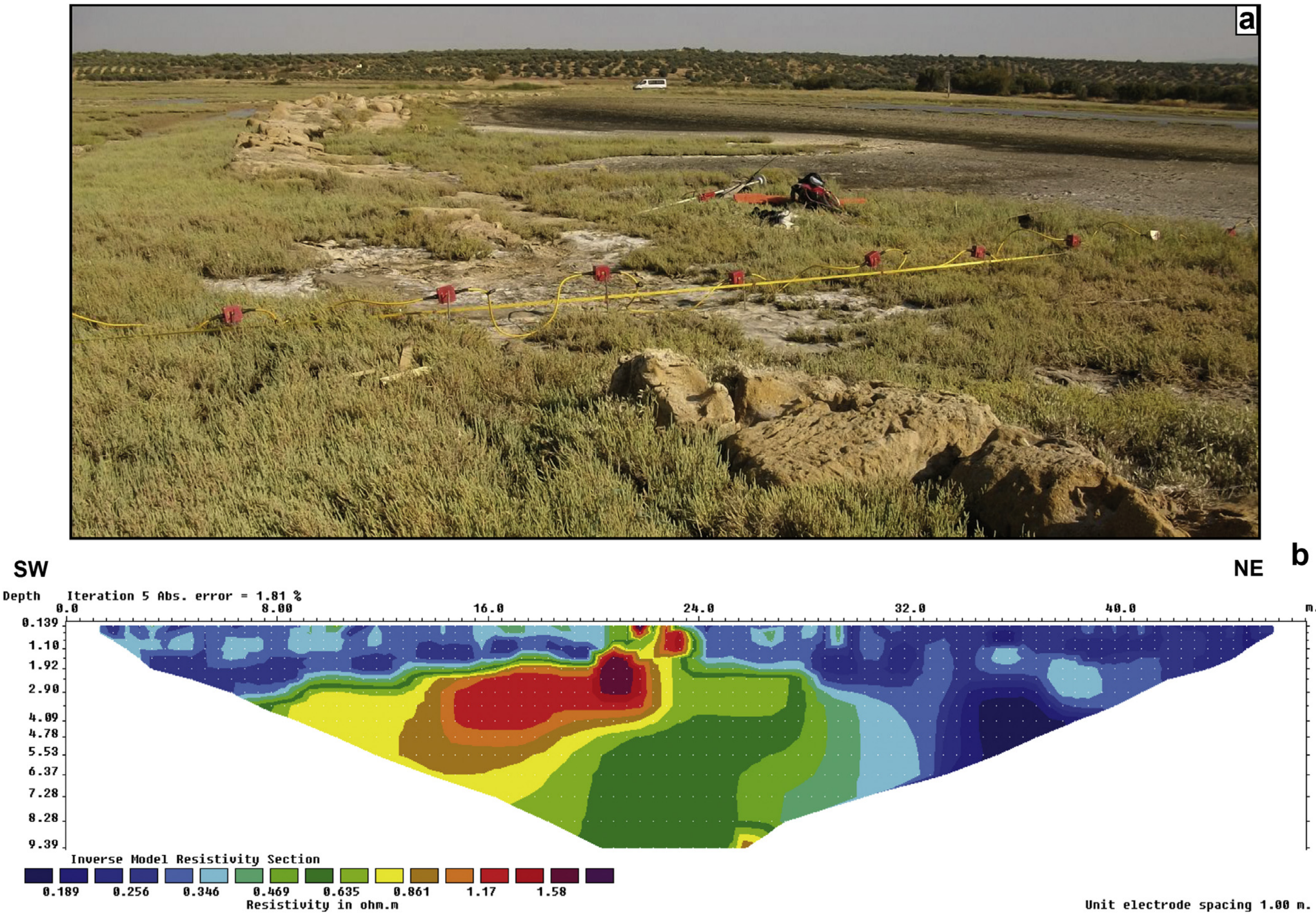

Fig. 8. Earth resistivity transect crossing the western harbour mole. Wenner–Schlumberger electrode arrangement, electrode spacing 1.0 m. (a) Transect with electrodes perpendicular to the western mole. The harbour basin is visible to the right of the mole. For location of transect see Fig. 4b. Photograph: Erkul (2010). (b) Simplified inverse model section of earth resistivity measurements. Source: Klein and Erkul (2010).

Posidonia oceanica and shell debris indicate an environment similar to the present one found on breakwaters and piers. Due to abrasion, the artefacts are well rounded. Several fragments of pottery and ceramics date to the Hellenistic – Roman era.

In the geoelectrical model, the parts with a relatively high resistivity (red colours in Fig. 8b) can be interpreted as the basement of the mole. Its width exceeds 8 m. The western, i.e. seaward, side is most likely a massive construction from a little less than 2 m down to about 4 m b.s. It is sloping gently to the west. In sharp contrast, the other side of the mole drops down like a plunging cliff. This is the inner side of the mole where ships could be moored. The geoelectric image also suggests that the top of the mole was dislocated. In the profile, the uppermost boulders are now lying in the mud of the silted-up harbour basin (Fig. 8a).

Unit 5 (Fig. 7) is a littoral facies with a high amount of sand and rounded components. The uppermost unit 6 is of nearshore origin: the lamination points to at least two different processes typical of a salt marsh. In particular during winter storms, the salt marsh area is flooded by the sea, resulting in the deposition of coarser material, mostly clayey sand. In contrast, long lasting dryness during the summer months causes the deposition of fine clayey silt layers. The present vegetation is made up of halophytes, such as *Salicornia* sp. In summary, units 5 and 6 are evidence of siltation after the harbour had been abandoned. The top of the mole's basement has since been covered by ~1.80 m of sediment. The setting is evidence that during the construction of the mole in the Hellenistic period, sea level was about 1.80 m lower than today.

6.4. *Harbour area – human-made coasts*

A synoptic view of all of the cores in the area under consideration shows that during Early Hellenistic times the marine embayment reached several hundred metres further to the north than it does today (cf. Brückner and Seeliger, 2009; Brückner et al., 2010a). Therefore, together with the moles part of the adjacent harbour area had to be built on shallow marine terrain (Figs. 9 and 10). Thus, there was a definite need for solid constructions. Moreover, they had to be thick enough so that the harbour could host ships.

The two moles are not the only anthropogenic structures of the closed harbour. The northern area adjacent to the harbour basin is also partly made of intentionally dumped material. It was done in order to consolidate the shallow marine and muddy terrain and create a solid ground for the erection of harbour-related facilities including warehouses and magazines. This interpretation is based on several cores, three of which are presented in Fig. 9 (locations in Fig. 4b). The anthropogenic infill is so massively consolidated that it could not be penetrated: nowhere was the marine strata below reached. It is definitely more than 2.5 m thick, most probably much thicker (Fig. 9). Further geophysical prospecting is needed in order to understand the 3D distribution of the infill.

7. Synthesis of the history of the closed harbour

Historical and archaeological evidence points to a construction of the moles in Early Hellenistic times. This is confirmed by

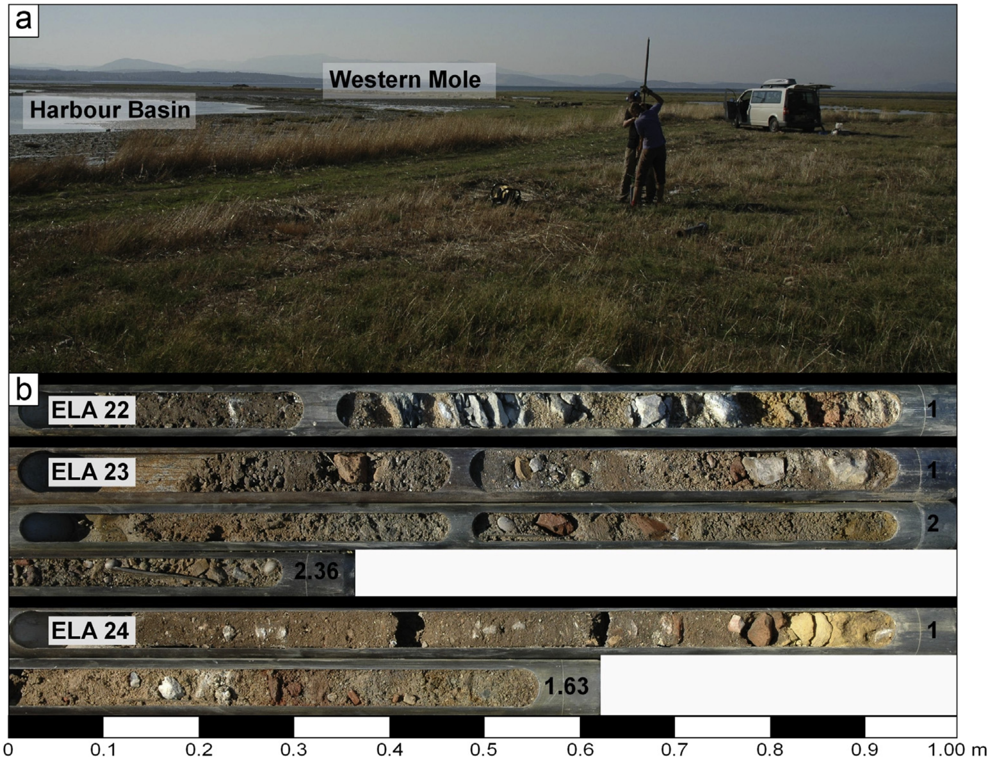

Fig. 9. Overview of the consolidated harbour area. (a) The infilled area, the harbour basin and the western mole; (b) Photographic documentation of the sediment cores ELA 22–24 (for location of cores see Fig. 4b). Due to the occurrence of angular and sharp stones as well as bricks, a strong consolidation of this area is evident. In each case, coring progress was stopped by large boulders. Photographs: Brückner and Seeliger (2009, 2010).

diagnostic ceramics in the basement of the moles. In combination with the results of the geoelectric profile, a detailed image can be given (Fig. 8). The basement has a width of nearly 8 m and a thickness of more than 2 m (1.80 m to >4 m below surface). Its asymmetric shape helped to buffer the wave energy on the seaward side, and the plunging cliff-like profile on the harbour side created opportunities for ships to be moored.

A set of cores directly north of the harbour basin revealed that this area was intentionally filled-in as one measure for the construction of the harbour. Very large boulders were deposited in order to consolidate the terrain, most probably in order to create space for loading and unloading of ships, and erect facilities for storing the goods (Figs. 9 and 10).

ELA 70 (Fig. 5) shows the definite change from a shallow marine (unit 2) to a lagoonal (unit 3) facies as a consequence of the construction of the moles. From that time, the harbour basin was connected to the open Mediterranean Sea by the 45 m wide port entrance only, resulting in a quiescent depositional environment.

Elaia's harbour was in use during Hellenistic and Roman times; it was gradually given up during late Antiquity. The siltation process is illustrated by the stratigraphical succession of ELA 13. Moderate sedimentation rates in the lower part (unit 3a) are followed by an increased sedimentation (6.9 mm/a) from 3.10 m b.s. upwards, some time before 283–391 cal AD (1569–1719 BP); sedimentary conditions similar to the present ones have existed since 340–532 cal AD (1418–1610 cal BP) with approximately 1.2 mm/a. The ^{14}C-age of ELA 13/22H (391–209 cal BC, 2158–2340 cal BP), which does not fit to this interpretation, can be explained as follows: (i) re-deposition of older material; or (ii) post-depositional contamination, e.g. by humic and fulvic acids (Törnqvist et al., 1992; Housley et al., 2012).

If the top of the mole's basement was more or less at sea level during construction in Hellenistic times, the difference to the present sea surface is approx. −1.80 m. As a consequence a maximum mean water depth of approximately 2.60 m in the northern part of the harbour basin can be estimated for that time. This calculation takes into account that (i) at the ELA 70 site the abrupt transition between shallow marine and lagoonal facies is at 4.38 m below surface (4.50 m below present mean sea level); and (ii) sea level was ∼1.80 m deeper than today. The tidal range is about 20–30 cm.

The original height of the mole may have been reduced by erosion/weathering, destruction of the coping blocks or by subsidence. As normally the draught of Hellenistic and Roman ships did not exceed 1.60 m, the postulated water depth was sufficient for them to make use of the harbour (Coates, 1987; Beltrame and Gaddi, 2007; Marriner and Morhange, 2007; Auriemma and Solinas, 2009).

The transition between the man-made mole basement (unit 4) and the littoral facies on top (unit 5) is dated to ca. 245–384 cal AD (1566–1705 cal BP). This is the time in late Antiquity when the harbour was given up. By then, despite the higher sea level as compared to the construction time, the littoral sediments could cover a possible walkway behind the mole top. A considerable amount of sediment was deposited in a short time, since the statistically identical ^{14}C-ages from unit 5 are 0.37 m apart from each other. The fine-grained unit 6 is an expression of the continued siltation process outside the closed harbour basin.

According to the radiocarbon ages of unit 5 in profile ELA 18, the siltation outside the harbour started sometime between the second half of the 3rd century and the end of the 4th century AD. As the beginning of strong siltation inside the basin was dated to 283–391 cal AD (1569–1719 BP; ELA 13/13HK), more or less simultaneous siltation is evident. The accelerated accumulation of sediments inside the harbour was due to the fact that the catchment area of the harbour basin is quite large, i.e., a relatively great

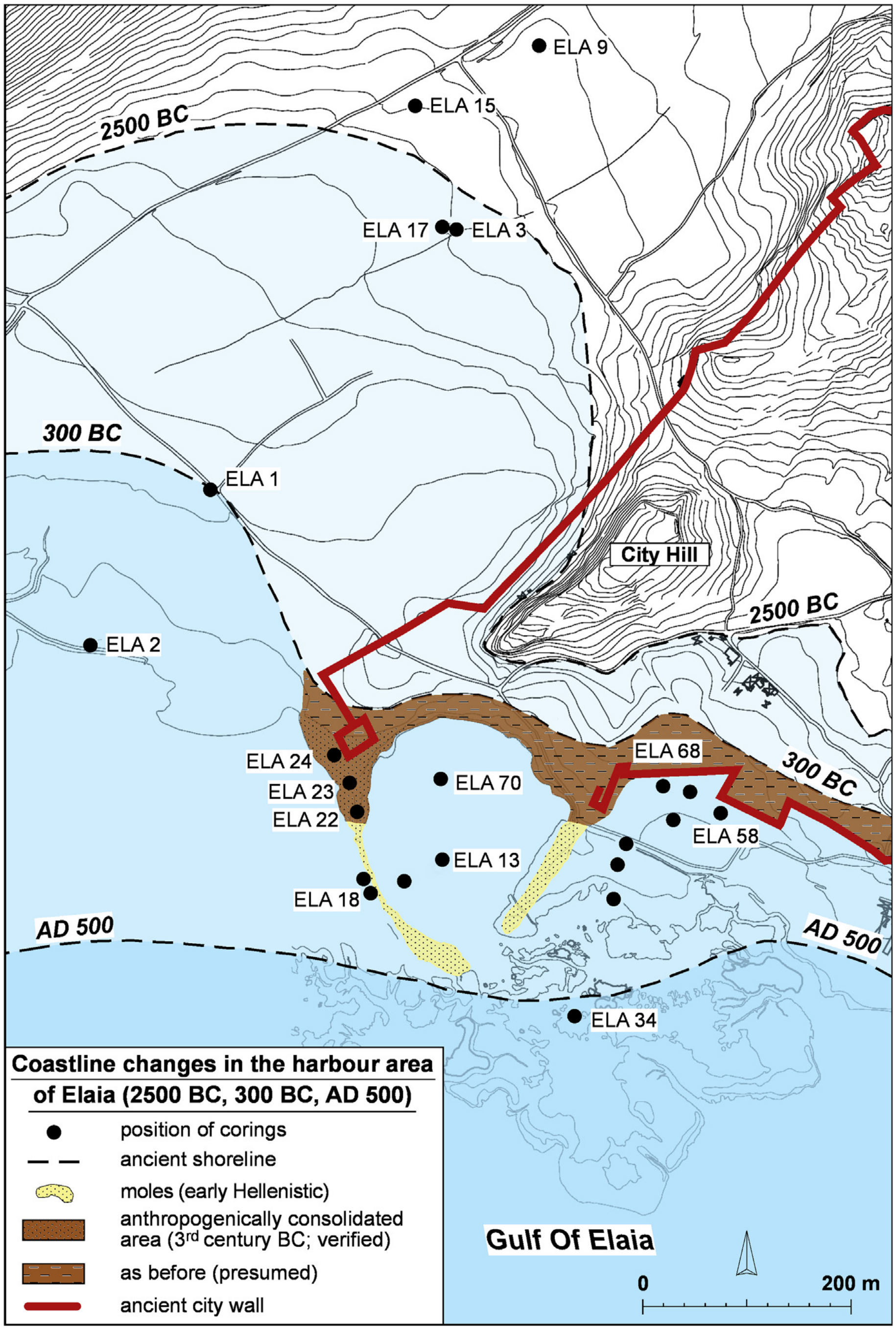

Fig. 10. Estimated coastline changes in the area of the closed harbour of Elaia 2500 BC, 300 BC and 500 AD. The palaeogeographies are based on the results of this paper, as well as on Brückner and Seeliger (2009) and Brückner et al. (2010a). For location of cores see Fig. 4.

area drains into it, whereas the siltation of the outside area was dependent on occasional strong flooding episodes with terrestrial input from the adjacent slopes and from sedimentation by marine currents.

From studies of nearby ancient settlements, it is well known that human impact is closely linked to increasing rates of erosion and sedimentation. The Great Harbour of Ephesus, for example, was endangered by siltation at the latest in Roman Imperial times when a canal was built as a reaction to the progressive siltation of the prograding Caystros delta (modern Küçük Menderes) (Kraft et al., 2000, 2007). From coring evidence, Brückner et al. (2006) concluded that the Theatre Harbour of Miletus was dredged during the 1st/2nd century AD, when the theatre was renovated. As for Elaia's harbour, however, no evidence of dredging has been detected as yet: there is no erosional disconformity in the sediment columns of the cores or mixing of archaeological layers (Marriner and Morhange, 2006b). Other than for Ephesus (Kraft et al., 2007), no literary evidence of dredging is known for Elaia. The ^{14}C dating results do not show age inversions.

8. Tectonic movement vs. sea level rise?

Little is known about the subsidence rate of the Bergama and Zeytindağ graben. Based on air-gun seismic reflection data gained on Pleistocene deltaic sediments in the Bay of Çandarlı, Aksu et al. (1987) stated a subsidence tendency of the submarine basin and in further consequence of the graben complex in total of approx. 1 m per 1000 years. Two reliable sea level indicators are presented in this paper, but both are opposed to the subsidence tendency calculated by Aksu et al. (1987). The transgressive contact occurs in Elaia's closed harbour basin at a depth of ca. 8 m b.s.l., dating to 7371–7641 cal BP. Assuming a subsidence of 1 m/ky, corresponding to 7.5 m since the time of the transgressive contact, sea level would have been more or less constant over the past seven millennia and a basin used for shipping would not be conceivable. This same logic applies to the second reliable sea-level marker: the harbour moles. During their construction in Hellenistic times, sea level was about 1.80 m deeper than today. Stating a subsidence of 1 m per 1000 years, i.e. more than 2 m since Hellenistic times, sea level would have remained constant over this period of time. The assumption of a constant sea level over the past millennia is definitely false and in contrast to published studies for adjacent regions of the Eastern Mediterranean (Kayan, 1997; Sivan et al., 2004; Lambeck and Purcell, 2005; Brückner et al., 2006, 2010b; Vött, 2007).

Thus, the subsidence rate must have been significantly lower. Aksu et al. (1987) did their research far out in the Çandarlı Bay where water depth reaches 100 m and more. The superimposed sediment load in this part is much higher, resulting in higher rates of subsidence as compared to the inner part of the Bay of Elaia. Leaving aside the question of subsidence, the presented palaeo-sea level in the harbour region of Elaia is in accordance to other studies of the Eastern Mediterranean.

9. Conclusions

Until the 7th century BC, the area of the later harbour basin was part of a marine embayment which reached several hundred metres further inland to the north and to the east than today (Fig. 10; see also Brückner and Seeliger, 2009; Brückner et al., 2010a). Most probably in the Early Hellenistic period the harbour basin was constructed: two harbour moles were erected with massive substructures and large capping sandstone ashlars. In addition, the area directly to the north of the present basin was filled with large stones in order to consolidate the terrain and to create space for loading, unloading and storing of cargo from the ships. As a consequence, the harbour area turned into a quasi-lagoonal environment, being connected with the open sea only by a 45 m wide port entrance.

The harbour was in use during Hellenistic and early Roman times. Based on the ^{14}C age estimates from the cores, the onset of substantial siltation occurred between the second half of the 3rd century and the end of the 4th century AD. These results confirm the archaeological evidence of a flourishing city of Elaia during the Hellenistic and early Roman periods, and its decreasing importance during Late Roman times.

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