Quaternary International xxx (2013) 1–21

Contents lists available at SciVerse ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Archaeological and geomorphological indicators of the historical sea level changes and the related palaeogeographical reconstruction of the ancient foreharbour of Lechaion, East Corinth Gulf (Greece)

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ARTICLE INFO

Article history:
Available online xxx

ABSTRACT

Study of the architectural, morphological and constructional features of the coastal harbour installations of the ancient foreharbour of Lechaion indicates that they were built or rebuilt during the period of the Roman domination of Corinth, and has facilitated the reconstruction of the vertical movements and the palaeogeography of the coast. On the basis of the current position of the sea level indicators including beachrocks, fossilized uplifted and submerged marine notches, and ancient coastal harbour installations, and the relationship between them, the sea level during the Roman operation of the harbour was determined to be 0.90 m lower than at present. Furthermore, the subsequent abandonment of the harbour and the siltation of its constructions were determined. During two successive tectonic subsidence co-seismic events, the sea level rose by 2.0 m in total, 1.60 m during the first event and 0.40 m during the second one. A strong uplift tectonic event followed and the sea level dropped by 1.10 m. This regression of the sea was responsible for the present shoreline morphology. Determination of the sea level fluctuation at the shore of the ancient harbour of Lechaion allowed the palaeogeographical reconstruction of the coast in different stages related to these changes.

1. Introduction

The Upper Holocene coastline of the Gulf of Lechaion is a highly dynamic zone in which the interaction of geography, geodynamics and human intervention has shaped, transformed and repeatedly overturned its balance and man's associated activities. Geography created the comparative advantage, ancient man exploited it and geodynamics reversed it.

Any attempt to decode the dynamics of the relationships between land and sea involves the articulation of sea level fluctuation with history. By detecting in space and time the relation between coastal geomorphological features and human constructions it is possible to understand the dynamics of the co-seismic vertical movements, their direction and magnitude, the palaeogeographical changes they caused to the coastline and the evolution of the natural and cultural environment they affected.

The ancient harbours of the Greek Mainland are a physical historical archive of Upper Holocene coastal changes, since they combine the possibility of understanding the palaeocoastal environment through the evolution of the coastal morphodynamic processes, the dating and the reconstruction of the harbour installations and their relation to the ancient city.

In the archipelago of the Cyclades, Negris (1904) and Cayeux (1907), in the early twentieth century, followed recently by Mourtzas et al. (2004), Desruelles et al. (2007) and Mourtzas (2012), reconstructed the palaeogeography of the submerged west coast of Delos and the shape of its ancient harbour. Mourtzas (2010) resynthesized the morphology of the submerged coastline and its relation to the ancient harbour installations in the bay of Classical Karthaia on the island of Kea (anc. Keos) in the western Cyclades. Further north, on the island of Andros and specifically the harbour of ancient Palaeopolis, the relation between sea level and the ancient harbour installations during the period of their use, points to one of the largest harbour works of Classical Antiquity, today submerged (Mourtzas, 2007). Scranton et al. (1978) mapped and studied the Roman harbour of Kenchreai on the west shore of the Saronic Gulf, and resynthesized and dated the phases of its submergence.

In the late 1960s Schlager et al. (1968) studied the ancient harbour installations of Anthedon in the Evoikos Gulf and

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http://dx.doi.org/10.1016/j.quaint.2012.12.037

Knoblauch (1969, 1972) the ancient port of Aegina in the Saronic Gulf.

The Classical–Hellenistic harbour of Phalasarna at the western tip of Crete, today elevated as a consequence of the earthquake in AD 365, has been studied by Hadjidaki (1988, 1996 and 2001) and Pirazzoli et al. (1992). On the south coast of central Crete, the reconstruction of the geomorphology of the coast of Minoan Kommos, when sea level was 3.90 m lower than at present, enhanced a now submerged shelter morphology which favoured the safe anchorage and beaching of ships (Mourtzas, 1988a; Shaw, 1990; Mourtzas and Marinos, 1994). On the south coast of central Crete, the now submerged harbour of ancient Lassaia has been studied by Mourtzas (1990), and Mourtzas and Marinos (1994).

Corinth played an important historical role throughout Greek Antiquity, mainly due to the Diolkos and to its two ports of Lechaion and Kenchreai. The entirely artificial harbour of Lechaion was in use continuously for 2655 years, from the seventh century BC until 1955, although its importance seems to have diminished after the Frankish period (AD 1500). It consisted of three inner harbour basins and one outer harbour with two curving harbour walls, along which piers, moles, breakwaters, a quay and a large number of warehouses and other installations were constructed.

Although the harbour of ancient Lechaion has never been excavated, it has been studied by numerous researchers since the early twentieth century. Georgiades (1907) and Paris (1915) give extensive descriptions of the ancient port, of its three inner basins, the entrance channel and the two breakwaters of the outer harbour. Pallas (1963, 1965), in the course of excavating the Early Christian basilica situated on the land barrier between the inner harbour and the coast, revealed important evidence on the early phases of its construction and its later development. Shaw (1969) described and dated the manmade islet in the middle of the west basin of the inner harbour, suggesting that it might have been the base of a lighthouse (pharos) or a statue. Rothaus (1995), in his thorough historical retrospection, describes the ancient harbour installations, emphasizing in particular the foreharbour, and tries to date them on the basis of their architectural and morphological features. Mourtzas and Marinos (1994), and Maroukian et al. (1994) were the first to refer to the elevation of the coastline of the outer harbour in historical times, while Stiros et al. (1996) attempted to date this tectonic rising event by the radiocarbon method and thus to estimate the date of construction of the ancient harbour. Theodoulou (2002) analysed the development of the ancient harbour on the grounds of historical data and literature, adding also new significant observations.

More recent stratigraphical investigations on the site of the ancient harbour identified two distinct tsunami layers (Hadler et al., 2011; Koster et al., 2011). Hadler et al. (2011) mention also a third violent flooding event, which was associated with earthquakes that struck in the first half of the sixth century AD. Morhange et al. (2012) estimated the sedimentation rates in the basins of the inner harbour and date by the radiocarbon method the tectonic event that elevated it.

2. Tectonic framework

The Gulf of Lechaion is a relatively shallow and asymmetrical trench structure trending NW–SE, located at the east end of the extensional sedimentary basin of the Corinthian Gulf, which is an active rift structure with very high deformation rates and seismicity (Fig. 1). It is about 17 km long and 10 km wide, with a maximum depth at its north end of 250 m. It is characterized by a steep fault margin in the north, smooth morphology at the bottom of the sea in the south and the east, and a layer of post-alpine sediments 2 km thick (Weiss et al., 2003; Sakellariou et al., 2004). The klippe of the Perachora peninsula, which comprises the northern emerged boundary of the trench, is formed between the north dipping Pisia and Skinos fault zone at the north and the south dipping Loutraki fault at the South. These are ENE–WSW to E–W normal faults, which have been active since the Pliocene and, according to palaeoseismic investigations, were reactivated in the periods AD 1295–1680, AD 670–1015 (Collier et al., 1998) and in the earthquake of 1981 with footwall uplift and hanging wall subsidence. During the 1981 earthquake the seismic surface ruptures displacements along the Pisia fault ranged between 0.50 m and 0.70 m, with a maximum value of 1.50 m, while the vertical displacement along the Schinos fault was almost 1.0 m (Jackson et al., 1982). At the same time, the co-seismic subsidence of the northern coast of the Perachora peninsula ranged between 0.60 m in its eastern section and 0.80 m in the western one (Andronopoulos et al., 1982; Jackson et al., 1982; Mariolakos et al., 1982; Hubert et al., 1996). The Loutraki fault, situated on the southern coast, was activated constantly during the late Quaternary, causing the elevation of the coast with an uplift rate of 0.29 mm/y–0.55 mm/y from W to E for the last 125,000 years (Cooper et al., 2007) and 0.75 mm/y for the last 6300 years (Pirazzoli et al., 1994). At the west entrance to the Isthmus Canal, in the area of Poseidonia, a reciprocating movement of the coast was determined with initial subsidence of 1.60 m and a following emergence of 0.70 m.

The basins of the Eastern and Western Corinthia grabens, on the northern shore of the Lechaion Gulf, which form the onshore prolongation of the present Gulf of Corinth, are undergoing lithospheric extension with active seismicity on both basin-bounding and intrabasinal normal faults (Jackson et al., 1982; Vita-Finzi and King, 1985; Davies et al., 1997; Hatzfeld et al., 2000). A complex history of extensional subsidence and deposition, periodically interrupted by intrabasinal tectonic uplift and erosion, is represented in the Lower Pliocene to Holocene sediments currently at outcrop levels (Freyberg, 1973; Collier and Dart, 1991). The high rates of the tectonic uplift, between 0.35 mm/y and 0.60 mm/y (Westaway, 1996), have dramatically changed its morphology raising marine deposits and terraces of 180–230 ka BP up to the elevation of 80 m (Vita-Finzi and King, 1985; Keraudren and Sorel, 1987; Collier et al., 1992; Westaway, 1996). The staircase Quaternary morphology is interrupted by the fault scarp of active normal fault zones. The whole area is characterized by the existence of large fault zones which separate it into blocks, forming large tectonic grabens and horsts (Papanikolaou et al., 1996; Kranis et al., 2004). The dominant neotectonic structure of the area is the active fault of the east margin of the Eastern Corinthian graben, known as the Corinthos–Dervenakia–Kaparelli fault zone, which separates it from the Western Corinthia graben, defining also the boundary between the marly marine sediments of the western basin and the lacustrine sediments of the eastern one. This is an oblique-dip slip, left-lateral, orientated NE–SW and 48 km in length. The Oneia fault zone, at the south of the basin, which demarcates the homonymous alpine mass at the north, and the Mavri Ora, Agios Dimitrios, and Agios Vasilios-Ryton fault zones parallel to it at the south, are actually normal faults trending E–W and dipping to the north, with their length varying from 7 km up to 24 km (Papanikolaou et al., 1996). The parallel fault of the Dervenakia–Kaparelli fault zone is the secondary neotectonic structure which forms the SE coast of the Gulf of Lechaion, passes through the city of Corinth, east of the Acrocorinth horst, and ends several kilometres to the south. Its length is about 20 km and it has a NE–SW direction. Some other faults, probably active, form also the north, west and south sides of the Acrocorinth horst. Parallel to the direction of the large oblique-slip, left-lateral structures of the east margin of the East Corinth basin, there are some smaller, secondarily activated normal faults of NE–SW direction which

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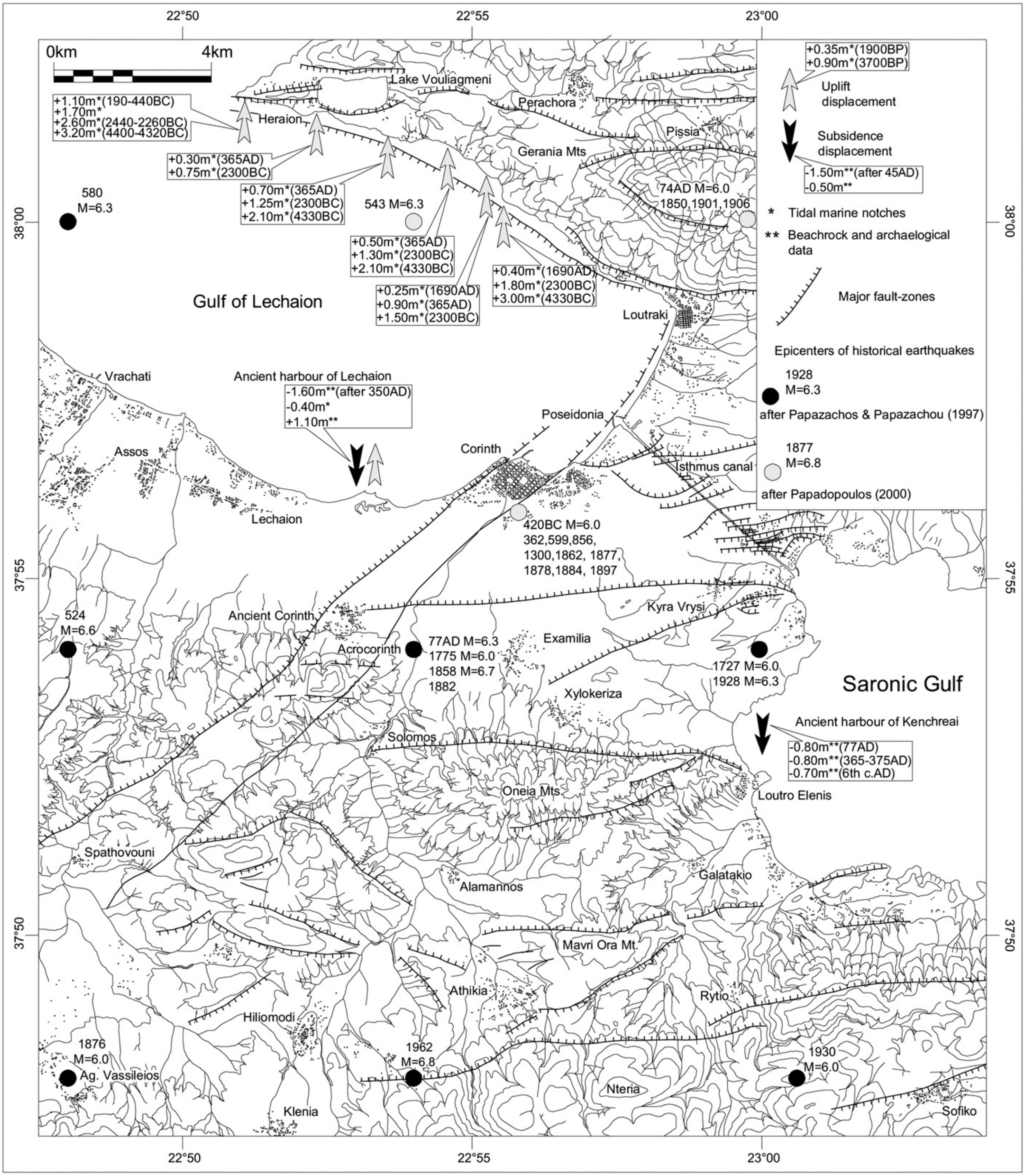

Fig. 1. Seismotectonic map of the wider area of Corinthia, showing the major neotectonic structures, the epicenters of the historical earthquakes, the type of sea level indicators, as well as the dating, magnitude, and direction of vertical tectonic movements during the Upper Holocene.

cross the Isthmus Canal, forming a horst structure with lateral extensional fault-induced subsidence accompanied by block rotations (Freyberg, 1973; Mariolakos and Stiros, 1987; Collier, 1990). Their recent activations have caused displacements of up to 0.15 m in the excavation materials of the Canal under a tensional regime with NNE–SSW direction (Mourtzas, 2004). A minimum uplift rate of 0.3 m/ky for the Isthmus area has been estimated for the late Pleistocene and Holocene (Collier, 1990).

3. Historical background and dating of the ancient harbour installations

In the absence of archaeological excavation data, it is difficult to date the harbour installations and it is only possible to correlate them with historical events, such as the phases of ancient Corinth's zenith and decline. The indirect dating of them is obtained by the accompanying constructions here investigated, that can provide indications also for dating the phases of building, repair and enlargement works.

On the site of the ancient port, there is a torrent originally debouched into the sea, with sporadic floods. In the area of its meandering estuary a shallow marsh formed, separated from the sea by a narrow sandy barrier (Fig. 2).

The present topography of the harbour of Lechaion (Georgiades, 1907; Skias, 1907; Paris, 1915; Shaw, 1969; Rothaus, 1995), with the harbour basins surrounded by sand mounds, is largely the outcome of human interventions in the natural landscape, in order to form the port of ancient Lechaion with an foreharbour and an inner harbour of overall area ~150,000 m^2 (Rothaus, 1995). It is a harbour of the 'dredged' category (Salmon, 1984) or a 'cothon', that is an artificially excavated harbor, a very valuable technical project, given that it is the only known example in Greece (Rothaus, 1995). The works in the foreharbour include the two extensive harbour basins, demarcated by two or three breakwaters constructed at the end of three corresponding sandy spits (Georgiades, 1907; Paris, 1915). The remains of the two west moles are still visible, and to the east a narrow stone-lined channel leads from the sea to the basins of the inner harbour. Paris (1915), Roux (1958), Sakellariou and Faraklas (1971), and Theodoulou (2002) argue that there was a second entrance, at the extension of the west mole, which also protected it. The foreharbour secured the entry of ships (Paris, 1915), the disembarkation of passengers and the unloading of cargoes. It is an anchorage in conditions of no wind but is exposed to the open sea in the prevailing NW and N winds. Consequently, it is not a safe haven for ships, which seek this in the inner harbour. The combination of outer and inner harbours minimized the disadvantages, making the port functional in all weathers. The installations also included quays, breakwaters, docks, as well as numerous warehouses and other auxiliary port facilities (Fig. 2).

The harbour was connected to the ancient city via the Lechaion Way, which commenced at the monumental entrance to the city's agora (Papachatzis, 1976) and terminated in the southern sector of the harbour, as well as by a secondary road to the west of it (Skias, 1907). The fact that the harbour was walled attests to its importance for the city (Skias, 1907; Parsons, 1932). A wall possibly existed also in the coastal zone north of the inner harbour basins. The ruins east and west of the entrance channel to the inner harbour are perhaps remnants of the coastal enceinte. Long walls running for 2 km fortified the access from the city of Corinth to the

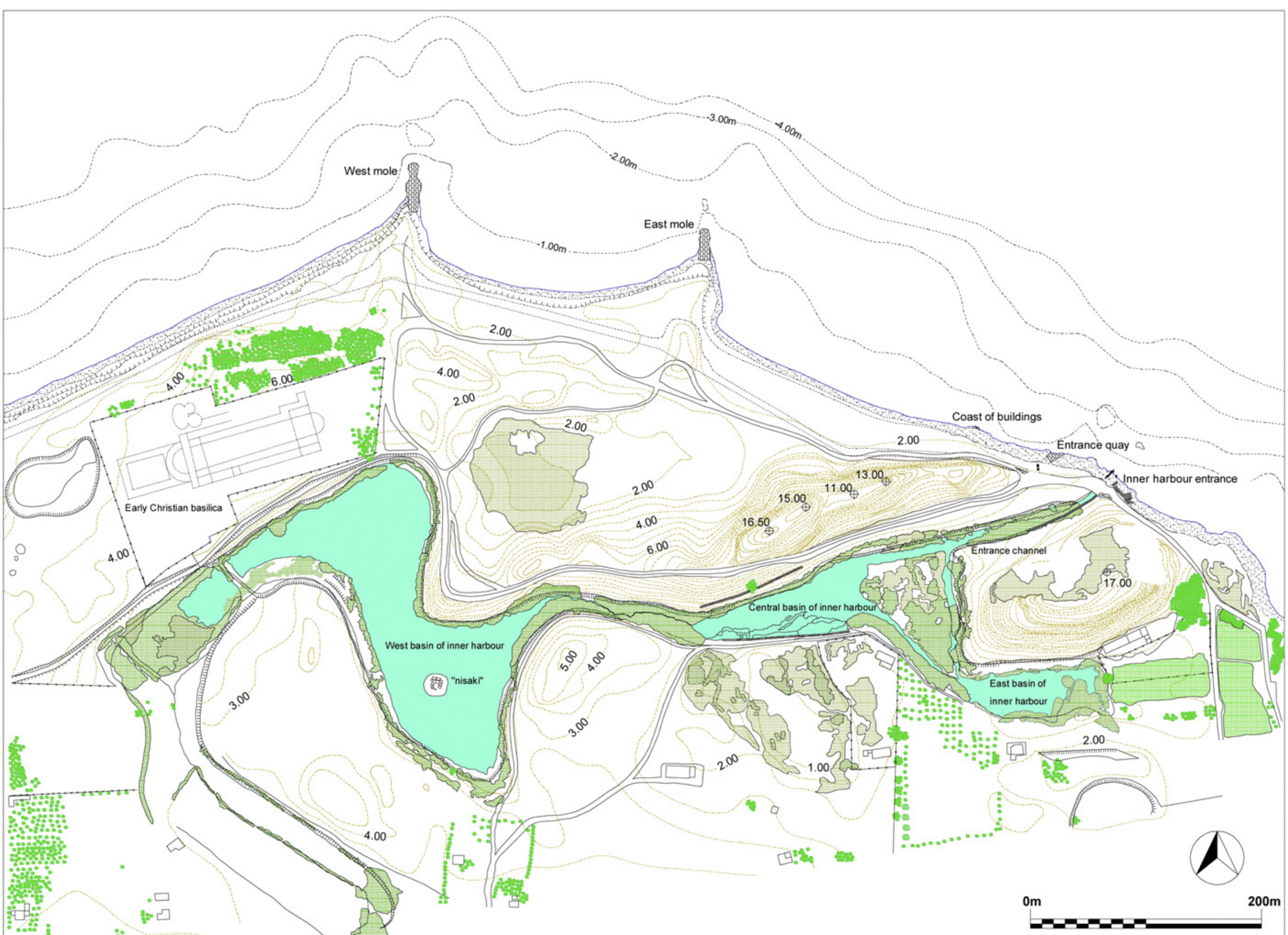

Fig. 2. Plan of the harbour of Lechaion.

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harbour of Lechaion (Parsons, 1932). Built in the mid-fifth century BC, they stood until 146 BC, when their gradual dilapidation began (Parsons, 1932). According to Parsons (1932), the end of the west branch of the walls (Skias, 1895) was a Roman construction, built of reused material (*spolia*) from the Long Walls. The end of the east branch of the walls, with courses of conglomerate blocks in the lower part, was the socle for the fired-brick upper structure, although the possibility that the construction was entirely of stone in certain parts cannot be ruled out (Parsons, 1932).

On Korakas hill, near the sea 1 km east of the harbour of Lechaion, was a prehistoric settlement that flourished in the third millennium BC and was abandoned at the end of the Mycenaean Age (~1000 BC) (Blegen, 1921). It could have been associated with the harbour or the coast of Lechaion, for which scholars have suggested the possible continuous use from prehistoric times (Rothaus, 1995).

Given that the coast of Lechaion was by far the best place for a port of Corinth, it has been proposed that its construction should be correlated chronologically with the turn of the Corinthians' interests to the sea lanes (Wiseman, 1978). With regard to the port's location, Romano (2003) proposes that the Greek harbour of Lechaion lies about 1 km further west and so no remains of this phase can be detected on the present site of the harbour of Lechaion.

However, even though the period of the Kypselids (7th–6th c. BC) is linked with the first phase of works in the harbour, it is quite possible that works on forming Lechaion started earlier, when the sea lanes were utilized in the commercial expansion of Corinth to the West and the founding of colonies. Specifically, in the early ninth century BC Corinthians were exporting Peloponnesian vases to Ithaca, and at the end of the century they founded a colony on the island for the purpose of controlling the routes to the Ionian Sea and servicing voyages to the Illyrian shores to acquire metals. Furthermore, in the eighth century BC (733 BC) they founded one of their most important colonies in the West, Syracuse.

The first works for creating harbour installations seem to have begun in the seventh to the sixth century BC, when the area between the marsh and the coast was filled in with boulders, so that the living space between them was reinforced and extended (Pallas, 1963). In the interstices between the boulders, at a current depth of 3.0–4.0 m, which was revealed after cleaning the wells of the houses around the Early Christian basilica of Lechaion, shreds of Corinthian vases were found. These indicate that the barrier of boulders was one of the first costly works of forming the harbour in the time of the Kypselids (7th–6th c. BC) (Pallas, 1963), during which Corinth enjoyed a great heyday. It could be supposed that already from this period parts of the meander were deepened and united in order to form at least three inner basins, and the exit channel to the sea was opened (Theodoulou, 2002).

The sand mounds, visible to this day beside the basins, are remnants of the artificial formation of the inner harbour and resulted from dredging and deepening works. However, it cannot be documented securely whether the formation of the sand mounds – and consequently the works to form the inner harbour – had begun already in the Archaic period. In Wiseman's view (1978) they most probably date back from the Roman phase of the refounding of Corinth in 44 BC. Rothaus (1995) too notes the difficulty in dating the constructional sequence of the harbour, observing that the shreds found in the interstices of the boulders merely set a *terminus post quem* for the accumulation of these.

It is very likely that documentation of the harbour through excavation could give more secure data on the constructional phases. The first phase of construction of the harbour, and indeed the formation of the inner harbour, is associated with the reign of the tyrant Periander ~600 BC. According to Salmon (1984), Periander's decision to build an artificial harbour at the closest possible point to Corinth, Lechaion, is indicative of the great mercantile activity that had to be served. He correlates the necessity of creating an inner harbour with the fact that the coast at Lechaion and the other littoral areas close by does not offer a suitable haven for ships. It is stressed also that a project of this scale responded to the abilities of Periander's engineers, who are further accredited with the constructing the Diolkos. Rothaus (1995) too associates the first phase of construction of the outer harbour with the time of Periander and with the construction of the Diolkos. On the basis of constructional similarities with the Diolkos, which, however, he qualifies as weak, he attributes the two moles of the foreharbour to the Archaic phase of construction of the port.

The excavation stratigraphy of the area between the mire and the sea is completed by marine sediments with fragments of lead sheet – possibly from ships' keels – Corinthian coins of the third century BC, shreds of Hellenistic vases and traces of conflagration from a major destruction that perhaps happened during the invasion of Roman legions and the razing of Corinth by General Lucius Mommius (Strab. 8.6.23) in 146 BC (Pallas, 1963). The destruction of Corinth, which is linked also with the desertion of the port of Lechaion, is referred to frequently in the ancient literature but is not confirmed by secure archaeological excavation data and was possibly less extensive than previously believed. In a few excavated buildings, however, there are clear traces of violent destruction, which can be attributed to that of 146 BC (Wiseman, 1979). Wiseman (1979) cites also testimonies of Cicero on the existence of Corinthians in 77 BC, the period of the supposed abandonment of the city.

Strabo, who visited Corinth about fifteen years after the colonization by the Romans in 44 BC (Strab. 8.6.21), writes that Lechaion was used as the port of departure by ships of Corinth bound for Italy and had few inhabitants, but he makes no mention of the presence of ruins (Strab. 8.6.22).

The Roman colonization of Corinth (44 BC) (Strab. 8.4.8) was followed by large-scale works on reconstructing the harbour. So, in the stratigraphy of Lechaion there is a layer of manmade accumulation of sand and sediment, which appears to have been created after the destruction in 146 BC (and not earlier than the 3rd c. BC) and refers to works on dredging the basins of the area (Pallas, 1963). The inner basins were dredged of the later fill of the period of the harbour's desertion and the material was deposited on top of the archaic piles of boulders, while concurrently the retaining walls of the inner basins and the entrance were constructed and reinforced (Theodoulou, 2002). Products of the extensive removals of earth, of overall estimated volume 85,000 m^3, are the sand mounds, of maximum height 17 m, on either side of the entrance channel and of the two central inner basins, which correspond to a mean thickness of 4 m of alluvium dug out of the basins.

This second major phase, which included works on the reconstruction, reorganization and expansion of the ancient harbour, is estimated to have been implemented in the new period of zenith for Corinth during Roman imperial times (Pallas, 1963). Indeed, it has been correlated specifically with the growth of Corinth in the reign of Claudius, between AD 40 and 45, which is documented by archaeological data (Rothaus, 1995). The remains of the port visible today are attributed to the period of Roman domination (Theodoulou, 2002). The surviving parts of the moles of the foreharbour can be traced some 20–25 m into the sea. They are built of large sandstone blocks (Paris, 1915), that likely were the foundation of the construction and bear traces of the existence of upper courses (Rothaus, 1995). The existence of swallow-tail clamp cuttings (Rothaus, 1995) on some blocks of the west mole not *in situ* refers to the Julio-Claudian era (44 BC – AD 68) (Williams, 1993; Rothaus, 1995). Similar cuttings are observed on blocks from the

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base of a monument in the inner harbour, of the Roman period. However, the date of the moles remains unclear (Rothaus, 1995). Both the east and the west mole preserve remnants of an upper structure of rude stones and mortar, characteristic of the Roman period.

The retaining wall on the perimeter of the inner harbour and the banks of the entrance channel was built or repaired in this period (Rothaus, 1995). Visible north of the east basin is the internal rubble masonry with mortar of the retaining wall, which refers to the Roman period. In the entrance channel are visible today large header sandstone blocks laid in courses, *in situ* in the east wall of the channel and disturbed in the west. The presence of mortar in the joints of the east wall is ascertained, while on the upper surface of the blocks are swallow-tail clamp cuttings 0.35 × 0.10 m, which have been filled in with mortar. The use of mortar for filling in swallow-tail clamp cuttings is recorded in the Odeum of Corinth (late 1st c. BC – 1st c. AD) (Broneer, 1932). The shape of the cuttings is also observed in corresponding ones of monuments of ancient Corinth (Stillwell, 1952), that are assigned to the Julio-Claudian period (2nd half of 1st c. BC – AD 68). It is noted that the dimensions of some clamp cuttings in the Odeum are 0.30 × 0.09 m in a lower foundation course and 0.26 × 0.08 m in the one directly above, which fact shows that the size of the cuttings decreases in the upper courses. Thus, it is possible that the clamp cuttings in the lower course, in which they cannot be measured because they are not visible, were of the same dimensions as those of the harbour (0.35 × 0.10 m), showing that the surviving stone blocks in the channel belong to a foundation course.

Characteristic of the clamp cuttings of the channel is that their two diametrically opposite finials curve slightly like the corresponding Roman ones of monuments of ancient Corinth, in contrast to the swallow-tail clamp cuttings in earlier monuments of ancient Corinth, in which the diametrically opposite finials are more regular and straight. Examples of earlier cuttings can be seen on pedestals near the frieze of triglyphs (Hill, 1964). Consequently, in all probability the attribution to the Archaic typology, which Theodoulou (2002) argues, should be rejected. Even so, we cannot say for certain whether these constructions have only one phase, the Roman. It is possible that the existing material throughout the harbour of Lechaion comes from formations of the harbour earlier than the Roman, perhaps also from the Archaic period.

Preserved along one edge of the blocks of the east wall of the channel is a groove of approximately rectangular cross-section, which has been correlated with the existence of a bridge or some other system of cordoning off the port (Theodoulou, 2002). This correlation is considered rather groundless. The groove appears on one of the lowest, very possibly, foundation courses of the wall of the channel. The support of a bridge or of some other construction at such a low level, very close to the surface of the sea, should be considered impracticable and thus precluded. In any case, the groove along the upper edge of the outer side of the blocks could be interpreted as indicative of the bedding course of the upper course of blocks in relation to the existing ones, on the inside of these as the width of the groove suggests.

One other project of the Roman phase is the rectangular base of a monument on an artificial islet (called '*nisaki*') in the west basin of the inner harbour (Shaw, 1969) (Fig. 2). The monument was dated preliminarily to the 2nd–3rd c. AD, on the basis also of the attributing of an unfluted column of green Karystos marble to its upper structure. However, swallow-tail clamp cuttings in several of its blocks refer to the Julio-Claudian period (second half of 1st c. BC – AD 68) (Shaw, 1969). The structure construction was possibly a pedestal of a monument or a statue with torch, which functioned as a lighthouse (Shaw, 1969), although Wiseman (1978) considers more likely the version of a pedestal of a statue or statues. The dating of marine/brackish bioconstructions on the monument moves the date of its construction to pre-330 BC (Morhange et al., 2012), that is, at least three centuries earlier than the archaeological dating.

It is very possible that repairs, reconstructions and additions were made throughout the operation of the ancient harbour, depending on needs of the time. Wide-scale works, dredgings, conservations and interventions in the outer and inner harbours, seem to be repeated in the mid-fourth century AD, as emerges from the finding of a plaque with a dedication to 'Flavius Hermogenes', Proconsul of Achaea (AD 353–358), who financed the construction project (Kent, 1966).

At various points in the narrow part of the harbour, foundations of buildings and ruins of fortification works, probably of Roman or Byzantine times, have been found. At the top of the northeast sand mound are two small constructions that may have been beacons or smoke-signaling stations (Rothaus, 1995). The west one, with masonry of small stones and tiles, may belong to the Roman of Byzantine phase. Also, there are three partition walls of rude stones in single line, in the east, central and west part of the inner harbour (Rothaus, 1995). All over the area there is Roman pottery, mainly of the second century AD, and limited Late Roman moveable finds (Rothaus, 1995).

Apart from the remains associated with the operation of the harbour, buildings for other uses are located in the wider area. One very important find is the Early Christian basilica of the martyr Leonides, north of the south end of the west inner harbour basin (Fig. 2). Founded around the mid-fifth century and completed by the end of the fifth – early sixth century, it seems to have been devastated in the earthquake of 551–552 (Pallas, 1961, 1965), although this view is doubted by Sanders (2005). Excavations near the basilica of Lechaion have revealed the remains of houses dating both before and after the destruction of the church (Pallas, 1965). There is also a Roman Nymphaeum of the third century AD, which was transformed into an Early Christian fountain in the sixth century (Philadelpheus, 1921).

The attempt to date the ancient harbour through radiocarbon dating of marine fossils, by Stiros et al. (1996), gives calibrated dates between 600 and 50 BC, which are then reconsidered by Morhange et al. (2012) to dates ranging from 493 BC to AD 54, thus transposing the *terminus post quem* for the construction or reconstruction of the harbour installations during the Roman period of the harbour's use.

4. Historical seismicity

The earthquake report for this area, during the Archaic and the Hellenistic period, are limited and based mainly on the dating of macro-seismic events (Fig. 1). The strong earthquake of 760 BC likely triggered a tsunami, which struck the northern coast of the Gulf of Lechaion (Hadler et al., 2011). The elevation of the coast was between 0.70 m and 1.20 m, and was evidently caused by a strong seismic event which took place between 600 BC and 46 BC (Stiros et al., 1996; Morhange et al., 2012). Thucydides mentioned that the earthquake of 426 BC struck Corinth and the Isthmus area (Spyropoulos, 1997). Sieberg (1932) reported that the strong earthquake of 227 BC, which affected the whole of Greece, was felt even in the Corinthian Gulf. Dating of co-seismic uplifted sea notches on the northern coast of the gulf, points to strong antecedent seismic events during the Final Neolithic period and the Early Bronze Age (Pirazzoli et al., 1994; Gaki et al., 2000; Cooper et al., 2007).

Strong seismic events hit the area of Corinth during the first century AD, between AD 69 and AD 79 (Guidoboni et al., 1994; Papazachos and Papazachou, 1997; Papadopoulos, 2000;

Ambraseys, 2009). Spyropoulos (1997) refers to a preceding earthquake in AD 23. The most important earthquake is the one that occurred on 20 June AD 77 (Papazachos and Papazachou, 1997; Spyropoulos, 1997), or according to others in AD 74 (Papadopoulos, 2000; Valkaniotis et al., 2008), which caused extensive damage to the public buildings of ancient Corinth. Roman historians Quintus Curtius (AD 41–79) and Gaius Suetonius (AD 69–122), and the Byzantine chronicler Ioannis Malalas (AD 491–578) interpreted it as an "Act of God" that hit Roman Corinth. They referred also to the extensive reconstruction project of the public buildings, funded by the Roman Emperor Vespasian, which commenced after the earthquake (Georgiadis, 1904; Stillwell, 1952; Williams and Zervos, 1987). The severe earthquake caused the submersion by 0.70 m of the NW coast of the Saronic Gulf, as well as the port facilities of the Roman harbour of Kenchreai (Scranton et al., 1978). The epicentre of the earthquake was located between Acrocorinth and Hexamilia, and its magnitude has been estimated to be $M = 6.3$ (Papazachos and Papazachou, 1997; Valkaniotis et al., 2008).

The data on earthquakes occurred in the area of Corinth, during the fourth century AD are not clear and the damage possibly caused by seismic events has been confused with destructions incurred during the sack of Corinth by the Visigoths in AD 369. There is reference to destructions and reconstructions of public buildings in Corinth by the end of the fourth century AD, but the reasons that necessitated these are not very well defined (Wiseman, 1972; Gregory, 1979). However, there are data which confirm that part of the damage to and reconstructions of public and private buildings in ancient Corinth was due to the earthquakes of AD 365 and AD 375, while the possibility that these were caused by the invasion of Visigoths is excluded (Meritt, 1931; Weinberg, 1960; Kent, 1966; Wiseman, 1967; Catling, 1976; Williams and Zervos, 1991; Blackman, 2001). Papadopoulos (2000) considers that the most likely seismic event that struck the area is the earthquake of AD 362, with a maximum intensity in MM I = 6+. The earthquakes of this period were also responsible for the second phase of the submersion of the ancient harbour of Kenchreai by 0.80 m (Scranton et al., 1978) and for the co-seismic uplifts by 1.10 m on the southern coast of the Perachora peninsula, near the Heraion (Pirazzoli et al., 1994) and in the eastern area, between Lake Vouliagmeni and the shore at the foot of Mount Flambouro, by 0.35 m up to 0.90 m (Cooper et al., 2007).

The seismic sequence in the second half of the sixth century includes at least four seismic events, which occurred between AD 518 and AD 551 (Tigarakis, 1987a; Evangelatou-Notara, 1988; Papazachos and Papazachou, 1997; Spyropoulos, 1997; Valkaniotis et al., 2008; Ambraseys, 2009). The earthquake described by the Byzantine chroniclers as the most destructive of this period occurred between AD 518 and AD 526 (Edwards, 1937; Spyropoulos, 1997), most probably in AD 522 (Robinson, 1976) or in AD 524 (Papazachos and Papazachou, 1997; Papadopoulos, 2000). Its epicentre was situated 5 km west of ancient Corinth, with an estimated magnitude of $M = 6.6$ (Papazachos and Papazachou, 1997). The city of ancient Corinth suffered serious damage during the earthquake, public buildings collapsed (Scranton, 1957; Wiseman, 1972; Robinson, 1976), while one of the most important Early Christian basilicas in the Greek world, dedicated to Saint Leonides and located at Lechaion harbour, was razed (Scranton, 1957; Pallas, 1965; Rothaus, 1995). Hadler et al. (2011) adopted the view that the AD 521 or 551 earthquake, which was coupled with a strong tsunami, destroyed the basilica. However, according to Sanders (2005), the Early Christian basilica remained in use until *ca* AD 600 at least and the area was not affected by the earthquake, which struck mainly the western part of the Corinthian gulf. According to Papazachos and Papazachou (1997), the earthquake of AD 551 (Georgiadis, 1904) or AD 552 (Evangelatou-Notara, 1988; Papadopoulos, 2000), which is described by the Byzantine chronicler Prokopios as extremely strong and accompanied by a tidal wave, was a seismic sequence that affected the whole of Central Greece and the Corinthian Gulf, causing the total destruction of 8 cities, including Corinth (Evangelatou-Notara, 1988). Due to this earthquake, the Early Christian basilica at Kraneio also collapsed (Catling, 1978). There is evidence for an earthquake in 580, in the Gulf of Lechaion, with a magnitude of $M = 6.3$, which seems to have caused damage to the city of Corinth (Papazachos and Papazachou, 1997; Papadopoulos, 2000). Finally, the third phase of submersion of the ancient harbour of Kenchreai, by 0.80 m, was caused by the earthquakes occurred in the sixth century (Scranton et al., 1978).

In the fifteenth century, the 1402 severe earthquake with a magnitude of $M = 6.8$ and its epicentre located 45 km east of Lechaion triggered a tsunami (Evangelatou-Notara, 1988; Papazachos and Papazachou, 1997; Papadopoulos, 2000).

During the eighteenth century, strong earthquakes struck the area of Corinth, the most notable being the 1742 earthquake with a magnitude of $M = 6$, that of 1753 with a magnitude of 6.2 and, primarily, the 1756 earthquake, which was very severe (Koustas, 1858; Papazachos and Papazachou, 1997; Spyropoulos, 1997; Papadopoulos, 2000). There is no historical documentation for the co-seismic uplift by 0.40 m of the shore of Mount Flabouro, on the southern coast of the Perachora peninsula, dating back to 1690 (Cooper et al., 2007).

During the nineteenth century, at least three major earthquakes occurred. The strong earthquake of 1817, with its epicentre in the western Corinthian Gulf, was coupled with a tsunami that caused damage in the coastal zone (Tigarakis, 1987a). Before and after the destructive earthquake of 1858, there were four other earthquakes, in 1850, 1855, 1876 and 1887, which caused limited damage, even though the last one had a magnitude of $M = 6.3$ and triggered a tsunami (Galanopoulos, 1955; Papadopoulos, 2000). The strong earthquake of 1858 ($M = 6.7$) razed Ancient Corinth (Papazachos and Papazachou, 1997; Papadopoulos, 2000) and initiated the founding of the modern city of Corinth, which was destroyed in its turn by the 1928 earthquake (Koustas, 1858; Tigarakis, 1987b; Papazachos and Papazachou, 1997; Spyropoulos, 1997). Even though the magnitude of the 1928 earthquake was moderate ($M = 6.3$), the inadequate constructions of the new city collapsed, and the after-shocks completed the destruction (Tigarakis, 1987b). Additional earthquakes occurred in 1930 and 1931 ($M = 6.0$), 1953 ($M = 6.0$), 1954 ($M = 5.8$), 1962 ($M = 6.8$), 1972 ($M = 6.3$), and finally in 1981 ($M = 6.7$) followed by two strong after-shocks ($M = 6.4$ and $M = 6.2$) with epicentres in the Gulf of Alkyonides, which caused serious damage in the prefectures of Corinth, Boeotia and Attica (Antonaki et al., 1988; Papazachos and Papazachou, 1997).

5. Approach methodology

The decoding of the indications of older sea levels on the coast of Lechaion and the related palaeogeographical reconstruction of the shore of the ancient harbour, was based on: i) the present submerged or uplifted position of the ancient maritime structures, lithified beach sediments, tidal notches and various sea abrasion features on the structure, ii) the dating of the ancient harbour installations, iii) the determination of the 'functional level' of the archaeological benchmarks and their relation to the past sea level indicators, and iv) the relationship between the lithified beach sediments and the ancient harbour installations. On the grounds of this methodology numerous surveys have been carried out in the central and east Mediterranean (Flemming et al., 1973; Flemming, 1978; Pirazzoli, 1979; Flemming and Webb, 1986; Mourtzas, 1988a,b, 1990; Lambeck et al., 2004; Sivan et al., 2004; Antonioli et al., 2007; Scicchitano et al., 2008; Auriemma and

Solinas, 2009; Faivre et al., 2010; Lambeck et al., 2010; Pirazzoli, 2010; Anzidei et al., 2011a,b; Florido et al., 2011; Evelpidou et al., 2011; Rovere et al., 2011; Scicchitano et al., 2011; Anzidei et al., in press; Furlani et al., in press).

The present-day uplifted and submerged position of the coastal harbour installations of the outer harbour of Lechaion, which had a direct or indirect relationship with the coastline in the period of their operation, are sensitive indicators of past sea levels and allow the determination of the vertical direction, magnitude and age of the Upper-Holocene changes in the sea–land relationship. In order to understand the function of specific architectural parts of the harbour installations and their relationship with the sea level at the time of the constructions, the architectural elements of the ancient port facilities were mapped and their depth and elevation with respect to the present sea level were measured. The dating of the ancient constructions was based mainly on architectural, morphological, constructional and historical data.

Beachrocks are accurate indicators of older sea levels in the Aegean. These are lithified beach sediments, formed through the precipitation of mainly calcium carbonates due to physicochemical and microbiological activity, under warm temperature conditions and possibly with the presence of meteoric water (Alexandersson, 1969; El-Sayed, 1988; Gischler and Lomando, 1997; Kelletat, 2006; Vousdoukas et al., 2007). Cementation processes are taking place in a zone located between the lower tidal level and the higher margin of swash and backwash zone of the low-energy constructive waves. The measured depth of the base of beachrocks coincides with the lower tidal level of the corresponding sea level and can be used as a reliable indicator for the determination of an average older sea level. Beachrocks are formed during periods of tectonic and eustatic stability of sea level, and thus represent the fossilized seaward part of the deposits of an older depositional coast. The fluctuations of the local can form successive beachrock outcrops; their submerged or uplifted position today reflects different past sea levels and the respective ancient coastlines, mainly in areas of low tidal range, such as the Aegean Sea. The dating of the Aegean beachrocks was based on the archaeological evidence and constructions incorporated in or covered by the formation. This defines an upper time limit (*terminus ante quem*) for the formation of beachrocks not exceeding the age of the incorporated archaeological constructions and artefacts (Mourtzas, 1990, 2010, 2012).

The submerged and uplifted tidal marine notches, which have been carved on the structural components of breakwaters, are also accurate indicators of the sea level, mostly in areas of limited tidal influence, such as the Aegean. These have been formed in the intertidal zone in periods of eustatic and tectonic stability, and their roof and base coincide with the upper and the lower tidal level respectively (Pirazzoli, 1986).

All measurements were collected during periods of low-energy wave, using mechanical methods. To account for tides that can affect the measurements of the elevation and depth of the archaeological indicators, observational data have been reduced for tide values at the time of surveys with respect to average sea level, using tidal data from the nearest tide-gauge stations. All records were corrected for tides using data from the Hellenic Navy Hydrographic Service, for the closest tide-gauge station at Poseidonia, situated 6 km west of the study area. The maximum tidal range for the time period and the measurement hours was 0.40 m. The low-energy wave swash and backwash zone ranged between 3.0 m and 3.50 m, determined by repeated measurements for different periods of the year, with the velocity of the dominant NW winds being 8–12 mph and a wave height of 0.50 m, with the maximum elevation of the upper limit being 0.15 m.

After determining the past sea levels positions, were used maps and bathymetric data as aids in the palaeogeographical reconstruction of the ancient coastline and the assessment of the type of harbour installations.

6. Description of the coastal harbour installations of the outer harbour

The works of the foreharbour of Lechaion are located along the coast, with a general NE–SW orientation and a length of about 680 m, and include two extensive harbour basins, the west one 270 m wide and the east 260 m. These are demarcated by two moles, constructed at the end of two corresponding sandy spits, an entrance quay, protected by an entirely submerged breakwater to the north of it, and the works in the entrance of the inner harbour, which included dredgings and retaining walls for the lateral support of the channel (Fig. 2).

6.1. Entrance area of the ancient harbour

In the entrance area of the ancient harbour remains of the walls of the entrance channel to the inner harbour are still visible today, as well as the entrance quay and its protective breakwater, and to the east the remnants of buildings and the piles of boulders (Fig. 3).

6.1.1. Entrance channel and retaining walls to the inner harbour

The entrance channel to the inner harbour has a NE (N50°) – SW (N230°) direction, total length 230 m and a width varying between 8 and 12 m (Fig. 2). In the early 1990s its coastal section was backfilled for a length of 23 m, in order to construct a dirt road. Due to these earthworks, just nine blocks of the upper course of the east wall of the channel are still visible *in situ*, for a length of about 10 m. The dimensions of the blocks, which have been placed with their header to the inner side of the channel, range between 1.60 × 0.80 × 0.45 m and 1.40 × 0.55 × 0.30 m. The dimensions of the blocks of the lower course are 1.70 × 1.20 × 0.50 m, according to measurements taken in 1990, before the backfilling of the channel. Rubble masonry of respective dimensions, comprising rude stones and mortar, fills the interstices between the visible blocks. On the upper surface of the blocks there are still swallow-tail clamp cuttings 0.35 × 0.10 m and 0.10 m deep, filled with mortar. Mortar was also found in the joins between blocks. Preserved along the west edge of the blocks of the wall is a groove, of approximately rectangular cross-section (0.17 m wide and 0.15 m high) (Fig. 3).

The west wall of the channel has been entirely destroyed, as the entrance area suffered large-scale interventions at the beginning of the twenty-first century. Sixteen of the blocks have been arranged in a course at right angle to the shoreline. Some of them enter the sea and at their continuation metallic piles, visible under the sea, formed a pile-driven dock, used in the early twentieth century and today destroyed. Lining the west side of the channel are rectangular sandstone blocks perforated by marine molluscs, with dimensions ranging from 1.10 × 0.65 × 0.30 m to 1.40 × 0.80 × 0.40 m. On one detached block, today half-submerged a short distance from the shoreline, there are remains of masonry of small stone and blocks cemented together, which was probably placed there later. The existence of a superstructure 1.50 m high on the blocks of the east wall is documented in older photographs taken in the 1960s.

The blocks of the lower course of the east wall of the entrance channel have been incorporated into the beachrock, remains of which also cover the blocks located higher, up to the elevation of 1.10 m. The beachrock formation on the west side extends also to the area between the walls (Fig. 3).

At the seafront, just in front of the entrance, there are sparse blocks and piles of rude stones with dimensions up to 0.40 × 0.25 × 0.15 m, which continue underwater for 35 m from the

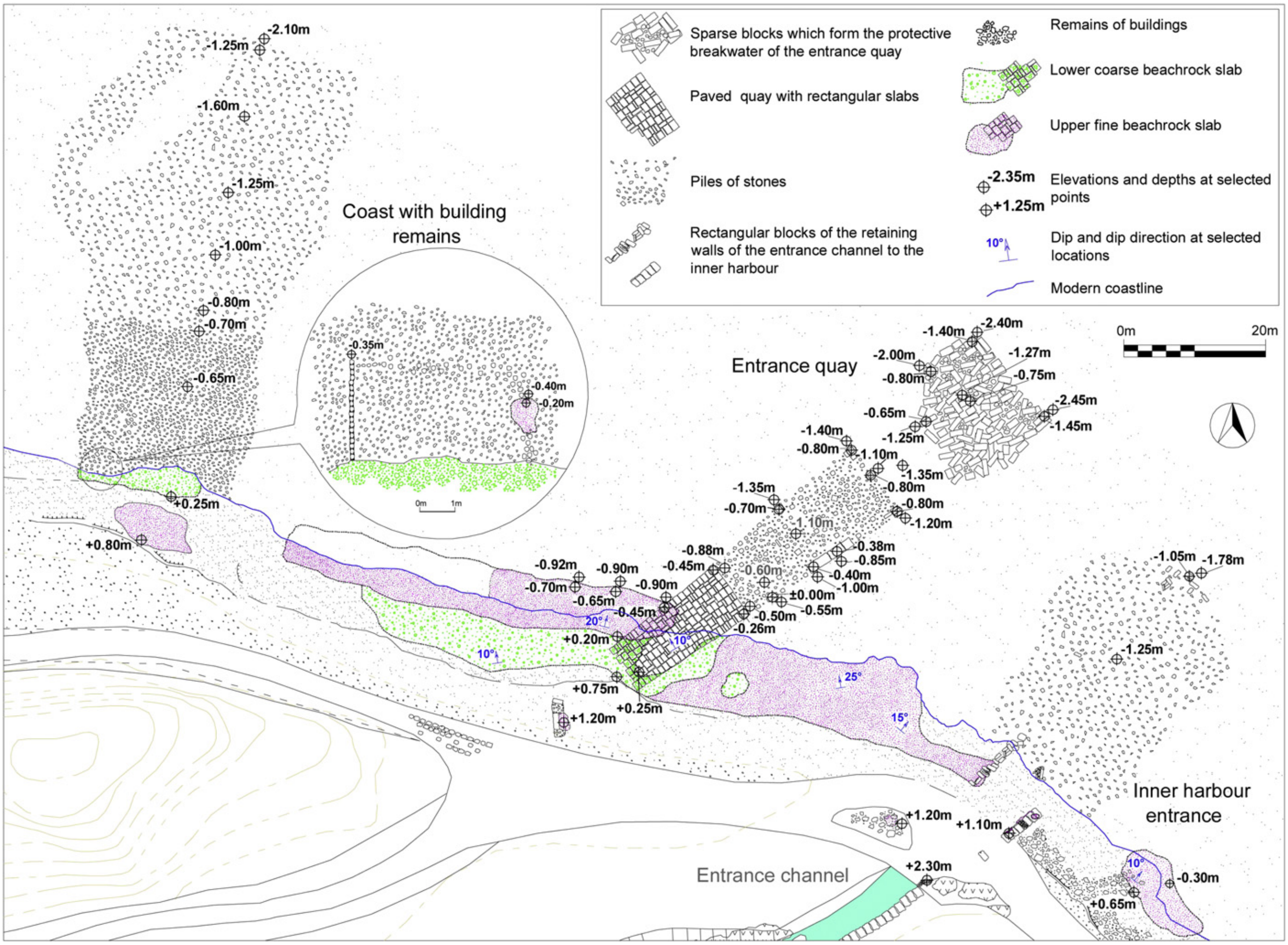

Fig. 3. Plan of the entrance area.

shore. At their end, their upper surface is at a depth of 1.05 m with the sea bottom being at 1.78 m (Fig. 3).

East of the entrance channel, in contact with the blocks of the east wall and for a length of 23 m along the coast, the remains of masonry of rude stones cemented together are visible. Part of the remains has been incorporated into the beachrock which develops along the shore for 15 m. It has a width of 6 m and dips at an angle of 10° to the NE under the sea up to a depth of 0.30 m.

6.1.2. The entrance quay and its protective breakwater

The ancient quay, of direction NE (N62°) – SW (N242°), is situated 33 m away from the entrance channel and its remains are visible for a length of about 20 m along the coast. Its orientation seems to coincide with that of the ancient road, which starts at the south end of the quay, skirts the east foot of the western sand mound and ends at the area of the Early Christian Basilica of the martyr Leonides (Fig. 2). This is a paved structure, well-preserved at present for a length of 18.50 m, of which 8.0 m runs along the present coast and 10.50 m under the sea. The pavement, with an inclination of 10° to the NW (330°/10°), is 7.0 m wide at its south preserved inland end and 8.50 m at its north undersea one. The southernmost remaining trace of the pavement, 20 m inland, with dimensions 5.40 × 1.50 m, is composed of blocks and rude stones cemented together. The pavement is constructed of rectangular sandstone slabs, of dimensions ranging between 1.0 × 0.60 × 0.20 m and 1.20 × 0.70 × 0.20 m. The blocks of the base of the pavement are not visible, but from the thickness of the construction at its north undersea edge we argue that it was composed of a course of blocks, of corresponding thickness to the overlying course.

Remains of the quay are visible under the sea for a length of 26 m (Figs. 3 and 4). These are sparse rectangular blocks from the pavement base and accumulations of rude stones of maximum dimensions 0.30 × 0.15 × 0.10 m, which were most likely the fill material of a riprap. In this destroyed undersea section of the quay a few blocks are preserved *in situ*, mainly at its north end. These are rectangular sandstone blocks with dimensions 1.20 × 0.40 × 0.40 m at its NW edge and 0.80 × 0.70 × 0.50 m at its NE end. On the west side of the central section there are still remains of masonry composed of rectangular blocks, probably, cemented. The length of the submerged wall is 7 m, its width 1.30 m and its height 0.60 m.

At a distance of 9 m from the north edge of the quay, the protective breakwater occupies an area of 250 m^2 and is composed of sparse rectangular blocks, of dimensions ranging from 1.70 × 0.90 × 0.80 m up to 2.50 × 0.70 × 0.60 m, in random arrangement, with rude stones up to 0.60 × 0.40 × 0.20 m between them (Figs. 3 and 4).

The upper surface of the quay at its north end is located at a depth of 0.80 m, while the depth of the sandy sea bottom varies between 1.10 m and 1.40 m. A seaway mediates between the edge of the quay and the breakwater, with the sandy sea bottom at a depth of 1.35 m. The upper surface of the breakwater is at depth 1.40 m in its north part, 0.75 m in the middle and 0.65 m in its south part, while the sea bottom is at depth 2.45 m to the north and 1.25 m to the south.

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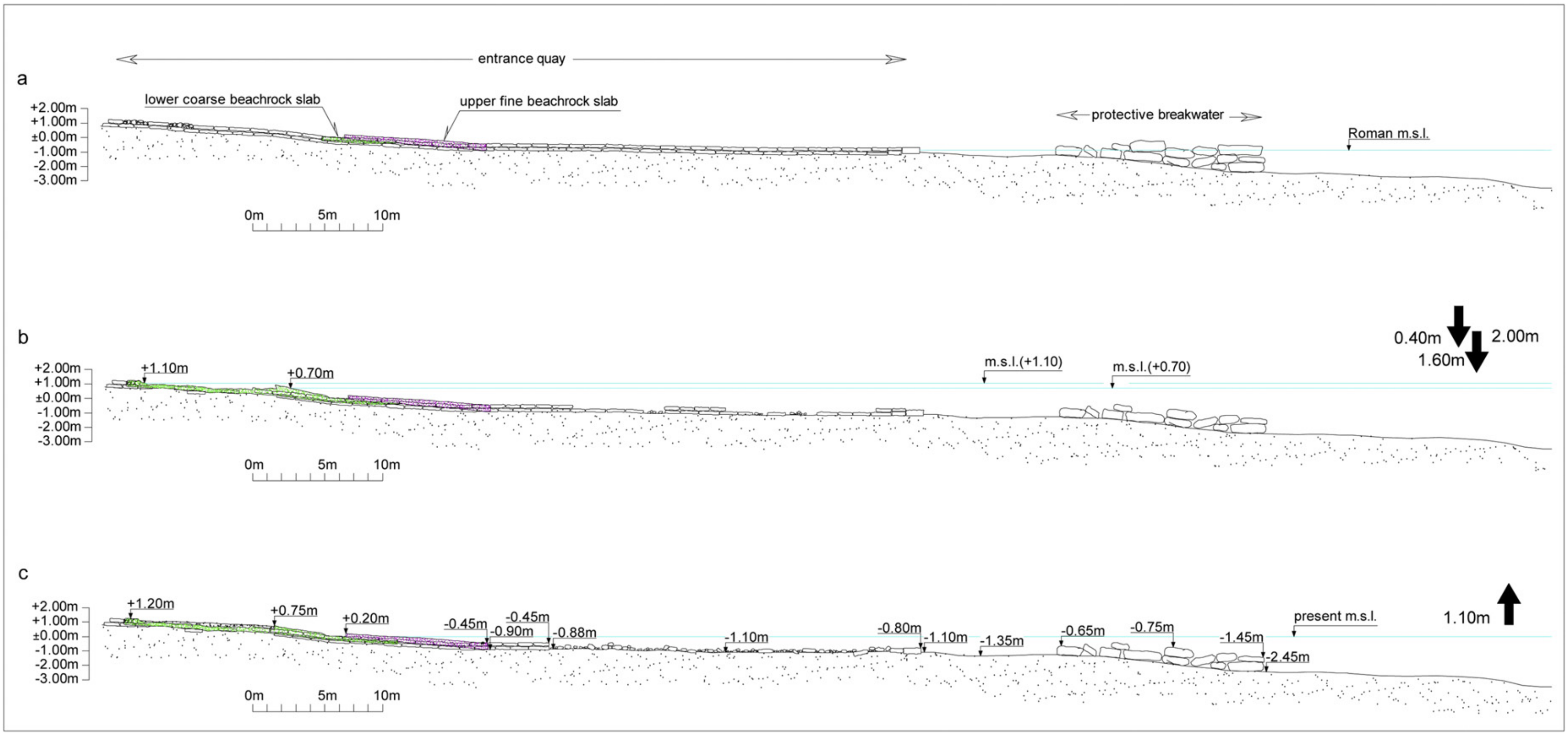

Fig. 4. Cross-section of the entrance quay, a: The sea level in Roman times was 0.90 m lower than the present. b: After the abandonment of the foreharbour and the siltation of its facilities, the area is submerged in two tectonic subsidence events and sea level rose by 2.0 m in total. During the first event, the mean sea level rose by 1.60 m and during the second one by 0.40 m, c: A strong tectonic uplift event followed and sea level dropped by 1.10 m.

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Along the coastline westwards from the entrance channel and for a length of about 100 m, two partly overlapping beachrock slabs have developed (Figs. 3 and 4):

- The lower, coarse, beachrock slab, 0.40 m thick, dipping 10°–25° mainly towards the NW, is composed of sand, cobbles with size up to 0.12 × 0.06 × 0.04 m, and angular coarse gravels with rounded edges, of size up to 0.35 × 0.30 × 0.15 m. It is a lithified allochthonous coarse-grained sediment, possibly of high-energy influence, located on the sandy coast with an inland width of 10 m up to a maximum elevation of 0.75 m. The entrance quay has been incorporated into this beachrock slab.
- The upper, fine, beachrock slab, dipping 20° towards the NNE, consists of sand and fine to coarse gravels, and is a lithified quiescent near-shore deposit. Of thickness 0.35 m and inland width 3.50 m, it covers the ancient pavement of the entrance quay and the lower beachrock slab as well. A handle and part of the rim of an amphora are incorporated into the undersea edge of the formation. It is submerged for a length of 5.0 m, at the north edge its top is at depth of 0.45 m–0.70 m, while its base is at depth of 0.90 m. Remains of the beachrock are preserved to the south of its main development and have incorporated the southernmost trace of the pavement of the entrance quay at an elevation of 1.20 m.

6.1.3. *Coast with building remains and piles of stones*

The oblong pile of boulders is today submerged and located at a distance of 75 m to the west of the entrance quay. It is mentioned as the east mole of the outer harbour, which probably belongs to an earlier building phase than the two west ones and chronologically coincides with the first phase of the works to protect the entrance to the inner harbour (Theodoulou, 2002).

The undersea investigation revealed that the piles of stones occupy an area of 1,900 m^2, NNE–SSW trending, 62 m long and with a maximum width of 37 m in its central section. They consist of boulders of dimensions between 0.30 × 0.20 × 0.10 m and 0.50 × 0.30 × 0.20 m. At the north end, the depth of the upper surface of the piles of stones is 1.25 m, while the sandy sea bottom is at depth of 2.10 m. The intermediate depths decrease gradually southwards. The greatest concentration of boulders is observed in the section adjacent to the coastline, approx. 20 m long, where the upper surface of the stones is at depth 0.70 m (Fig. 3).

The foundation of a building, constructed of rounded stones cemented with mortar, starts from the coastline at the SW edge and continues under the sea for a length of about 3 m and to the depth of 0.35 m. Part of the foundation on the east side of the building has been incorporated into the beachrock and is today at depth of 0.40 m (Fig. 3a).

The coarse beachrock slab is developed along the coast for a length of 17 m and a width of 5 m, and consists of cobbles to angular coarse gravels, which probably come from collapsed masonries and belong to an ‘archaeological destruction level’. The fine beachrock slab is developed inland, a few meters south of the shoreline, up to the elevation of 0.80 m (Fig. 3).

6.2. *East mole*

The east mole is located at the end of a sandy spit, which interrupts the continuity of the straight NW–SE orientated coast, and penetrates into the sea in a N–S direction for a length of 65 m approximately (Fig. 2). Today’s visible section protruding from the sea is 27.0 m long, with a width varying from 5.50 m at its north end, to 9.50 m at in the middle and up to 10 m at its south visible end. The undersea section is 26.50 m long and 34.50 m wide in its north part. The east and west parts of the protruding section are 30 m and 8.50 m wide, respectively. Thus, the total length of the east mole is 54 m and its width varies from 12.70 m at its north undersea end to 48 m at the south one. Further south, its remains are covered by the coastal deposits.

From a constructional point of view, the mole is divided into three sections (Figs. 5 and 6):

The inner section paved with rectangular sandstone slabs of dimensions between 1.10 × 1.0 × 0.30 m and 1.50 × 0.80 × 0.60 m comprises the quay (Fig. 5a). The base of the pavement consists of sandstone blocks of dimensions ranging from 0.90 × 0.80 × 0.20 m to 3.30 × 0.60 × 0.50 m, laid in two – at least – intersecting courses. The total length of the paved section above and below the sea level is approx. 42 m and its width varies between 9.0 m at its north end and 29.0 m at its south one. The pavement seems to form a smooth curved surface, slightly inclined at angles 2°–4° towards its north, east and west edges. The northernmost part of the pavement has been cracked, probably due to the subsidence of the base. The cuttings on the blocks of the pavement at the north end of the quay, of dimensions 0.30 × 0.20 m and depth 0.20 m, probably were used to fix wooden elements either for mooring of ships or to support wooden cantilevers.

The paved part of the quay is surrounded by sparse blocks of dimensions up to 2.70 × 0.80 × 0.40 m in the north section, 1.60 × 0.80 × 0.50 m in the west and 1.10 × 0.70 × 0.30 m in the east one, which form the protective breakwater (Fig. 5b). In the north section, its length reaches 12.50 m and its width 21.0 m, while on its east and west sides its width varies between 6.0 and 6.30 m, respectively. The protective outer part of the quay is not extended over the south section of the quay, thus allowing the approach and beaching of ships.

On the NE side of the mole, the breakwater is completed by a riprap of rough stones of dimensions between 0.30 × 0.20 × 0.10 m and 0.50 × 0.30 × 0.20 m, probably added later.

At the SW end of the mole a masonry 0.30 m thick, composed of rude stones measuring 0.30 × 0.20 × 0.10 m cemented together, covers the pavement and is developed parallel to the coastline. Probably, this construction was the base of a lighthouse building or a guardhouse (Figs. 5 and 6a).

The higher preserved section of the paved quay is located at its south visible end at the elevation of 0.90 m, while in the north section, protruding from the sea, it does not exceed 0.40 m. Concerning the undersea section, the depth of the pavement to the north reaches 0.95 m, while in the east and west sections is 0.15 m and 0.33 m, respectively. The northernmost cracked edge of the quay is at a depth of 1.45 m. In the northernmost section of the protective breakwater, the upper surface of the blocks is at a depth of 1.35 m, while the sandy sea bottom at 1.95m. The corresponding depths in its west section are 0.90 m–1.00 m for the surface of the stones and 1.50 m for the sea bottom. On the east side the upper surface of the breakwater is at depths between 0.70 m and 0.80 m and the sea bottom at 0.95 m (Fig. 5).

On the north and west sides of the quay a marine notch has been formed on the blocks at the depth of 0.90 m. Sparse traces of intertidal sea erosion have also been found at the same depth, which correspond to a past sea level. Remains of a beachrock, into which the pavement and the overlying masonry have been incorporated, are situated in the SW section of the quay, while their continuation to the west submerges undersea level to a depth of 0.15 m. Finally, a tidal marine notch has been formed on the blocks of the pavement in the south visible section of the quay, with its base is at the elevation of 0.55 m (Fig. 5c). Traces of intense sea erosion at the same elevation have also been observed over the entire visible south section of the quay.

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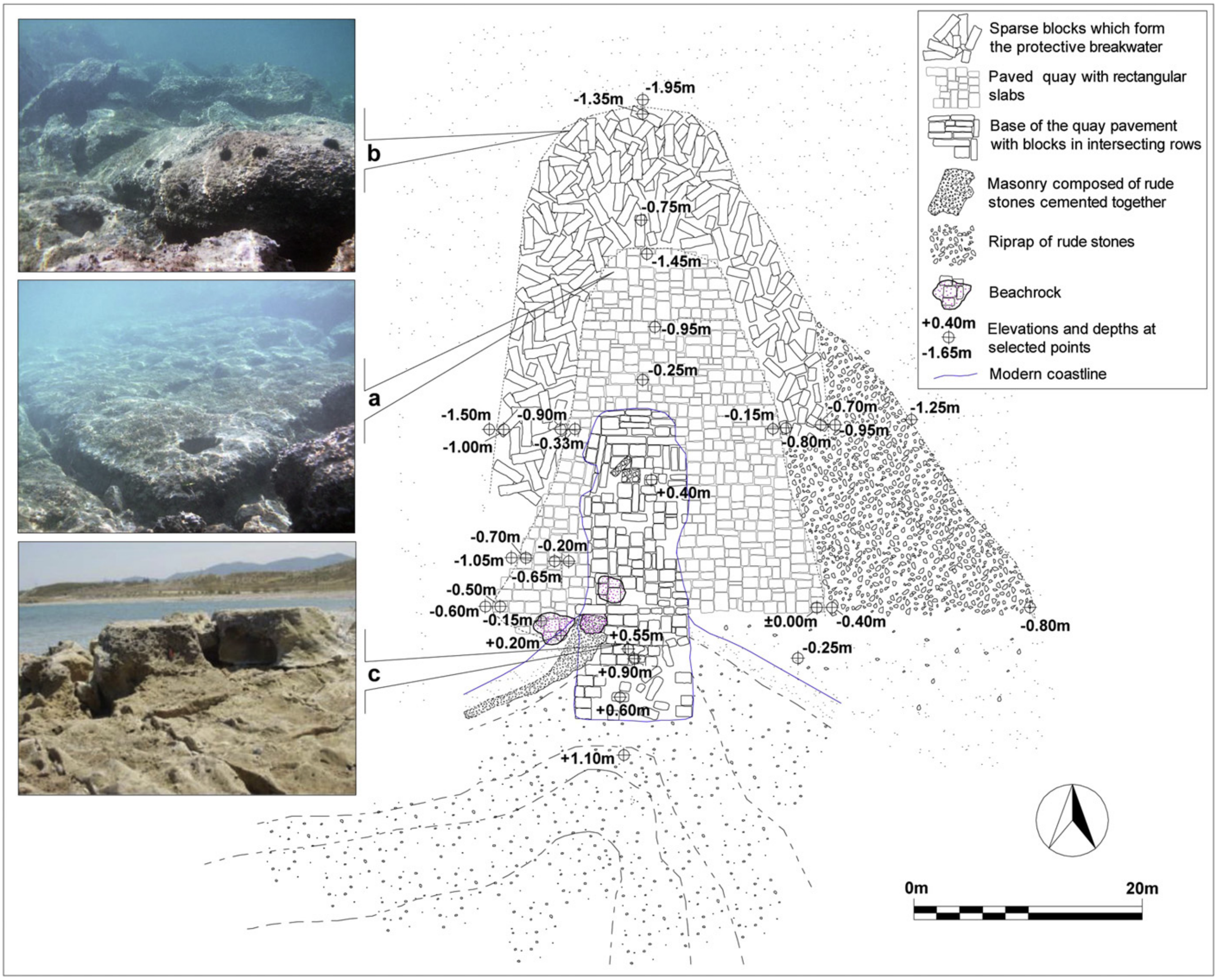

Fig. 5. Plan of the eastern mole. a: view of the submerged quay pavement, b: view of the submerged breakwater, c: view of the tidal marine notch formed on the blocks of the quay pavement which corresponds to the earlier phase of submersion.

6.3. West mole

The west mole is located at a distance of about 250 m from the east one. It has been constructed at the north end of a sandy spit, which thrusts out into the sea in a N–S direction for a length of about 50 m (Fig. 2).

Today's visible section of the mole, which protrudes from the sea and has not been covered by sand, is 43 m long and varies in width from 8 m at its north end, 13 m in the middle part up to 10 m at its southern end. Under the sea, it is developed northwards for a length of 34.50 m, eastwards for 23 m and westwards for 20 m. The total length and width of the mole is 77.50 m and 55 m, respectively (Fig. 7).

The inner quay and the outer breakwater that surrounds it are the main architectural features of the mole.

The surface of the quay is paved with rectangular sandstone slabs, of dimensions between 2.0 × 1.10 × 0.35 m and 1.80 × 0.90 × 0.30 m (Fig. 7a). The base of the pavement is composed of sandstone blocks of corresponding dimensions, laid in two – at least – intersecting courses. The total length of the paved section above and below the sea level is 40 m, and its width varies between 22 m and 34 m at its northern and southern end, respectively. As regards the east mole, the pavement of the quay seems to form a smooth curved surface, slightly inclined at angles 2°–4° to its north, east and west edges.

The quay is enclosed by a protective breakwater composed of sparse blocks of dimensions ranging from 1.20 × 0.70 × 0.40 m to 3.0 × 1.10 × 0.40 m. In the north section, its length is 27.0 m with maximum width 45.0 m, while on its east and west sides the width varies between 12.0 m and 16.0 m, respectively.

At the SW end of the mole, a masonry 0.30 m thick, similar to that of the east mole, composed of rude stones 0.30 × 0.20 × 0.10 m cemented together, covers the pavement over an area of 65 m^2. This likely was the base of a lighthouse building or a guardhouse (Figs. 7 and 8a).

The paved section of the quay protrudes from the sea by 0.90 m in its visible south section, 0.14 m–0.20 m in the central one and 0.55 m in the north. Concerning the undersea section, the maximum depth of the pavement in its north part is 0.40 m, in the east 0.20 m and in the west 0.28 m. In the northernmost section of the breakwater, the surface of the blocks is at depths varying between 0.75 m and 1.50 m, with the depths of the sandy sea bottom at 1.45 m–1.95 m. On the west side of the breakwater, the respective depths of the surface of the stones and the sea bottom range from

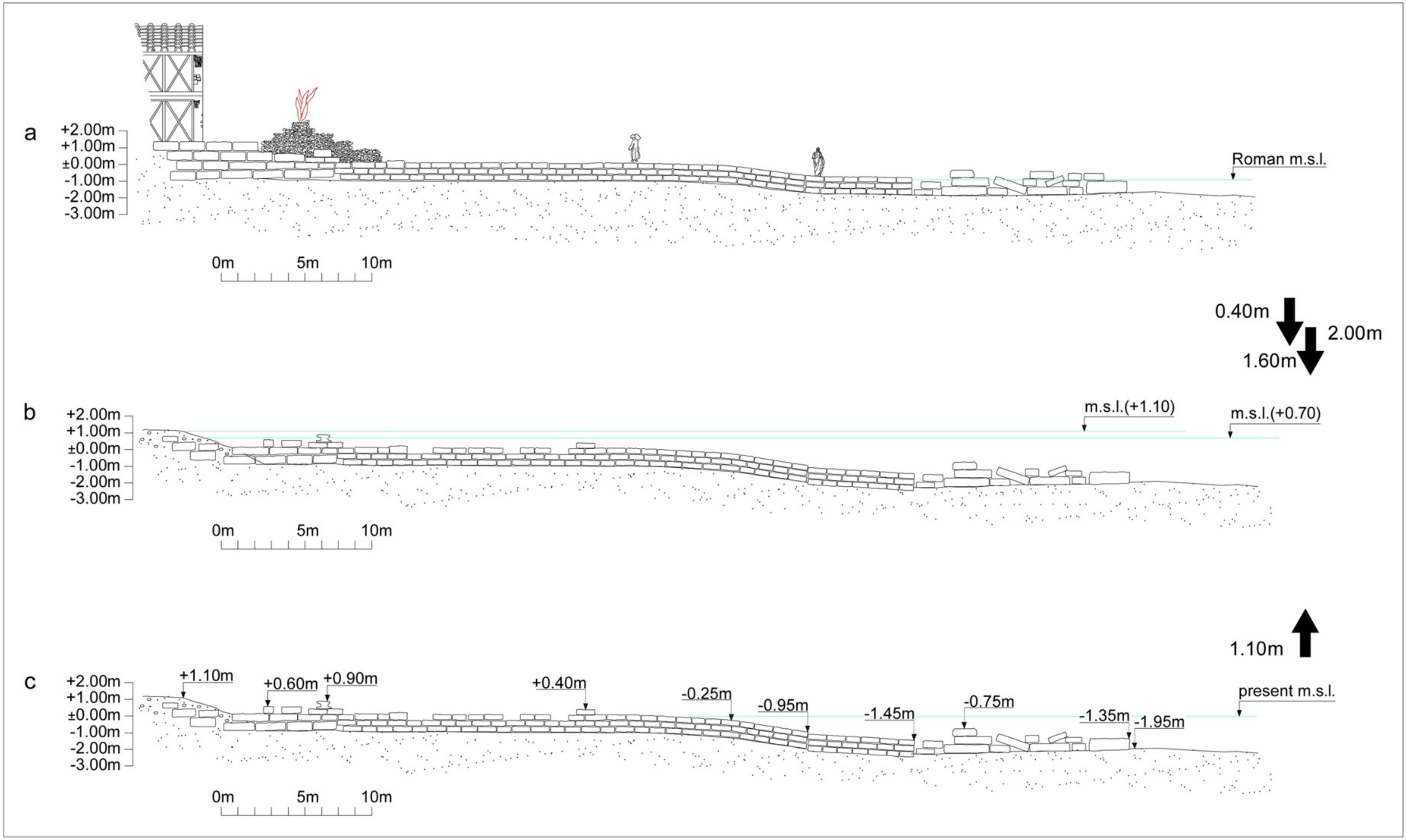

Fig. 6. Cross-section of the eastern mole, a: The sea level in Roman times was 0.90 m lower than the present. b: After the abandonment of the foreharbour and the siltation of its facilities, the area is submerged in two tectonic subsidence events and sea level rose by 2.0 m in total. During the first event, the mean sea level rose by 1.60 m and during the second one by 0.40 m, c: A strong tectonic uplift event followed and sea level dropped by 1.10 m.

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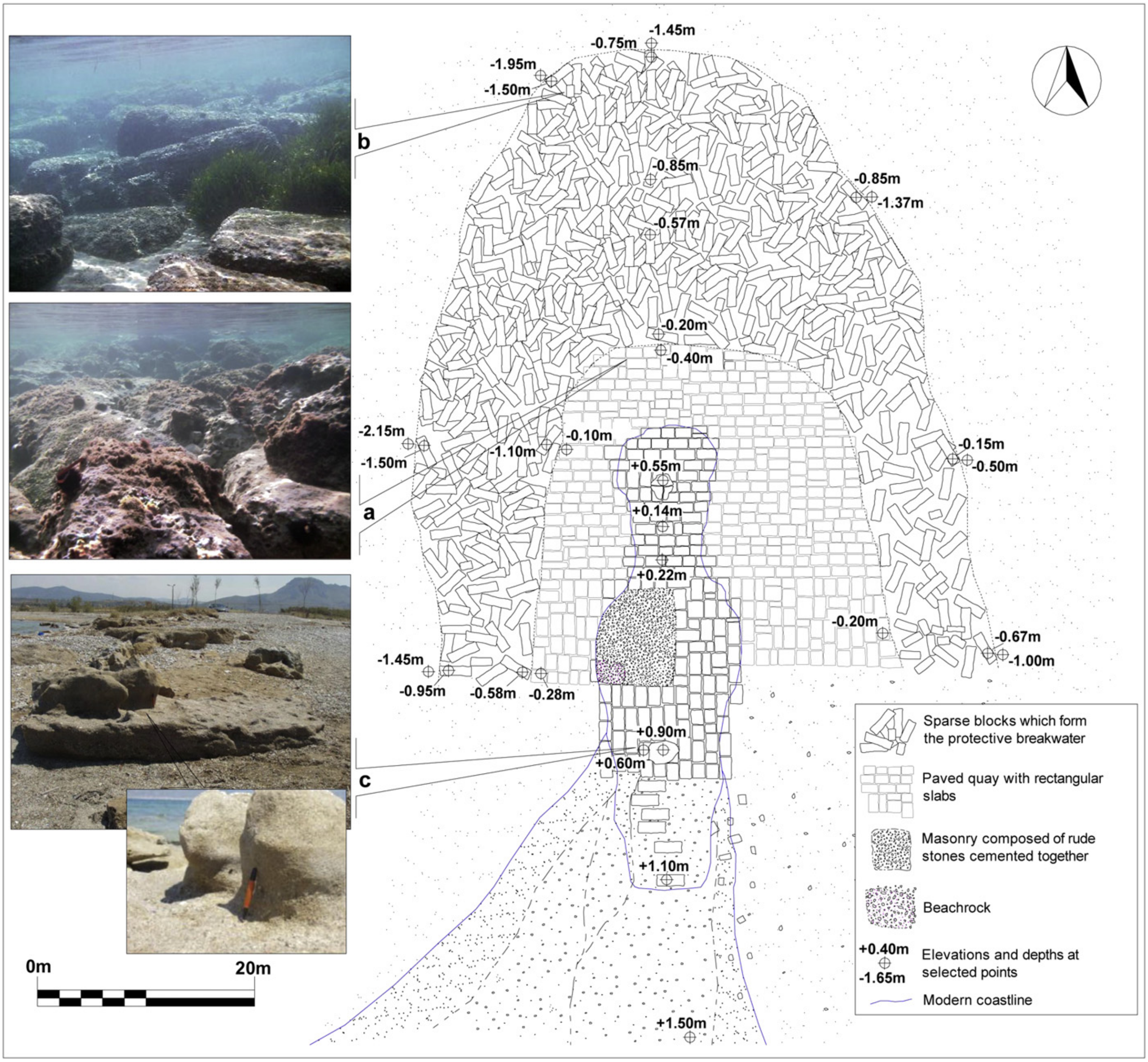

Fig. 7. Plan of the western mole. a: view of the submerged quay pavement, b: view of the submerged breakwater, c: view of the tidal marine notch formed on the blocks of the quay pavement which corresponds to the earlier phase of submersion.

0.95 m to 1.50 m and 1.45 m to 2.15 m, respectively. On its east side, the surface of the blocks is at depths of 0.15 m–0.67 m and the sea bottom at 0.50 m–1.00 m.

Remains of a beachrock, into which the pavement and the overlying masonry have been incorporated, are located on the west side of the protruding section of the quay. A tidal marine notch, similar to that of the east mole, has been formed on the blocks of the pavement in the visible south section of the quay. The opening of the fossilized notch is 0.25 m, its base is at elevation 0.60 m and the surface of the blocks on which it has been formed is at 0.90 m (Fig. 7b). Traces of intense sea erosion at the same elevation have also been found over the entire visible south section of the breakwater.

7. Indications of the sea level fluctuations

The paved surfaces of the entrance quay and both the moles provide reliable archaeodetic clues for estimating the sea level during the period of operation, because these pavements certainly protruded above the then sea level. Today, their maximum depth ranges from 0.40 m at the quay of the west mole, to 0.80 m at the entrance quay and 0.95 m at the quay of the east mole. The marine tidal notch on the blocks of the west and north sides of the quay of the east mole, at a depth of 0.90 m, is indicative of the older functional sea level of the quays. The sea level was 0.10 m–0.50 m lower than the pavement surface, so as not to flood it even during the high tide. The functional sea level coincides with the present depth of the submerged section of the beachrock, which is 0.65 m at its top and over 0.90 m at its base. The northernmost section of the beachrock was formed when the sea level was 0.90 m lower than at present, incorporating part of the entrance quay and pottery shreds.

A sea level 0.70 m higher than at present is defined by the uplifted marine notches, with an opening of approx. 0.25 m, formed on the blocks of the south inland section of the east and the west

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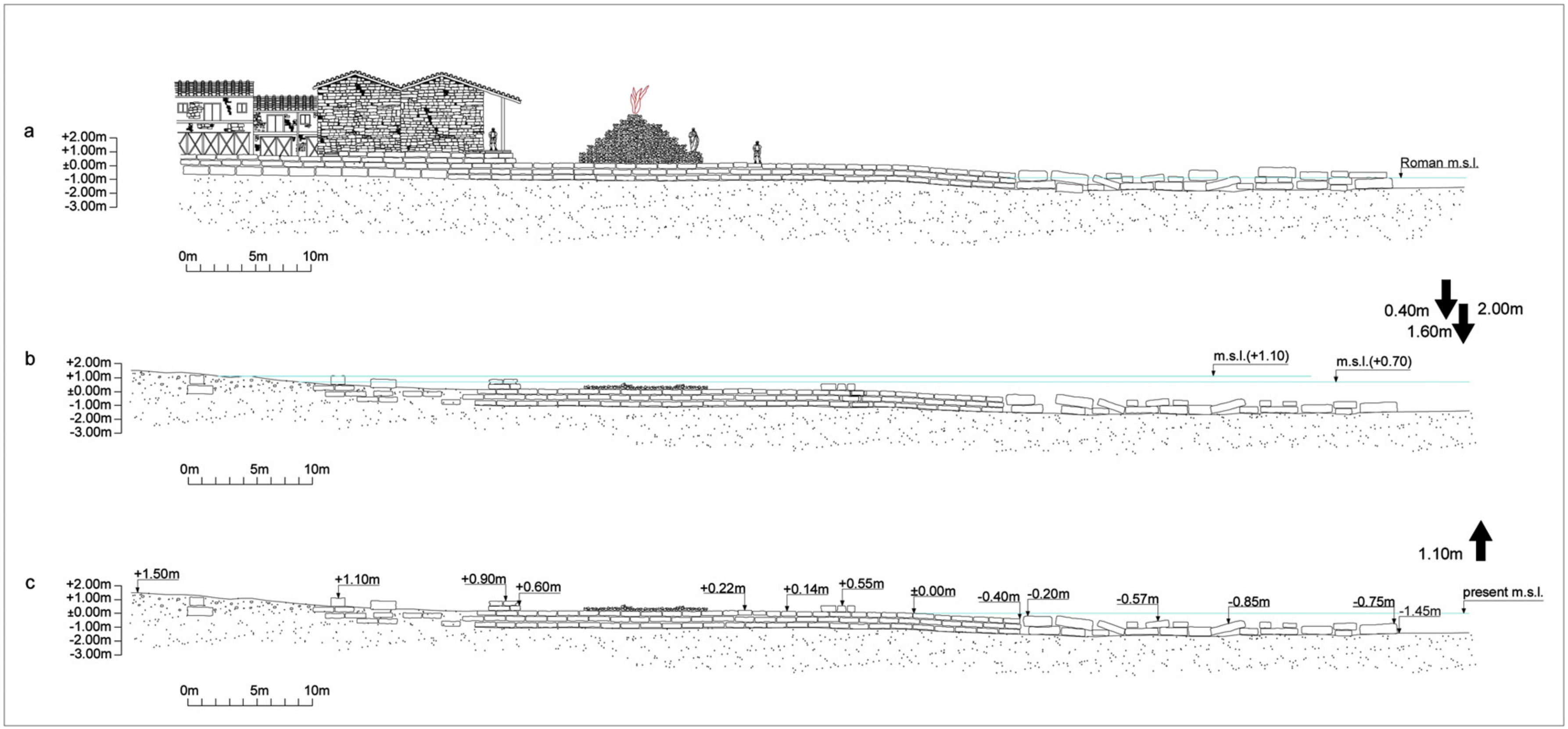

Fig. 8. Cross-section of the western mole. a: The sea level in Roman times was 0.90 m lower than the present. b: After the abandonment of the foreharbour and the siltation of its facilities, the area is submerged in two tectonic subsidence events and sea level rose by 2.0 m in total. During the first event, the mean sea level rose by 1.60 m and during the second one by 0.40 m, c: A strong tectonic uplift event followed and sea level dropped by 1.10 m.

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mole. The base of the notches is at an elevation of 0.55 m and 0.60 m, respectively, and traces of intense sea erosion have been found at the same elevation over the entire visible south section of the moles. The beachrock, which has incorporated and covered sections of the paved surfaces of the quays and of the remnants of masonry on them, is located at elevation 0.20 m. It was formed by a sea level higher than the initial functional level, after the abandonment of the outer harbour installations and their subsequent siltation.

Indications of a higher mean sea level at the elevation of 1.10 m are: i) the borings of marine lithophaga fossils on the blocks of the entrance channel up to the elevation of 1.20 m, ii) the beachrock that has incorporated and covered *in situ* blocks of the east wall of the entrance channel up to the elevation of 1.10 m, iii) the remains of the beachrock that cover the destroyed masonry just east of the channel, and finally iv) the beachrock that has incorporated and covered the pavement of the entrance quay at an elevation of 1.20 m.

The indications of the past sea levels, as presented above, allow us to reconstruct the evolution, as well as the amplitude and direction of the vertical tectonic movements responsible for the observed changes.

During the period of operation of the foreharbour, sea level was 0.90 m lower than the present. Beachrock was formed at the same time, by the cementation of the coastal sediments, incorporating part of the foundation of the entrance quay. This process continued even after the abandonment and siltation of the harbour constructions (Fig. 4).

In the time following, the coast submerged and the sea level rose by a total of 2.0 m during two paroxysmal tectonic subsidence events. During the first event, sea level is estimated to have risen by 1.60 m, which is the present elevation of 0.70 m, as proved by the marine notches on the breakwaters which are located at the respective elevation. At this new sea level the intermediate – up to elevation 0.70 m – beachrock was formed, which has incorporated and partly covered the ancient quay. During the second tectonic subsidence event the mean sea level rose by 0.40 m, to the present elevation of 1.10 m, forming the upper section – at elevation 1.10 m – of beachrock, which has incorporated the upper section of the paved entrance quay, the blocks of the east wall of the entrance channel and the remains of the masonry east of this. A strong tectonic uplift event followed, causing a drop in sea level by 1.10 m and the emersion at the current level of parts of the previously submerged beachrock and the entrance quay incorporated into it, the entirely submerged – during the previous subsidence events – quays of both moles and the walls of the entrance channel. However, significant sections of the entrance quay with the corresponding beachrock and the quays of both moles, as well as the entire breakwaters, remain below the present sea level (Figs. 4, 6 and 8).

8. Dating of sea level

Mourtzas and Marinos (1994) described the recent tectonic evolution of the area after the abandonment of the ancient harbour, which seems to have caused an uplift of at least 1.10 m and in part emersion of the ancient harbour, while the subsequent subsidence, which does not exceed 0.70 m, resulted in partial submersion of the harbour installations. Maroukian et al. (1994) consider that the coast of Lechaion has uplifted by at least 0.70 m and date this tectonic event back to the end of the Hellenistic and Roman period of the harbour.

The dating of the relative sea level fluctuations along the coast of Lechaion harbour using the radiocarbon dating method on marine fossils is a complicated issue. Stiros et al. (1996) analyzed with the AMS technique two samples of marine fossils collected from the east retaining wall of the entrance of the inner harbour, '*from a wall appeared to be in situ*' without providing evidence and despite the view of Scranton et al. (1978) on the reuse of blocks of this wall. The samples were collected at a distance of 100 m and 120 m from the coastline and an elevation of '*approximately 1.10 m above the water*', and '*correspond to marine organisms that drilled the limestone blocks after the construction of the wall, when the latter was still in the water*'. According to the authors, the calibrated ages of samples are between 600 and 50 BC, thus these are assigned arbitrarily '*the date of 340 BC, which is the most probable date for the fossils analysed*'. Moreover, they claim that the '*fossils at the entrance of the harbour at Lechaion were killed by an episodic land uplift with an amplitude of at least a few tens of centimeters; this uplift probably occurred between 500 and 200 BC, according to the radiometric data*' (Stiros et al., 1996). In a recent republication of these results by Morhange et al. (2012), the elevation of sampling is presented to be at 0.70 m and the calibrated ages of the equivalent uplift co-seismic movement is dated between 493 BC and AD 54. These new assessments modify significantly the previous estimation, because they reduce the vertical displacement of the coast by 0.40 m and shift the *terminus post quem* of the tectonic event to at least 100 years later, that is after the Roman period of construction or reconstruction of the harbour. In addition, the relativity of radiocarbon ages determined for the boring bivalve *Lithophaga lithophaga* found on the same substrate should be taken into consideration, as the observed ages may show deviation by 350–2000 years from the date of the event that uplifted and exposed them above sea level (Shaw et al., 2010).

Moreover, Morhange et al. (2012) date the marine/brackish bioincrustations on the structure in the middle of the former Lechaion basin, called '*nisaki*' and conclude that they correspond to an uplifted shoreline about 1.20 m above sea level, dated to 330–46 BC. However, the fluctuation of the water level in the inner harbour, which was isolated from the sea for significant time periods, is determined -as at present- by the volume of water that ends at the basin and is not subject to sea level variations. The dated biomarkers are located in the central section of the west basin of the inner harbour, at a distance of 650 m from the coast. The basin was isolated from the sea not only due to the siltation of the artificial entrance, as is indicated by the presence of beachrock incorporating its wall, but also because of the periodic blockage of the natural narrow communication channel between the central and the west basin. High water levels are observed during wet periods, when a significant volume of water ends at it, while it becomes completely dry during the summer. This is confirmed by the presence of marine and brackish organisms, and various erosion forms throughout the installations of the inner harbour. Therefore, it is erroneous to consider as indicators of the vertical direction, magnitude and age of sea level variations, the independent fluctuations of the water level inside the basin of the inner harbour and their dating as well. Moreover, the radiocarbon ages of biomarkers are in direct contradiction to the archaeological dating of the construction [second half of the first century BC – 68 AD (Shaw, 1969)] that the biomarkers cover, which is clearly subsequent to the lower radiocarbon age [330–46 BC (Morhange et al., 2012)].

Key factor for dating the vertical co-seismic tectonic events on the coast of Lechaion is the determination of the time of construction, the period of operation and the time of abandonment of the foreharbour installations, which have been incorporated into the beachrock. The cementation of this formation is contemporary with the operation of the ancient foreharbour, incorporating also some of its structural elements when the sea level was 0.90 m lower than at present. The cementation process and the incorporation of the coastal constructions into the beachrock was gradual and definitely continued after their abandonment and siltation, when sea level rose to elevations 0.70 m and 1.10 m above the present one.

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Based on architectural, morphological and constructional data of the coastal port facilities, the Roman phase of reconstruction and use of the installations of the outer harbour was confirmed until at least the mid-fourth century AD. Consequently, the *terminus post quem* for the incorporation of the coastal harbour facilities into the beachrock is the mid-fourth century AD, which means that this process evolved after the last evidence of use and renovation of the ancient harbour. The view adopted by previous scholars (Maroukian et al., 1994; Mourtzas and Marinos, 1994; Stiros et al., 1996; Morhange et al., 2012) on a one and only uplift phase of the coast of ancient harbour, certainly did not take into consideration the process of formation of beachrock, the incorporation of ancient Roman constructions into this, and their submerged position at present.

9. Palaeogeographical reconstruction of the coast of the outer harbour of ancient Lechaion

The paleogeographic reconstruction of the coast, after the determination of the initial functional sea level of the harbour installations during the Roman phase of the ancient harbour, and the direction and magnitude of the three vertical tectonic movements which caused the fluctuation of sea level, is based on topographical and bathymetric maps of the area (Papafotiou, 2009) completed by the bathymetric and elevation data of the present investigation (Fig. 9).

The sea level in Roman times was 0.90 m lower than at present. During this period, the coast at the basins of the outer harbour was about 40 m wider than at present, while the paved quays and the upper section of the protective breakwaters were above the then sea level (Fig. 9a).

In the area of the entrance channel to the inner harbour, the coast during the period of its operation was at least 18 m wider than at present. Although many interventions have been made in this area since the early nineteenth century, the underwater investigations confirmed its continuation only for a short stretch off the coastline. However, the possibility that during the Roman phase of the harbour the ships – after unloading their cargo at the quays of the moles and the entrance – were pulled along the sandy seabed up to the area of the entrance channel, through which they were brought into the inner harbour, cannot be ruled out (Fig. 9a).

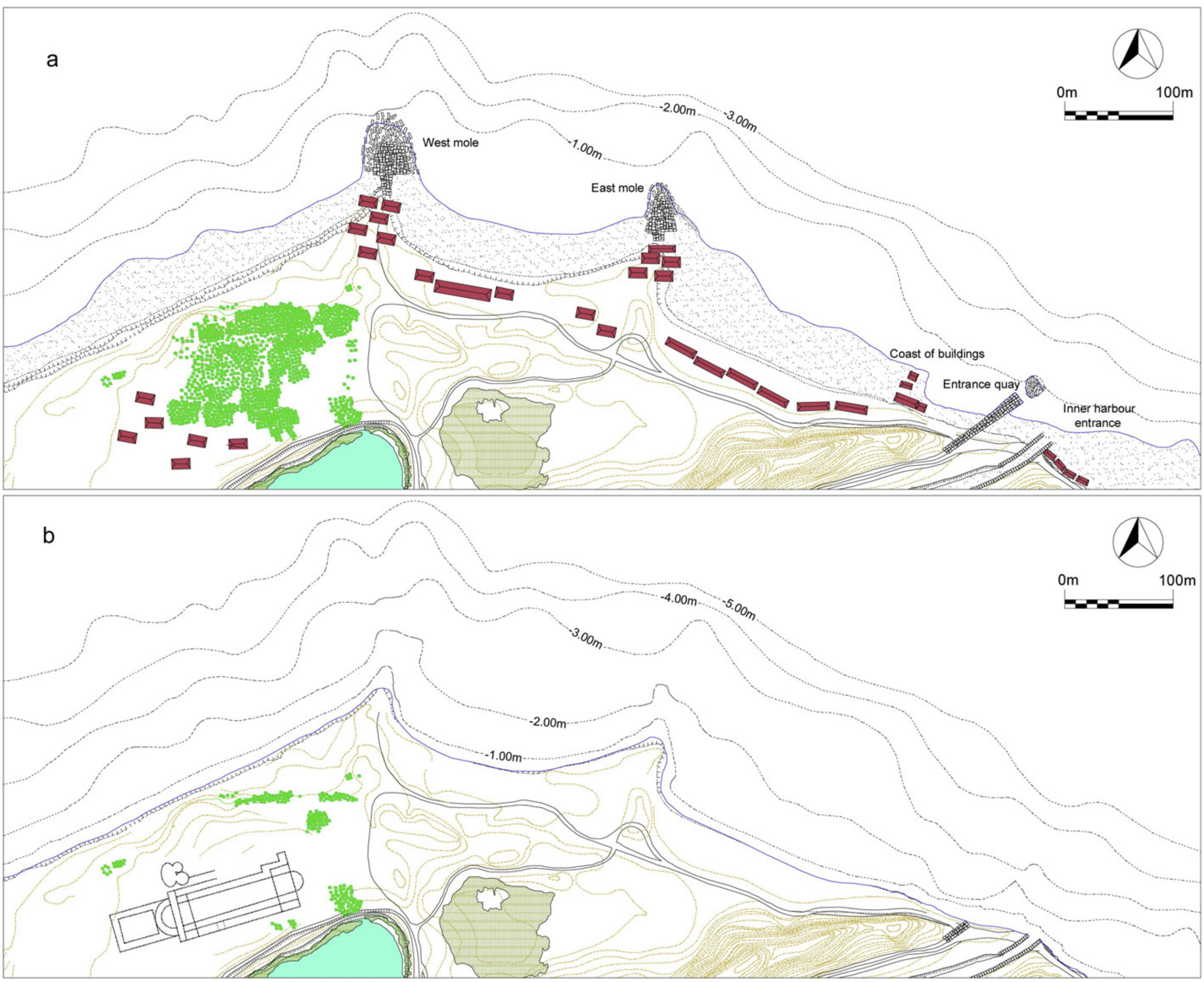

Fig. 9. Palaeogeographical reconstruction of the coast of the foreharbour of ancient Lechaion. a: The sea level in Roman times was 0.90 m lower than the present. b: After the abandonment of the foreharbour and the siltation of its facilities, when the sea level rose by 2.0 m. At the same period the installations of the outer harbour were entirely submerged.

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Westwards of the area of the entrance quay, the Roman coast was 35 m wider than at present. The quay was founded on the sandy coast and between its end and the protective breakwater a seaway was formed, today shallow. Probably, the seaway was deeper during the period of operation and its siltation followed. The breakwater of the quay protruded above the then sea level or might have been even higher, if it is supposed that the upper course of the blocks has collapsed (Fig. 9a).

The section of the coast with the building remains and the piles of stones east of the entrance quay will have been approx. 20 m wider during the Roman period, as it is deduced from the abundance of remains and stones in the current depth of 0.70 m. This area probably accommodated the coastal ancillary buildings and warehouses, which subsequently collapsed forming the piles of stones (Fig. 9a).

After the abandonment of the outer harbour and the siltation of its facilities, the area was submerged by 2.0 m and the coast shrank by 9 m in the area of the basins, narrowing by 16 m at the entrance area of the inner harbour. At the same period the installations of the outer harbour were entirely submerged and the sea filled up the inner basins (Fig. 9b).

Finally, after the last uplift phase and the drop of sea level by 1.10 m, the sea regressed and the coast acquired its present configuration (Fig. 2).

10. Discussion

The south coast of the Gulf of Lechaion is a tectonically active area where uplifting and downlifting events repeatedly occurred during historical times. In this complex region, this study provides new insights on the sea level change and vertical tectonic movements of the land since historical times.

The sea level during the Roman operation of the harbour was 0.90 m lower than the present. This functional level is in agreement with the predicted sea level of the glacio-hydro-isostatic and eustatically corrected model of Holocene relative sea level for the Peloponnesus developed by Lambeck and Purcell (2005). According to the glacial isostatic adjustment model for late Holocene presented by Evelpidou et al. (2012a), the relative sea level in the study area is estimated *ca* 0.45 m lower than the present sea level, an assessment remote from the conclusions of the present study (Fig. 10).

After the roman reconstruction of the outer harbour and its renovation in AD 358, which was followed by the abandonment and siltation of the ancient harbour installations, three vertical co-seismic tectonic events seem to have caused the sea level fluctuation. The severe earthquakes of the period AD 362–375, which hit the area causing the elevation of the northern coast of the Gulf of Lechaion and the submergence of the western coast of the Saronic Gulf, are probably the beginning of these recent sea level fluctuations and the initial subsidence of the south coast of the Gulf. The earthquakes between AD 522 and AD 580 which caused extensive destructions in the area of Corinth, is very likely to be linked with the second vertical tectonic subsidence of the coast of Lechaion. The severe earthquakes of the fifteenth, eighteenth and nineteenth centuries and probably that of 1402 and the seismic sequences of 1742–1756 and 1817–1858, seem to be connected with the third strong tectonic event or a series of smaller ones that caused the uplift of the coast.

Given that the predictive sea level curve estimated by Lambeck and Purcell (2005) models the crustal response to the glacio-hydro-isostatic signal, then significant differences between the observed and predicted sea level change should be interpreted as being of tectonic origin (Sivan et al., 2001; Anzidei et al., 2011a,b, in press; Furlani et al., in press). Comparison between our observed data and

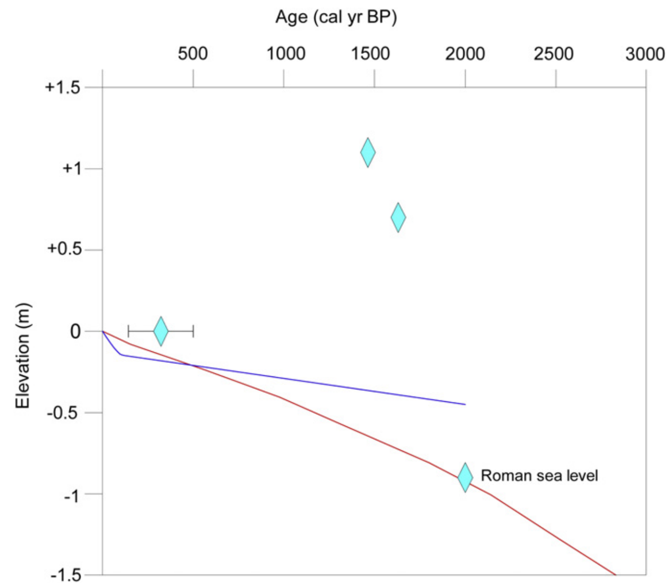

Fig. 10. Plot of the predicted sea level curve for the Peloponnesus developed by Lambeck and Purcell (2005) (red line) and curve constructed using the data provided by Evelpidou et al. (2012a,b) (blue line) compared with the elevation of the archaeological and geomorphological indicators of the ancient harbour installations (diamonds with error bar for age). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the predicted sea levels by Lambeck and Purcell's (2005) model for the Peloponnesus indicates that the magnitude of the two initial, paroxysmal, vertical, subsidence, tectonic movements on the coast of the ancient harbour of Lechaion is estimated *ca* 1.40 m and 0.30 m, respectively. The magnitude of the most recent uplift tectonic movement, assumed that this occurred during a unique co-seismic paroxysmal event, can be estimated between 1.30 m and 1.60 m, depending on the event date (Fig. 10).

If we concurred with the view of Evelpidou et al. (2012a) that sea level during the Roman period was slightly lower than at present, with a great part of the sea level rise to have been realized during the last two centuries (Evelpidou et al., 2012b), the major part of the sea level fluctuation on the coast of Lechaion should be attributed to the seismo-tectonic factor (Fig. 10).

The above maximum vertical displacements (MVD), applying the empirical quantitative relationships provided by Wells and Coppersmith (1994) for normal faults and Pavlides and Caputo (2004), correspond to earthquakes' magnitudes ranging from 6.7 to 6.8 (for MVD = 1.40 m), 6.2 to 6.4 (for MVD = 0.30 m), 6.7 to 6.8 (for MVD = 1.30 m) and 6.75 to 6.9 (for MVD = 1.60 m). The calculated magnitudes are comparable to these of the related historical seismic events. It is worth mentioned that the recent strong earthquake of 1981 ($M = 6.7$) in E Corinthian Gulf caused a maximum vertical displacement of 1.50 m.

11. Conclusions

The available sea level indicators, which include beachrocks, fossilized submerged and uplifted marine notches, marine erosion forms of the intertidal zone and ancient coastal harbour installations, and the relationship between them, led to the reconstitution of the vertical land movements and the palaeogeographical reconstruction of the coast of the ancient harbour of Lechaion.

The geoarchaeological approach of the ancient harbour of Lechaion attempts to contribute to the deepening of knowledge of the ancient coastal installations, but also in understanding the timeless struggle of human societies to manage a coastal

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environment that is continuously changing under a complex geodynamic regime. However, several aspects of the diachronic development of the ancient harbour are still obscure. Only archaeological excavation and an interdisciplinary approach to the finds will resolve these in the future.

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