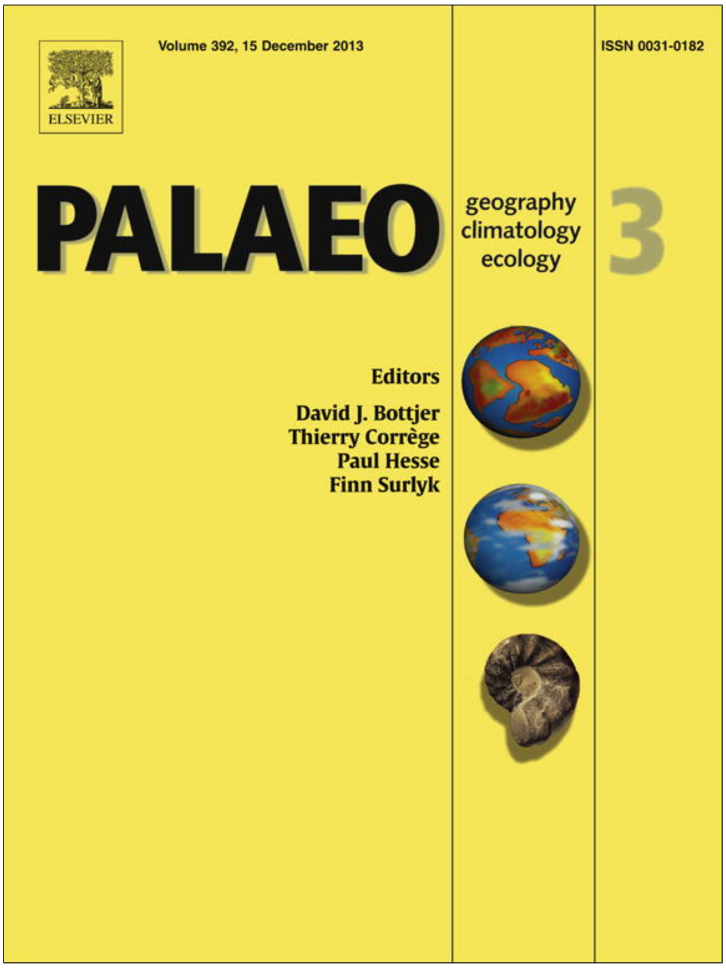
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Historical coastal evolution of the ancient harbor of Aegina in relation to the Upper Holocene relative sea level changes in the Saronic Gulf, Greece

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ABSTRACT

The extensive ancient harbor installations — today submerged — on the seafront of Kolona in Aegina are associated with the great trading and maritime development of the island from the Middle Bronze Age to the Middle Classical period.

Based on geomorphological and archeological indications, three distinct relative sea levels can be defined at depths of 3.17 ± 0.05 m, 0.97 ± 0.05 m and 0.52 ± 0.05 m. The dating of the sea level changes based on archeological evidence and historical sources shows that the initial sea level change in Aegina occurred certainly after AD 170 and most likely after AD 250. The intermediate change is dated between AD 1586 and AD 1839, and the most recent change occurred between 1839 and 1999. A transgression followed a long period of sea level stability that lasted at least 2200 years, from the Middle Bronze Age (ca. 3900 yr BP) to the Late Roman period (ca. 1700 yr BP).

According to the paleogeographical reconstruction of the coast, the ancient harbor installations stretch along 1600 m of coastline. The north harbor is bounded by the north breakwater, the riprap on the once wide sandy coast, the detached west breakwater, and the uplift morphology of the west end of Kolona Hill. On the south coast, the harbor installations comprise the fortified "closed harbor" with the shipsheds, the commercial harbor, which is entirely destroyed by the modern port, the anchorage area that is bounded by the west breakwater and built of cone-shaped piles of stones, the tops of which once projected above the sea level, and the south curved breakwater at its southernmost boundary.

1. Introduction

Sea level rise is the result of a complex eustatic, glacio-hydro-isostatic and tectonic process of climatic and geodynamic forcing mechanisms (Morner, 1996; Pirazzoli, 1996; Lambeck and Purcell, 2005; Stocchi and Spada, 2009; Lambeck et al., 2010) that caused extensive changes in the paleogeography of the shoreline in the Upper Holocene. During prehistoric and historical times, the land planning and the cultural, economic and social conditions of coastal communities have been affected by sea level rise.

Ancient harbor installations are sensitive indicators of the recent changes in sea level and the interaction between human activity and the coastal environment. These installations were constructed in direct relation to a past mean sea level, and any change in this had a decisive effect on their functionality. Consequently, the ancient harbor basins are noteworthy information sources where natural and anthropogenic processes are "imprinted" and "entrapped", thus remaining indelible over time (Marriner and Morhange, 2007).

The Saronic Gulf is an ideal place to study sea level changes and their times of occurrence (Fig. 1a,b). At least six submerged harbors and port installations of Classical and Roman antiquity are found along its coast: the Roman harbor of Kenchreai and the Roman port installations in the bay of ancient Epidaurus on the north and central parts of the west coast of the Saronic Gulf, the Classical harbors in Salamis and in the bays of Zea and Mounichia on the shores of Piraeus to the north, the naval base of the Sounion promontory at the south end of its west coast, and the ancient harbor of Aegina in the middle of the Saronic Gulf.

Although the information is rich in quantity and quality, previous surveys — even from the early twentieth century — estimated different rates of Upper Holocene sea level change for the Saronic Gulf. According to Scranton et al. (1978), in the bay of Kenchreai, the Roman port installations were submerged gradually by 2.30 m during three co-seismic subsidence events. Nixon et al. (2009) argue that the sea level has risen by 2.94 m in the last 5000 years southwards along the west coast of the Saronic Gulf in the bay of Korfos. This submersion, which occurred during five distinct tectonic phases of subsidence, produced a sea level of −1.20 m 4000 yr BP, −0.80 m 2350 yr BP, −0.34 m 1350 yr BP, and the approximate present level of 400 yr BP. Negris (1904) estimated that the sea level of Classical antiquity was at least 3 m lower than today. Traces of quarrying in the port of Piraeus and Zea Harbor, remains of masonry on the coast of Drapetsona, parts

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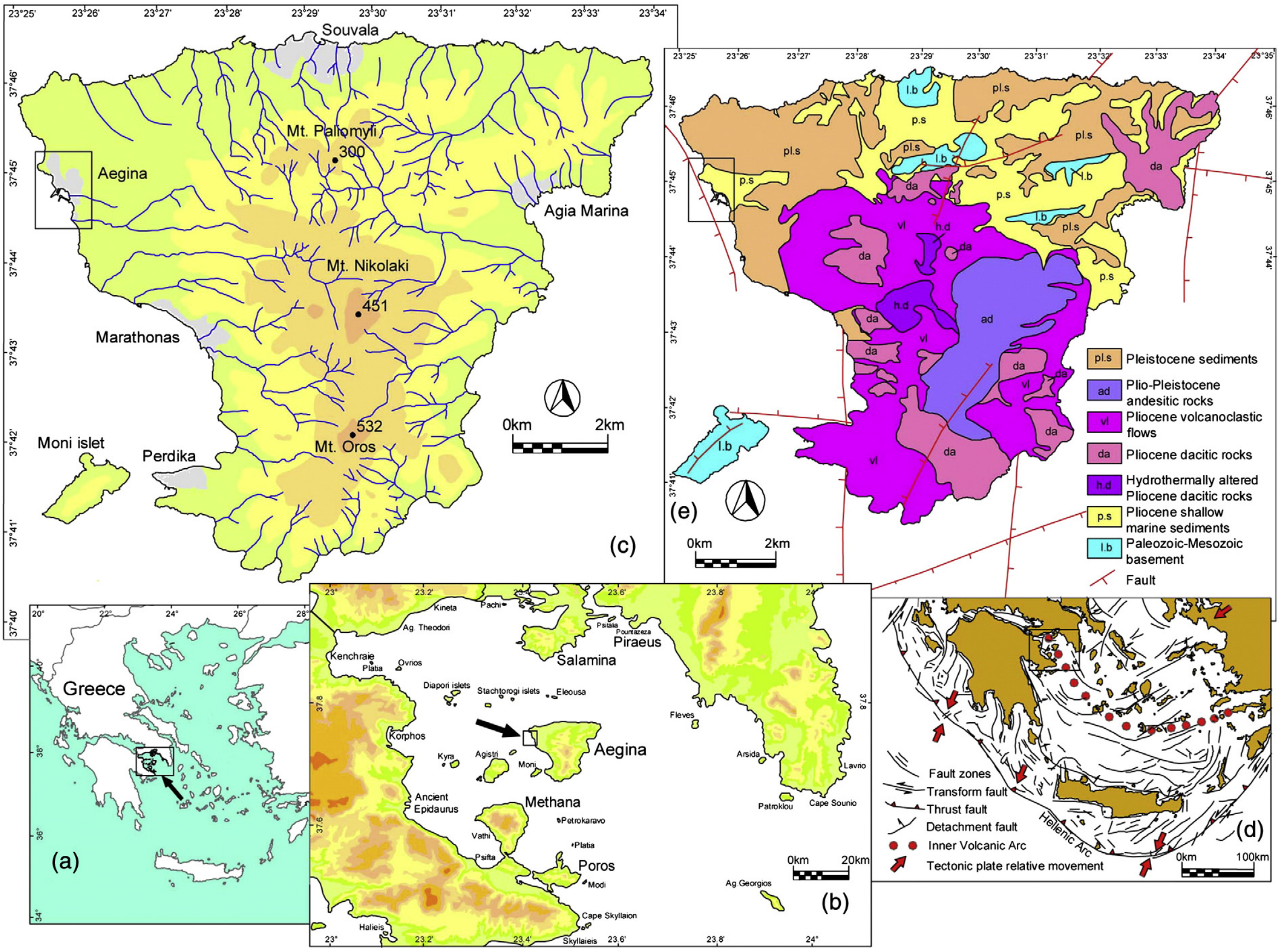

Fig. 1. (a), (b): Location maps of the Saronic Gulf, (c): map of Aegina island indicating the study area (rectangle), (d): geodynamic frame of the Hellenic Arc, (e): geological map of Aegina.

of the Long Walls in Piraeus, and ruins of a breakwater in Faliro were found submerged at depths of 2.0 m to 3.50 m (Negris, 1904). According to Lovén et al. (2007) and Lovén (2011), the function of the Classical slipways and shipsheds in Zea Harbor required a minimum sea level of −1.90 m and a maximum sea level of approximately −2.90 m. Classical period quarrying, foundation blocks and Classical to Hellenistic rock-cut foundations at Zea and at Mounichia indicate a sea level of −1.90 m to −2.0 m (Lovén, 2011). At Cape Sounion, several remains of submerged walls, a rock-cut naval base with two shipsheds and an ashlar masonry construction most likely from the Hellenistic period, at a depth of approximately 2.35 m to 2.65 m (±0.30 m), indicate a relative sea level change of at least −2.20 m (±0.30 m) (Baika, 2008).

Negris (1904) estimated that the detached west breakwater of the ancient harbor on the coast of Kolona Hill in the ancient city of Aegina has been submerged by 3.70 m since its operation. Knoblauch (1969, 1972) considered that over the last 3800 years (since 1800 BC), the sea level has risen by 3.55 m to 4.05 m in the ancient harbor of Aegina. He also suggested that during the Classical period (482 BC) sea level was at −2.20 m to −2.50 m, whereas in Late Roman times (ca. AD 250), it was at −1.60 m to −1.90 m.

2. Geological setting

The island of Aegina is in the middle of the Saronic Gulf. It has an area of 87 km^2 and 57 km of coastline. Its highest point is Mt. Oros, at 531 m (Fig. 1a,b,c).

Aegina lies at the northwest end of the South Aegean Volcanic Arc (Fig. 1d) where the crust thins to 20 km because of the active tensional regime and the rise of mantle material (Papanikolaou et al., 1988; Drakatos et al., 2005). It is characterized by Pliocene volcanism, which occurred in two major phases (Pe, 1973; Pe-Piper et al., 1983; Dietrich et al., 1988; Dietrich et al., 1991; Seymour, 1996; Morris, 2000). The first volcanic phase started 4.4 myr ago, initially overlapping the limestones of the par-autochthonous Sub-Pelagonian units and the remnants of allochthonous and tectonically higher thrust sheets of ophiolitic mélange and flysch with rhyodacitic ashes and pumice. Andesitic–dacitic lava flows that followed, formed the central part of the island ca. 2 myr ago. The deposition of Neogene sediments of marl and tuffitic material occurred throughout a long restoration period. After this and during the second volcanic phase, minor amounts of pyroclastics and flows of basaltic andesites, high-alumina basalts, and hypersthene andesites were produced, thus forming the south part of the island. This was followed by subsidence of the north part of the island and the deposition on the north coasts of hard, white, sandy–marly limestone of marine-origin (Fig. 1e) (Dietrich et al., 1988; Dietrich et al., 1991).

Tensional tectonic structures, represented by three major NE–SW, E–W and ENE–WSW striking fault systems, were activated during the Middle to Late Miocene, Pliocene and Plio-Pleistocene boundaries, respectively, causing uplift and subsidence movements, horst and graben structures and the emplacement of magmas (Fig. 1e) (Papanikolaou et al., 1989; Dietrich et al., 1991).

Increased seismic activity, under a tensional regime with a NNE–SSW direction, is observed mainly on the northwest and north margins of the Saronic Gulf, areas of strong historical seismic events. In the central and eastern parts of the island, the microseismic activity is related more to the crustal deformation extensional stress regime rather than to the volcanism of the area (Makropoulos and Burton, 1981; Bath, 1983; Makris et al., 2004; Paradisopoulou et al., 2010).

3. Approach methodology

The paleogeographical reconstruction of the ancient harbor of Aegina was based on: i) the definition of past sea levels by the study of geomorphic features that are associated with them, ii) the mapping of the extensive submerged harbor installations, beachrocks, tidal notches and various other sea abrasion features on the ancient constructions, iii) the accurate depth measurements at selected points of the ancient harbor constructions and the geomorphic features that are related to past sea levels, iv) the dating of past sea levels and ancient harbor installations, and v) the relationship between past sea levels that have been dated and the "functional level" of the ancient harbor constructions.

The ancient harbor installations were mapped using satellite images (Google Earth, 2012) and high-resolution orthophotos at a scale of 1:500 (Ktimatologio SA). The map was updated during an undersea survey at positions where data accuracy was required to reconstruct past sea levels and the precise definition of the "functional level" of the ancient maritime constructions. Data from Knoblauch's (1969, 1972) detailed survey in the area of the "closed harbor" ("κρυπτός λιμένας") were also used, as well as those from the survey in the area of the detached west breakwater that was performed by the Ephorate of Underwater Antiquities (Ministry of Culture) in 1999, in the framework of a project to construct a breakwater in the modern port of Aegina.

For drawing the depth contours in the area of the ancient harbor basin, apart from the depth measurements of the present survey, the bathymetric data from the nautical chart sheet Aegina, in a scale of 1:5.000 of the Hellenic Navy Hydrographic Service, was also used, complementary to the bathymetric data of Knoblauch's (1969, 1972) survey. Maps and bathymetric data from the early seventeenth century (Graves, 1839), predating the extensive interventions in the seafront to construct the new port of Aegina and the ensuing natural processes, were mainly used to reconstruct the initial level of the detached west breakwater and the ancient commercial harbor, which today are completely destroyed.

All measurements were collected during calm sea conditions using mechanical methods. To account for tides, 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 Piraeus, 31 km northeast of the study area. All measurements were made during high water periods, with sea level from 0.07 m to 0.13 m higher than the mean sea level.

Previous depth measurements of the harbor constructions, given by Knoblauch (1969, 1972), show a systematic deviation in the range of 0.20 m to 0.90 m from the corresponding tide-corrected measurements of this survey. This deviation, significant for survey accuracy, in some cases leads to different conclusions regarding the use and the "functional level" of the ancient harbor installations.

The submerged tidal marine notches, which have been carved on the structural components of breakwaters, and the beachrocks consisting of lithified archeological material and beach sediments, are used as indicators of past sea levels. Beachrocks are accurate indicators of past sea levels for the Aegean low tide area (Goudie, 1966; Erol, 1972; Bener, 1974; Kampouroglou, 1989; Mourtzas, 1990; Bodur and Ergin, 1992; Avsarcan, 1997; Ertek and Erginal, 2003; Erginal et al., 2008; Desruelles et al., 2009; Erginal et al., 2010). In the eastern Mediterranean, they are rapidly lithified beach sediments formed in the intertidal zone through the precipitation of mainly calcium carbonates due to physicochemical and microbiological activities, under warm temperature conditions and possibly with the presence of meteoric water (Goudie, 1966; Friedman and Gavish, 1971; Alexanderson, 1972; Bener, 1974; El-Sayed, 1988; Kampouroglou, 1989; Bernier and Dalongeville, 1996; Avsarcan, 1997; Ertek and Erginal, 2003; Vousdoukas et al., 2007; Desruelles et al., 2009; Erginal et al., 2010). Numerous observations throughout the Greek coastal area on the relationship between the beachrocks with both tidal notches and ancient maritime constructions have led to the conclusion that they are formed in a zone located between the lower tidal level and the higher margin of swash and backwash zone of the low-energy constructive waves (Mourtzas, 1990, 2010, 2012; Mourtzas et al., 2013). 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 a relative older sea level. The mean sea level during the formation of the beachrocks of the study area results from the depth of their base minus half the difference between the mean higher high water and the mean lower low water, which is 0.15 m for the Saronic Gulf.

The beach rocks are formed during periods of tectonic and eustatic stability of the sea level (Dalongeville and Sanlaville, 1984; Neumeier, 1998; Vousdoukas et al., 2007; Mourtzas, 2012; Mourtzas et al., 2013), thus representing the fossilized seaward part of the deposits of an older depositional coast. The positive or negative sea level change potentially forms successive beachrock outcrops. Their submerged or uplifted modern position reflects different past sea levels and respective ancient coastlines. The dating of beachrocks is based on archeological findings and constructions incorporated into or covered by the formation or on their relationship with them. This defines an upper time limit for the formation of beachrocks not exceeding the age of the incorporated or related archeological constructions and findings (Mourtzas, 2012; Mourtzas et al., 2013).

The tidal notches are formed in the intertidal zone during periods of eustatic and tectonic stability, and their roof and base coincide with the upper and the lower tidal levels, respectively (Pirazzoli, 1986a). The mean sea level that corresponds to each tidal notch formed on the harbor installations of the study area results from the depth of their well-formed base minus half the difference between the mean high water and the mean low water, which is 0.05 m for the Saronic Gulf.

The dating of older sea levels was based on the relationship between the indicative geomorphic features and the ancient constructions, both in the area of the ancient harbor and along the west coast of the Saronic Gulf. The dating of the ancient constructions was based mainly on architectural, morphological, constructional and historical data. After defining and dating the past sea levels, the spatial distribution of the ancient harbor installations and the bathymetry of the ancient harbor area, the paleogeographical reconstruction of the ancient coastline and the harbor installations was attempted.

4. Description of the coastal harbor installations

The seafront of the ancient city of Aegina is divided into two sections, north and south, by Kolona Hill, which thrusts into the sea in a NW–SE direction for a length of approximately 300 m. The north coast is an embayment facing west with steep edges. The coastline is developed linearly in a general N–S direction for 480 m at the end of a steep relief. The south smooth coast, oriented NNW–SSE for 1 km, runs south of Kolona Hill in three successive bays facing southwest (Fig. 2).

The ancient harbor installations extend along 1600 m of coastline. They are bounded in the north by the long linear breakwater in the middle of the north coast and in the south by the south curved breakwater. They include the north harbor, the "closed harbor" ("*κρυπτός λιμένας*") in the north part of the south coast and the commercial harbor immediately to the south, as well as the wider anchorage area. As mentioned above, the ancient commercial harbor has been destroyed entirely, and there are no remains of ancient constructions.

The harbor installations of ancient Aegina are one of the largest artificial harbor projects of Classical antiquity, with a total length of 1600 m and an average width of 270 m, occupying an area of 500,000 m^2 (Fig. 2).

4.1. The north harbor

The north harbor is formed in the south half of the north coast, for 220 m, between the elongated manmade protective construction to the north, the north sheer coast of Kolona Hill to the south, and the detached west breakwater seaward (Fig. 3).

The north protective construction develops in a WSW direction for an overall length of 320 m and is now entirely submerged. It can be divided into three sections in seaward order: a building on the contemporary coastline, an intermediate rockfill and the breakwater.

The building, of which detailed measured drawings have been made by Knoblauch (1969, 1972), today enters the sea for 30 m, projecting slightly above the surface (Fig. 4a). Its landward continuation is covered by recent slope deposits. On its structural blocks, two marine notches with apertures of 0.20 m have been shaped by past sea levels, with their bases at depths of 1.03 m and 0.53 m below the sea surface (Fig. 4b).

Between the seaward end of the building and the landward beginning of the breakwater, there is a rockfill for 80 m. Approximately 20 m in width, it widens to 45 m at its west end where it meets the breakwater.

The breakwater is 210 m long, between 13 m and 18 m wide, and up to 4.80 m high from the sea bottom. It consists of accumulated rounded stones, not cemented together, which in the external layer are of maximum dimensions 0.80 × 0.50 × 0.30 m (Fig. 4c). Its steeply sloping sides terminate in the sandy seabed, which dips slightly to the southwest to a depth of as much as 8.0 m (Fig. 4d). The upper surface of the breakwater is raised in its central part, where there is an accumulation of sizeable stones from an elevated terrace approximately 7 m wide. For a length of 180 m, its depth remains stable between 2.30 m and 2.60 m, whereas for the last 30 m, the depth increases from 3.60 m to 3.70 m because of a sharp demotion.

Ninety meters south of the breakwater and aligned with its landward end is a rocky riprap, 100 m long and up to 8 m wide. It is developed in a NNE–SSW direction, parallel to the contemporary shoreline and within 100 m of it, between isobaths −4.00 and −3.00. The depth of the surface of the riprap, in which large concentrations of potsherds and traces of building foundations are visible, ranges from −2.60 m to −2.80 m (Fig. 4e). The seabed on the seaward side of the riprap is at −4.20 m and on the landward side at −3.20 m. The surface of the beachrock slab formed by cemented sands on the south landward side of the riprap is at a depth of 2.75 m.

The craggy north coast of Kolona Hill and its submerged continuation to the west supplement the morphology of the ancient north harbor. The rocky underwater ledge, with protrusions and hollows on its surface, dips slightly to the northwest. Approximately 100 m long and 20 m wide, the depth of its surface reaches 4 m at its end.

The detached west breakwater runs NNE–SSW, is 215 m long and 20 m wide, and consists of 13 successive cone-shaped piles of stones. It starts 70 m south of the west end of the north breakwater, thus forming the north entrance to the north harbor. The present depth of the apex of the cone-shaped piles of stones ranges from 3.20 m to 4.70 m and the bases range from 9.0 m to 10.0 m. The corresponding depths in the nineteenth century, as given on Graves's chart (1839), were at 2.45 m for the apex and 9.0 m to 10.0 m for the base.

Along the entire length of the coastline, and for a width of approximately 30 m under the sea is an area with evidence of human activity during antiquity, consisting of submerged building remains, construction material of collapsed walls, and numerous potsherds and stones (Fig. 4f).

Observations of the morphology of the seabed in the area of the north harbor reveal that all contour depths up to −4.00 are developed in a NNE–SSW direction, parallel to that of the contemporary coastline, forming a smooth sandy bottom dipping slightly to the northwest. At greater depths, the sandy seabed sinks abruptly to contour −9.00, forming an elongated depression with the main axis running NW–SE.

4.2. The south coast of Kolona Hill

4.2.1. The "closed harbor" ("κρυπτός λιμένας")

At the south, smooth end of Kolona Hill, in the northernmost of the three successive shallow bays indenting the south coast, the so-called

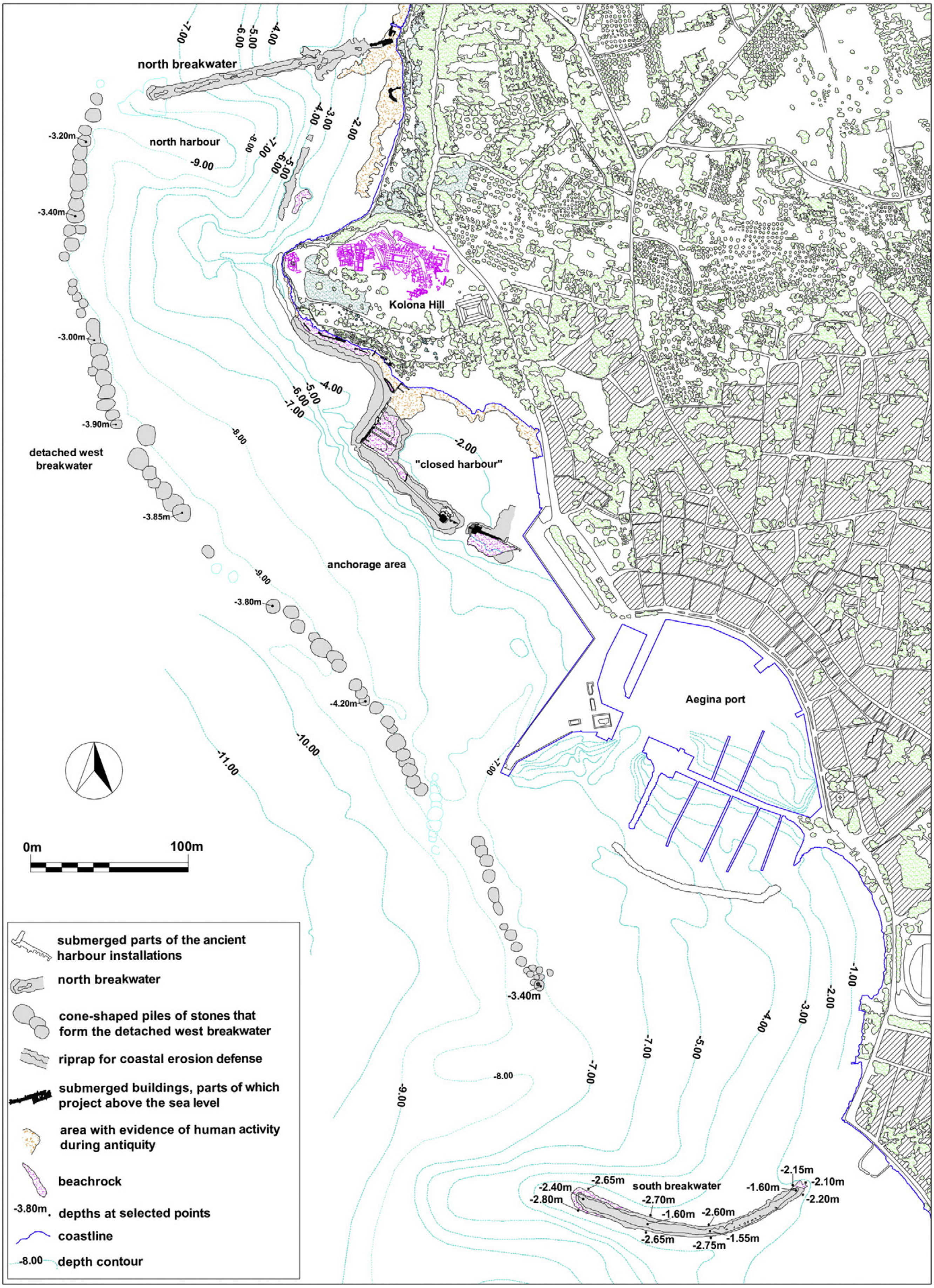

Fig. 2. Plan of the seafront of the ancient and modern city of Aegina.

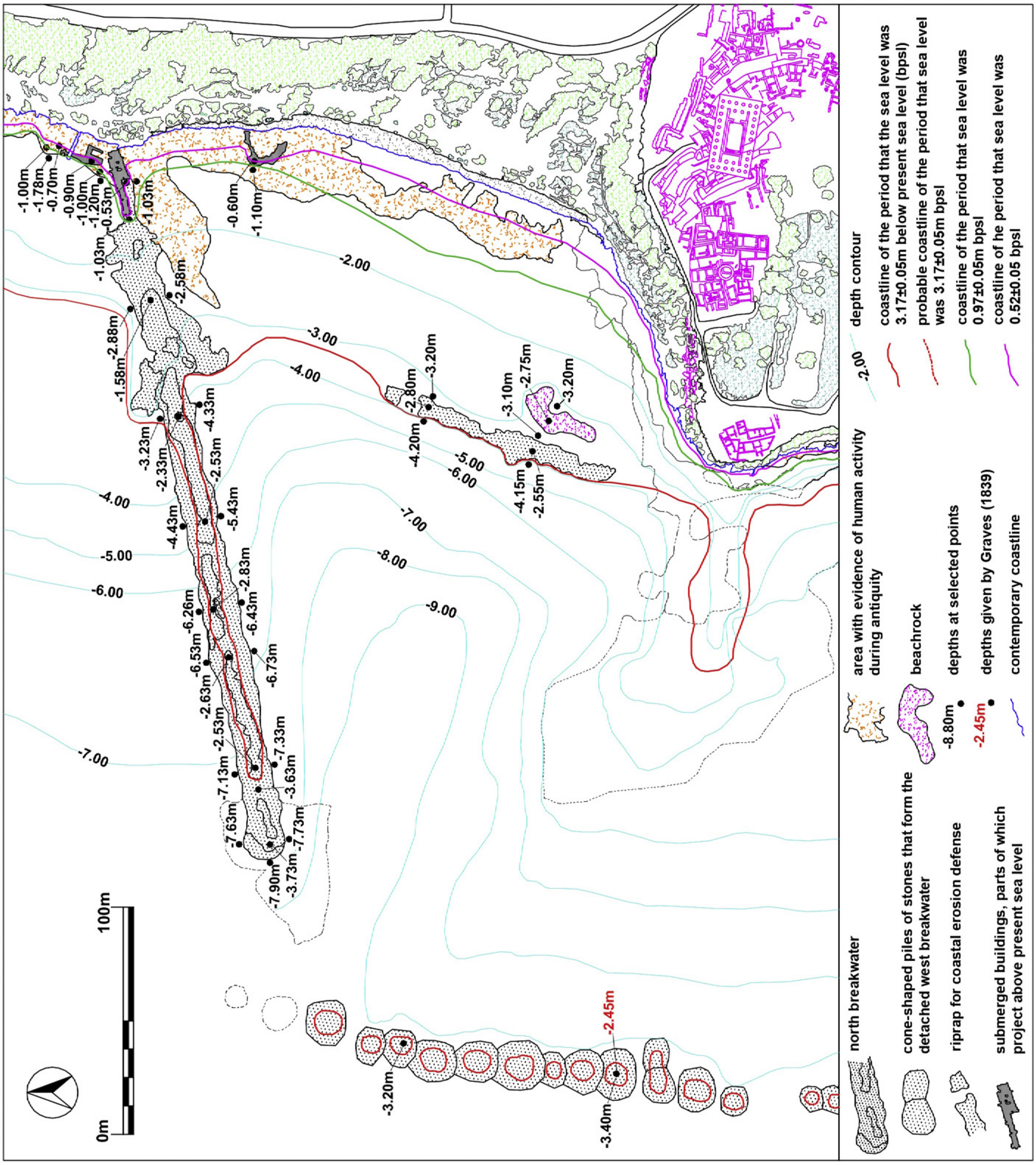

Fig. 3. Plan of the ancient north harbor.

"closed harbor" was created by constructing a wall to demarcate its seaward sides (Fig. 5).

The north section of the wall begins 35 m from the present coastline and between them are the remains of a rectangular building (Fig. 4g). It is S–W oriented for a length of 70 m, then turns at a right angle to the southeast, continues, curving slightly, for a length of 67 m, and then continues in a straight line for 73 m, ending at a tower-like building surrounded by remains of foundations. Of the south wall, only the end section survives, approximately 60 m long, which also terminates at a tower-like building surrounded by ruins of auxiliary buildings (Fig. 4h).

The thickness of the wall masonry ranges from 2.0 m to 2.80 m. The superstructure comprises three parallel courses of ashlar blocks, remaining at a maximum height of 2.0 m above the riprap that protects

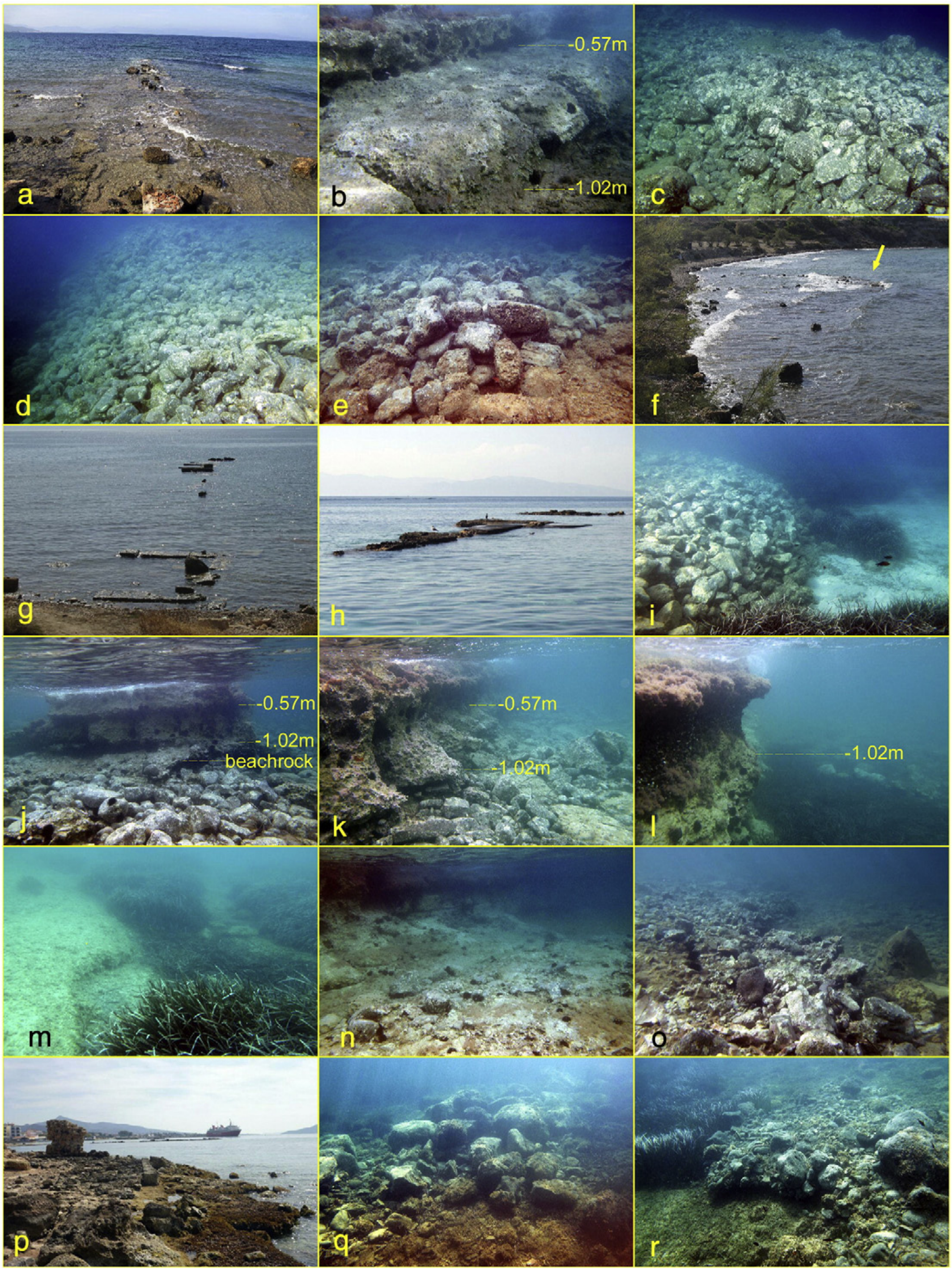

Fig. 4. Ancient north harbor (a): submerged building of the north protective construction, (b) submerged tidal marine notches that have formed on the building, (c): the upper surface of the north breakwater, (d): south slope of the breakwater, (e): the upper surface of the rocky riprap on the north coast, and (f): submerged building remains. Ancient "closed harbor" (g) the submerged north walls and the remains of ancient shipsheds, (h) entrance, (i) riprap for the protection of the wall, (j): the submerged tidal marine notches that have formed on the inner face of the wall and the related beachrock slab, (k): unified marine notch on the outer face of the north wall, (l): unified marine notch on the outer face of the northwest wall, (m): the end of the thick beachrock slab in front of the south wall, (n): the south wall that has been incorporated into the beachrock, (o): beachrock on the surface of the north fill inside the "closed harbor" basin. West coast of Kolona Hill (p) beachrock consisting of cemented archeological material. South breakwater (q): the upper surface of the curved breakwater, (r): beachrock slab.

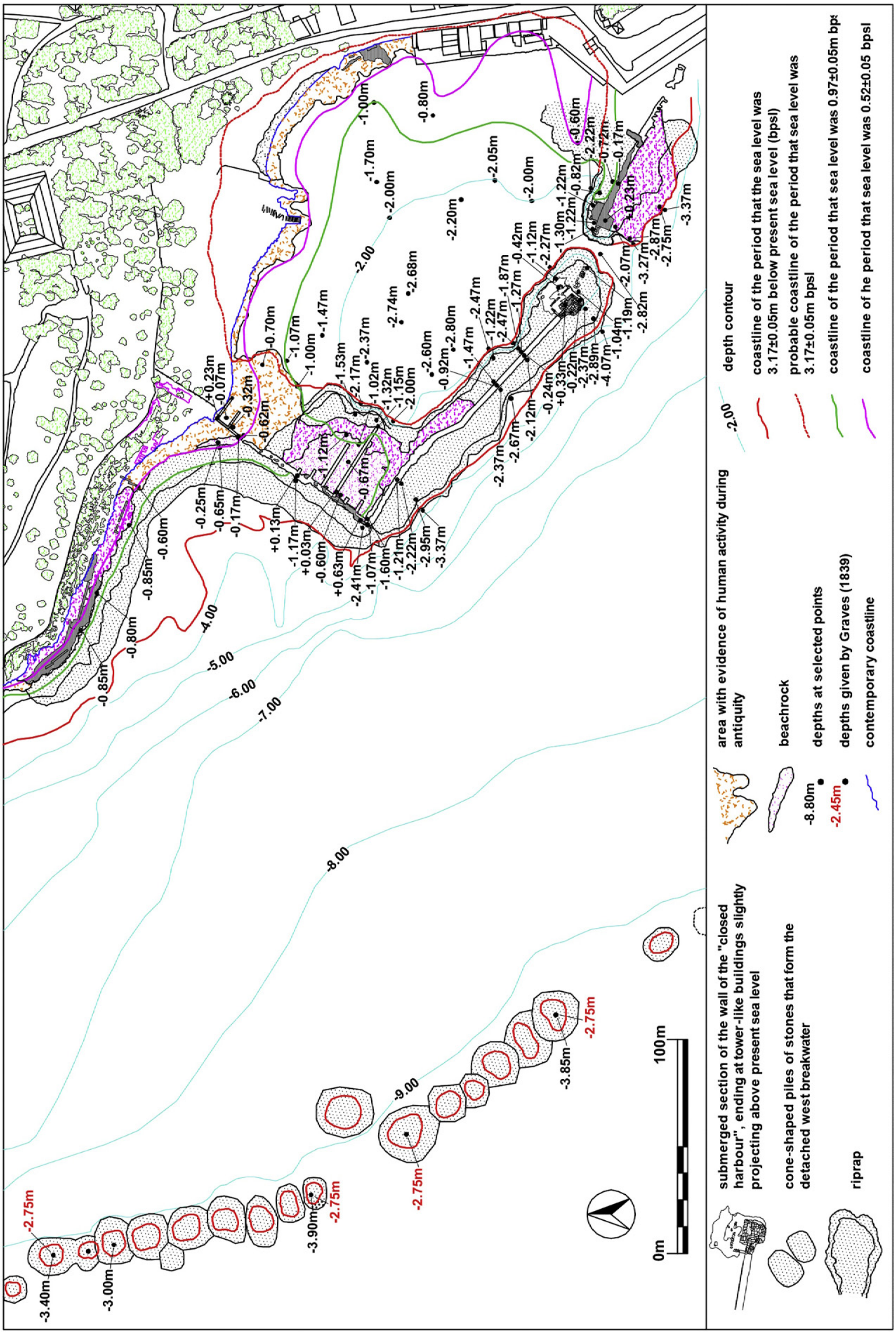

Fig. 5. Plan of the ancient "closed harbor" and the northwest coast of Kolona Hill.

it. Today, only intermittent small parts of the wall project above the sea surface by 0.30 m at the most (Fig. 4g,h).

The harbor entrance on the southwest side has an opening ranging from 6 m to 13 m at the top and the base of the riprap, respectively. The depth of the entrance was measured at 2.82 m, whereas the corresponding previous measurement by Knoblauch (1969, 1972) was 3.40 m to 3.50 m. This difference in depth is most likely because of siltation over the last 30 years.

The usable area of the harbor basin is estimated at 16,000 m^2, and the depth in the central part ranges between 2.60 m and 2.80 m. Extensive fills occupy the north and south parts of the basin, a total area of 7.000 m^2. The width of the north fill reaches 40 m, with a thickness ranging from 1.0 m to 1.50 m. At the north fill, at a right angle to the north wall, there are six rows of walls, each 38 m long, parallel to one another at a distance of 6 m. Today, only the foundation and parts of the superstructure, 1.50 m thick, survive to a height of 0.70 m. The deepest trace of their foundations is at −1.15 m. Knoblauch (1969, 1972) has described these constructions in detail, considering them to be shipsheds.

The wall is protected by a riprap of rounded stones of up to 0.30 m × 0.15 m (Fig. 4i). Externally and in the entrance area, the thickness of the riprap reaches 1.50 m and the width ranges between 13 m and 20 m. Inside the harbor basin, the corresponding thickness reaches 1.0 m, and the width ranges between 7 m and 15 m. The top of the riprap lies at a depth ranging between 2.10 m and 2.40 m, and the base ranges from 2.30 m to 2.50 m. Inside the basin, the respective depths range from 1.0 m to 1.50 m at the top and 2.30 m to 2.50 m at the base. The riprap appears to continue further north, covering the now undersea slope of the narrow and steep southwest coast of the hill. Most likely, it protected the coastal part of the city wall from the waves; the ruins of the wall are located along this section of the coast (Fig. 5).

Along the entire length of the inner and outer faces of the wall, two marine notches with apertures of 0.20 m to 0.25 m have been formed, with their bases at depths of 1.02 m and 0.57 m, which correspond to two past sea levels (Fig. 4j). At some points outside the wall, the two marine notches have been merged into one large aperture (Fig. 4k,l).

The riprap in front of the south preserved section of the harbor wall has been cemented together with stones, sands and potsherds to form a thick beachrock slab, into which the superstructure of the walls has been incorporated. The base of the beachrock slab is at a depth ranging from 3.27 m to 3.37 m, and the top is at a depth ranging from 2.75 m to 2.87 m (Fig. 4m,n).

In the north part of the harbor basin, a thin beachrock slab consisting of cemented coarse materials and numerous potsherds has been formed at a depth of 1.15 m. It occupies the entire surface of the fill to a depth of 0.60 m incorporating the superstructure of the shipsheds and the walls (Fig. 4j,o).

A younger beachrock has been formed along the entire southwest coast of Kolona Hill. It comprises submerged lithified coarse-grained sediments and archeological materials and has an inland width of 8 m. Remains of the coastal walls have been incorporated into this beachrock slab, the base of which is at a depth of 0.65 m to 0.85 m and the top is at a depth of 0.25 m (Fig. 4p).

4.2.2. *The anchorage area*

The anchorage has an area of 350,000 m^2 and is delimited to the north by Kolona Hill, to the west by the cone-shaped piles of stones forming the detached west breakwater and to the south by the curved breakwater (Fig. 2).

The west breakwater begins north, in alignment to the west coast of Kolona Hill and its undersea continuation. Located 265 m from the coast and 30 m from the south end of the corresponding breakwater of the north harbor, it follows the morphology of the coast for a total length of 1100 m in a general southeasterly direction and comprises 53 successive cone-shaped piles of stones. Opposite the entrances to the "closed harbor" and the commercial harbor, two openings have been formed, 110 m and 95 m long, respectively, permitting the ship access. The depth of the apex of the cone-shaped piles of stones today ranges from 3.0 m to 6.0 m and that of the base ranges from 7.0 m to 9.50 m. The corresponding depths in the nineteenth century, as given on Graves's chart (1839), are from 2.45 m to 2.75 m for the apex and 9.0 m to 10.0 m for the base, which coincides with the present depth (Fig. 2).

The south breakwater is curved, with an arc length of 317 m, and its east end is 97 m from the coast (Fig. 2). It is formed by piles of stones, up to 0.40 m × 0.80 m (Fig. 4q), and a large accumulation of potsherds is observed on its surface. The width of the west half reaches 25 m and decreases to 15 m in the east. The depth of its upper surface is 2.40 m at the west end and 1.60 m elsewhere. The depth of the breakwater base ranges from 2.60 m to 2.80 m, except at the east end where it is 2.20 m. At the east and west ends of the breakwater, the lithified fill materials form a beachrock slab to a maximum depth of 2.80 m (Fig. 4r). Between the south end of the west breakwater and the west end of the south breakwater, an extra south entrance to the anchorage area with an opening of 25 m has formed.

The construction of the new port of Aegina and the intensive maritime traffic has changed the morphology of the sandy seabed of the anchorage, mainly in the wider area of the ancient commercial harbor. Based on the bathymetric data given by Graves (1839), the reconstruction of the sea-bottom morphology in the north shows relatively high gradients of approximately 10% toward the southwest to the −7.00 contour and then a smooth bottom to the −10.00 contour. In the south, the sea bottom appears smooth with a slight inclination to the NNW.

5. Indications of relative sea level changes

The beachrock slab formed on the north coast, with base and top depths of 3.20 m and 2.75 m, respectively, the thick beachrock slab of the riprap material and potsherds in front of the south preserved part of the walls of the "closed harbor", with base and top depths of 3.27 m to 3.37 m and 2.75 m to 2.87 m, respectively, and the beachrock at the east and west ends of the south breakwater, with base at −2.80 m, all refer to an older relative sea level that was 3.17 m ± 0.05 m lower than the present one, according to the conditions mentioned in the approach methodology. The value ±0.05 m indicates the variation from the mean depth of the base of the beachrock slabs.

Two marine notches with apertures of 0.20 m to 0.25 m have formed along the entire length of the inner and outer faces of the walls of the "closed harbor", with their bases at depths of 1.02 m and 0.57 m. They correspond to two previous relative sea levels at −0.97 m ± 0.05 m and −0.52 m ± 0.05 m, respectively, according to the conditions that were mentioned in the approach methodology.

The two younger beachrock phases are associated with these sea levels. The deeper phase, at −1.15 m, consists of cemented coarse materials and abundant potsherds. It covers the entire surface of the north fill of the "closed harbor" basin, and the superstructure of the wall and the shipsheds have been incorporated into it. The younger and shallower beachrock phase has formed along the entire length of the SW coast of Kolona Hill. It comprises archeological materials and has incorporated the superstructure of the coastal wall. Its base ranges from a depth of 0.65 m to 0.85 m and the top is at a depth of 0.25 m.

6. Dating of relative sea level changes

When Pausanias visited Aegina in AD 170, he wrote that "of the Greek islands, Aegina was the most difficult of access, for it is surrounded by sunken rocks and reefs which rise up", thus describing the cone-shaped piles of stones forming the west breakwater: "*προσπλεῦσαι δὲ Αἴγινά ἐστι νήσων τῶν Ἑλληνίδων ἀπορωτάτη: πέτραι τε γὰρ ὕφαλοι περὶ πᾶσαν καὶ χοιράδες ἀνεστήκασι*"

(Pausanias, 2.29.6). When the English Commander Thomas Graves visited the island in 1839, he found that the depth of the apex of the cone-shaped piles of stones was 2.45 m to 2.75 m lower than the sea level at that time (Graves, 1839). Therefore, for Pausanias's description to be valid, the sea level in AD 170 should have been at least equal to or lower than the depth measured by Graves (≥ -2.50 m). Such a level corresponds to the oldest relative sea level, at -3.17 m $\pm$ 0.05 m.

This sea level is consistent with the "functional level" of the harbor installations of the seafront of Kolona. Furthermore, it is consistent with the stability of the sea level from the period of construction of the north breakwater (ca. 1800 BC) until at least AD 170. Accordingly, at that time, the north breakwater projected 0.50 m to 1.0 m above the sea level, the west breakwater projected 0.20 m to 0.80 m, the wall surrounding the "closed harbor" was built on land, the coastline at that time followed the base of the ripraps of the "closed harbor" and the west coast of the hill, and the south breakwater projected 0.80 m to 1.60 m above the then sea level.

The French explorer and cosmographer André Thevet who visited the harbor of Aegina most likely in 1555 described it as "the third harbor located in the western part", "very dangerous due to many reefs near the surface, which appear when the sea is calm" and remarked that "the depth is only appropriate for fishermen who go out with their small boats and say that the best fishing in the island is this place" (Thevet, 1586). Interpreting Thevet's (1586) description, we surmise that he was referring to the anchorage area in front of the "closed harbor" and the west detached breakwater. Assuming a sea level that was lower by 1.0 m, we conclude that the cone-shaped piles of stones were at a depth of 1.50 m, which indicates that they could be observed when the weather was calm but were extremely dangerous for ships. If this assessment is correct, the 1555 relative sea level was lower by 0.97 m $\pm$ 0.05 m and corresponded to the lower marine notch. The relative sea level change by 0.45 m, from -0.97 m $\pm$ 0.05 m to -0.52 m $\pm$ 0.05 m which corresponds to the higher marine notch, should have occurred between 1555 and 1839 when Graves (1839) measured the piles at a depth ranging from 2.45 m to 2.75 m.

Comparison of the depth measurements in the shallower parts of the west breakwater (1999) and on the surface of the south breakwater of the present study (2012) with the corresponding measurements of Graves (1839), provides differences of 0.25 m to 0.55 m (Fig. 2). This discrepancy could be attributed to the most recent relative sea level change by -0.52 m $\pm$ 0.05 m, which appears to have occurred between 1839 and 1999.

7. Historical background and dating of the ancient harbor installations

Aegina developed into a maritime and trading center even in prehistoric times because of its privileged position in the middle of the Saronic Gulf, between Attica and the Peloponnese (Fig. 1b). The first inhabitants came from Peloponnese in the second half of the 4th millennium BC (3500–3000 BC) and settled on Kolona Hill. Settlement of the island continued during the Early Bronze Age (2500–2000 BC). By the Middle Bronze Age (2000–1600 BC) Aegina was involved in seafaring and trade. The impressive building complexes and fortifications constructed by the end of Middle Helladic I phase (ca. 1800 BC) indicate the growth and prosperity of the ancient settlement at Kolona, which was the seat of a central administrative authority. The island was deserted at the end of the Myceanean period. During the Geometric period (1200–900 BC) first the Mirmidones from Thessaly and then the Dorians (950 BC) moved there. Aegina, along with five other cities, was a member of the Amphictyonic League of Kalauria, established in the seventh century BC (although some scholars maintain its existence since the Myceanean period) as a religious organization and later transformed into an economic and political union. In the period between the second half of the eighth century BC and 459 BC, Aegina was developed into an important nautical and mercantile power, with its own coinage, minting of which began ca. 650 BC. Around 500 BC Aegina was at the height of its prosperity and power, enjoying the monopoly of trade in the Eastern Mediterranean, and took part in the naval battle of Salamis (480 BC), along with the other Greeks against the Persians. However, rivalry with the Athenians, the other great naval power of antiquity, was crucial for the island's fortune. Aegina had entered into friendship with Sparta and in 459 BC allied with Corinth, enemy of Athens. A year later the Athenians attacked the island, defeated the Aeginetan fleet, destroyed the city walls, forced the Aeginetans to hand over their ships and imposed swingeing taxes. During the Peloponnesian War (431–404 BC) the Athenians exchanged the people of Aegina with lot-holders (cleruchs). Thereafter, Aegina, like the rest of Greece, was dominated successively by the Macedonians, the Aetolians and King Attalos of Pergamon, who around 133 BC ceded Aegina to the Romans. The new masters hastened the island's decline, sacked the city and plundered what was left of its old splendor. After AD 400 many Peloponnesians went to Aegina, seeking refuge from pirates, the city was rebuilt and trade was revived. In the ensuing centuries Aegina suffered several piratical raids and the inhabitants were forced to abandon the shore and move inland (Welter, 1938; Koulikourdi, 1990; Nikoloudis, 1993-4; Niemeier, 1995; Pennas, 2004; Felten, 2007; Gauss and Smetana, 2010; Gauss et al., 2011).

The construction of the harbor installations of Aegina, one of the most important engineering projects of antiquity, demanded ability to conceive and design, constructional and technical capability, but mainly a sufficiency of resources. Consequently, the extensive and expensive harbor works on the seafront of Aegina can be linked with the period of the island's maritime and mercantile heyday, which commenced around 1800 BC and was terminated by the Athenians in 458 BC. However, the construction techniques, which do not refer to a specific period because they were the same over time, and the absence of excavation data, do not give the possibility of an accurate dating.

According to the attempted dating performed by Knoblauch (1969, 1972), the sea level throughout that period was constantly changing, and the construction, expansion, and renovation of the harbor installations followed this change. Thus, assuming a linear rise in sea level and combining this with historical evidence, he dated the construction of the north breakwater around 1880 BC, when the sea level was -4.0 m to -3.55 m lower than today. He also considered that the harbors of the south coast were constructed around 480 BC, when the sea level was at -2.20 m to -2.50 m, and he dated the last reconstruction of the "closed harbor" in AD 250, with the sea level at -1.60 m to -1.90 m (Knoblauch, 1969, 1972).

However, by considering relative sea level stable during the entire period from the Early Bronze Age (ca. 3900 yr BP) until the beginning of the Late Roman period (ca.1700 yr BP), it is concluded that the construction, expansion and renovation of the harbor installations refer to the same functional level. Therefore, the precise dating of harbor constructions cannot be based on a constantly changing sea level, to which even the function of the constructions is adjusted. If, moreover, sea level was linearly changing, indications of this change should be imprinted on subsequent harbor constructions, as happened with the younger sea levels (of -1.05 m and -0.57 m). Furthermore, the foundation of the wall and the construction of the superstructure could not be constructed underwater, since around 480 BC when the "closed harbor" wall was built according to Knoblauch (1969, 1972), sea level was at -2.20 m to -2.55 m. Finally, the beachrock formation on the riprap of the "closed harbor" wall, indicates a sea level previous to this construction, 3.30 m lower than the present one, and hence not consistent with Knoblauch's (1969, 1972) dating.

8. Paleogeographical reconstruction of the ancient Kolona seafront and its harbor installations

The paleogeographic reconstruction of the coast was made after determining and dating of the three past sea levels, and drawing the

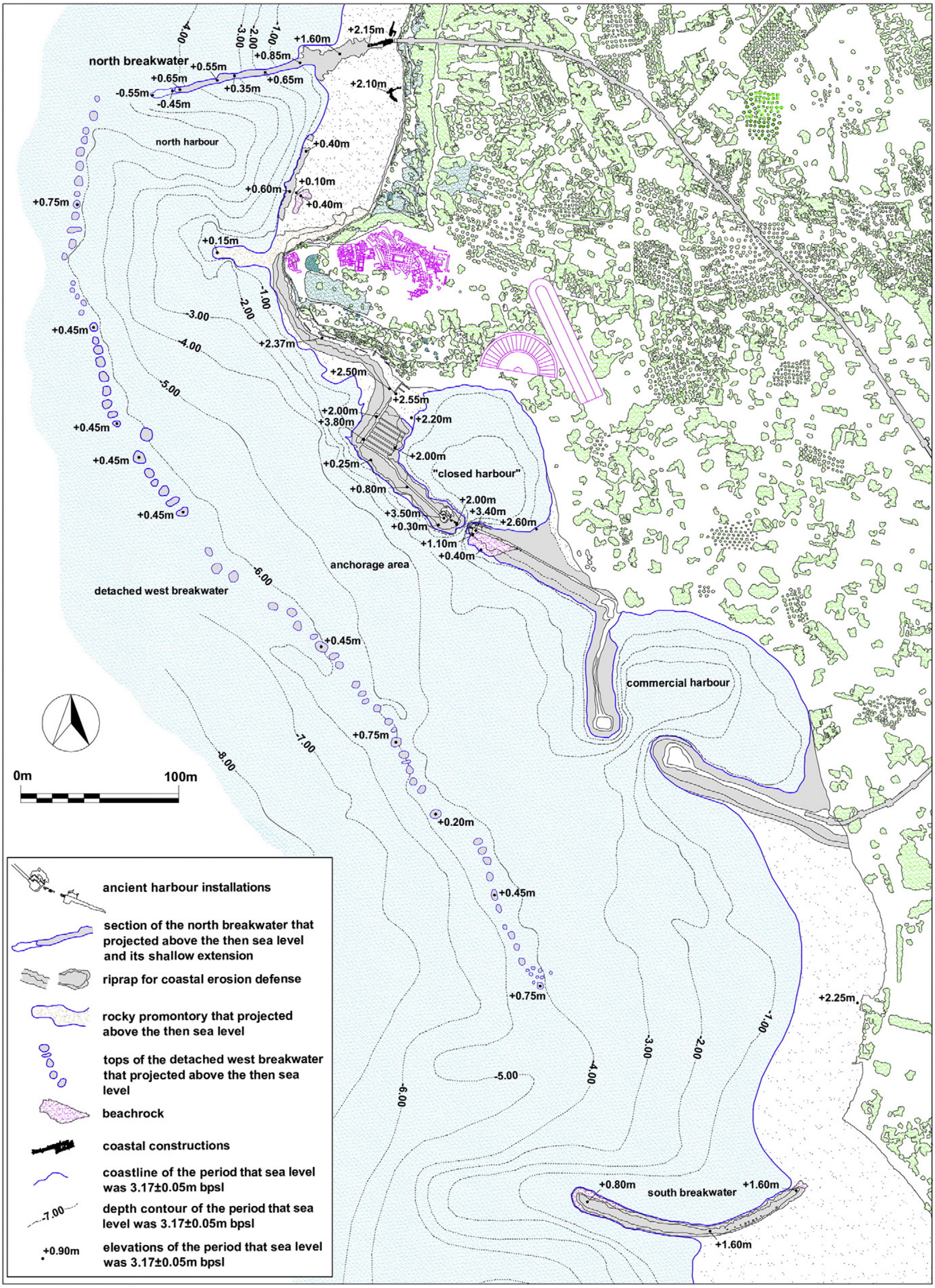

Fig. 6. Paleogeographical reconstruction of the seafront of the ancient city of Aegina.

bathymetric chart. It took into consideration both the natural processes and the human interventions that created the present morphology of the coast and the seabed over time (Fig. 6).

In the course of the past 2200 years or so, from the Early Bronze Age until the Late Roman period, the sea level on the shores of ancient Aegina, as well as on the opposite coast of the Peloponnese, remained more or less stable, at 3.17 m ± 0.05 m lower than today.

Throughout this period the sandy coast of the north harbor was 100 m to 110 m wider than the present one. The breakwater that was constructed thrust into the sea for 210 m in a WSW direction. It was approximately 7.0 m wide and projected at least 0.50 m to 1.0 m above the sea level. The lateral parts of its surface were at −0.50 m to −1.0 m. The western end of the breakwater, 30 m long, was approximately 0.45 m below the sea surface. The sandy coast next to the inland end of the breakwater was filled with rock materials. The fill was 20 m, increasing to 45 m on the coast, to protect it. Auxiliary harbor facilities were constructed on the coast at the foot of the hill slope (Figs. 3, 6).

However, the pre-existing natural, dynamic balance was disturbed by the construction of the north breakwater, which caused erosion of the sandy south coast. To protect the coast from erosion, a riprap was constructed along it, 100 m long and 8.0 m wide, and projected approximately 0.50 m above the sea level at that time (Figs. 3, 6).

The south end of the extensive sandy coast was delimited by the steep north slopes of Kolona Hill. The rocky westward continuation of the hill thrust into the sea for 90 m and projected approximately 0.15 m (Figs. 3, 6).

The detached west breakwater was not continuous. Only the tops of the cone-shaped piles of stones projected up to 0.80 m above the sea level at that time (Figs. 3, 6).

At the northwest side of the harbor, between the west end of the north breakwater and the north end of the west breakwater, an entrance to the anchorage area, 70 m wide, was formed. The depth of the north harbor reached 6.0 m, with the sandy seabed sinking abruptly to the northwest, forming an elongated depression toward the harbor entrance (Figs. 3, 6).

On the south coast natural processes but mostly the recent large-scale human interventions have altered the ancient morphology, particularly in the area of the ancient commercial harbor, so that it can be reconstructed only based on assumptions and historical evidence.

The ancient coastline more or less followed the course of the riprap that protected the "closed harbor" wall and the coastal wall of the west side of the hill (Figs. 5, 6). The top of the riprap projected 1.0 m above the sea level at that time and the highest — at present — part of the wall projected 3.50 m. In front of the south wall the rocky materials of the riprap were cemented together forming a thick beachrock slab, into which the superstructure of the wall was incorporated. The riprap continued to the entrance and inside the basin of the "closed harbor", shallow at present because of siltation. This finding indicates that at that time the harbor basin was deeper and there was water inside. Given that the draught of ancient vessels did not exceed 1.50 m (Morrison et al., 2000), it is estimated that the depth of the basin reached 2.0 m to 2.50 m. The interior of the basin in its north part was filled with rocky materials, upon which the shipsheds were founded. Most likely the south part of the basin was also filled, as evidenced by rock debris. As shown in Graves's chart (1839), the south wall of the "closed harbor", of which only the northwest end survives, appears to run in a straight line for 210 m toward the southeast, and to meet the inland beginning of the north mole of the commercial harbor. The area between the coast and the south wall seems to have been filled in (Figs. 5, 6).

The top of the fill projected 2.0 m in the north part of the basin and 2.60 m in the south part. The ancient basin, of estimated area 25,000 m^2, was enclosed by the rockfills and the area of human activity during antiquity, which is attested by submerged building remains and numerous potsherds and stones. The entrance to the "closed harbor" was narrow, not exceeding 7.0 m. Given that the largest ancient ships were up to 5.50 m wide (Morrison et al., 2000), the harbor basin was most likely used by smaller ships (Figs. 5, 6). The small capacity of the basin, the narrowness of the entrance and the harbor hazards were verified by Thevet (1586): "*because its basin is not so large nor its entrance so wide, like that of the other, they were guarding the oared ships, such as galleys, galliotes etc. When the south wind blows, it is dangerous, so the pilot must be on the alert and be careful, equally by day and at night*".

The reconstruction of the commercial harbor to the south of the "closed harbor" can be based only on historical testimonies (Montagu, 1799; Collignon, 1913) and especially on Graves's chart (1839).

The French consul Jean Giraud, who visited the island in 1673, described the harbor as a "*daily port, which is very good and safe in any kind of wind, though somewhat exposed to W and SW winds, but without risk*" (Collignon, 1913). The English John Montagu, 4th Earl of Sandwich, who visited Aegina in 1738, referred to it as "*the port, composed of two artificial moles*" (Montagu, 1799). Graves's chart (1839), which was drawn up before any significant intervention in the commercial harbor area, shows that its north mole had a slightly curved course toward the southwest for 160 m, ending where the small church of St. Nicholas stands today. The south mole, which ran to the northwest for 240 m, is entirely covered by the modern dock. It seems that the basin of the commercial harbor was also of limited area, most likely because of artificial fills, mainly in the south part (Fig. 6). Montagu (1799) wrote: "*by its smallness is proven that the ships of the ancients were not so large as is generally imagined, it being, both on account of the depth and the circumference, not capable of containing other than a few small barks*". Based on Graves's data (1839), the estimated area of the basin is 25,000 m^2 and the maximum depth in the central part must have exceeded 4.0 m, since it was 3.40 m in 1839 (Fig. 6).

The sandy coast south of the commercial port was 100 m wider than at present and the past coastline appears to have followed more or less the outline of the present one (Fig. 6). The anchorage area in the north part was up to 6.0 m deep, while south of the "closed harbor" the maximum depth was reduced to 4.0 m. The west breakwater was not continuous. Only the tops of the cone-shaped piles of stones, which compose the breakwater, projected 0.20 m to 0.80 m above the sea. Opposite the entrances to commercial port and the "closed harbor" there are two gaps in the breakwater, which were most likely used as

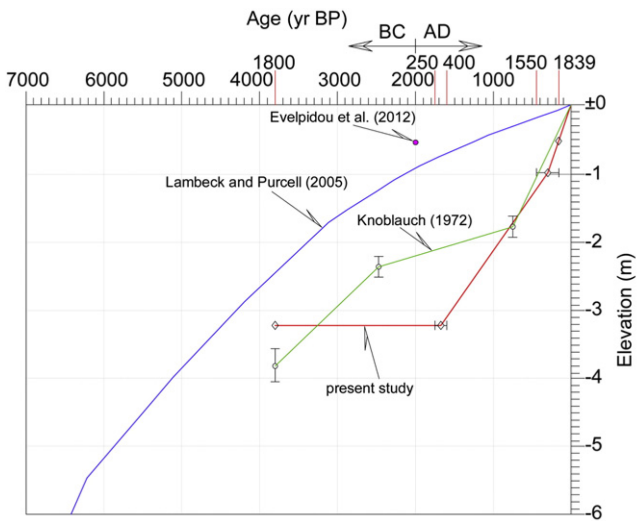

Fig. 7. Plot of the predicted sea level curve for the Peloponnese that was developed by Lambeck and Purcell (2005) (blue line) and Evelpidou et al. (2012) (magenta dot) and the curve that has produced using Knoblauch's data (1969, 1972) (green line) compared with the curve of the present study (red line). Circles and diamonds with error bar for depth and age.

west entrances of ships into the anchorage area (Fig. 6). Although the overall structure of the detached west breakwater reduced wave energy, it definitely served defensive purposes, as it was extremely dangerous to those who were not aware of the entrances to the area of the harbors. Its defensive role is preserved through tradition and is also mentioned by Pausanias who wrote that the island "*was surrounded by sunken rocks and reefs which rise up. The story is that Aeacus devised this feature of set purpose, because he feared piratical raids by sea, and wished the approach to be perilous to enemies*" ("*πέτραι τε γὰρ ὕφαλοι περὶ πᾶσαν καὶ χοιράδες ανεστήκασι. μηχανήσασθαι δὲ εξεπίτηδες ταῦτα Αιακόν φασι ληστειῶν τῶν εκ θαλάσσης φόβῳ, καὶ πολεμίοις αν δράσι μὴ άνευ κινδύνου εῖναι*") (Pausanias, 2.29.6).

The curved breakwater delimiting the anchorage area to the south projected 0.80 m in the west part and 1.60 m in the east part. At the east and west ends of the breakwater, the rocky materials of the riprap were cemented together forming a beachrock slab. The wide opening between the west and the south breakwater, with the seabed at approximately −4.0 m to −5.0 m, formed the south entrance to the anchorage area (Fig. 6).

During the Roman domination of Aegina, which was a period of decline and desertion for the island, sea level rose by 2.20 m. This event is estimated to have occurred after AD 250, since in the time of Julia Domna new city walls were built and the harbor was renovated. The sea flooded the north sandy coast, sinking the top of the north breakwater by 0.60 m to 1.70 m, the rockfill and buildings on the coast by 0.50 m, the top of the riprap in the south half of the north coast by 1.60 m to 1.80 m and the south rocky ledge of Kolona Hill by approximately 2.0 m. On the south coast, the protective ripraps of the walls sunk to a depth of 1.40 m and the marine notch of −1.02 m was formed on its superstructure. The top of the fill inside the harbor basin was inundated, as well as the foundations and floors of the shipsheds, which were then incorporated into the beachrock slab that was created at this sea level. In the south part of the anchorage area the sandy coast flooded and shrank by approximately 70 m.

The south curved breakwater was submerged at −0.60 m to −1.40 m. Finally, the detached west breakwater sunk with the tops of the cone-shaped piles of stones at −1.50 m. According to Thevet (1586), they could only be seen when the weather was calm, and therefore were perilous for ships (Figs. 3, 5).

The more recent phase of submersion by 0.45 m, which occurred between 1586 and 1839, does not seem to have caused as dramatic changes as the previous phase. The city of Aegina was at that time a small village under Ottoman rule, and what was left of the harbor installations above sea level was used as a shelter for small boats. The north coast was just 9.0 m to 12.0 m wider than the present one, and the notch of −0.57 m was created at this time on the surface of the ruined buildings. Along the west coast of Kolona Hill a beachrock was formed, incorporating the remains of the coastal wall. Additionally, the marine notch of −0.57 m was formed now on the superstructure of the "closed harbor" wall and the coast shrunk to a width of 12 m to 15 m (Figs. 3, 5).

Finally, after the most recent submergence phase of the coast, which caused a sea level change by 0.52 m ± 0.05 m, the coast acquired its present configuration, submerging the harbor constructions to their current position (Figs. 3, 5).

9. Discussion

A comparison of the curve resulting from relative sea level stands on the coast of Aegina, their dating and their rates of change with the curve obtained by the composition of Knoblauch's (1969, 1972) data and the predicted curves of the glacio-hydro-isostatic and eustatically corrected model of Holocene relative sea level for the Peloponnese, developed by Lambeck and Purcell (2005) and for the central Mediterranean, presented by Evelpidou et al. (2012), reveals fundamental differences (Fig. 7).

Knoblauch (1969, 1972) determined past sea levels by initially interpreting the function of harbor constructions and then estimating their functional level. Some characteristic examples are listed below. The top of the north breakwater is presented as sloping, sinking gradually from east to west from 2.50 m to 4.50 m. However, in the present study, it was found that its depth remains stable at approximately 2.60 m in its greater part, with the exception of its 30 m long end section, which was designed to be at a small depth below the sea for coastal engineering purposes. According to Knoblauch (1969, 1972), for the breakwater to be functional, it should be 3.55 m to 4.0 m below the present sea level. Moreover, Knoblauch (1969, 1972) did not evaluate the location, development, contemporary depth and functionality of the riprap that was constructed in the south half of the north paleocoast. He also interpreted the wall that surrounds the "closed harbor" on the south coast as a "mole", completely ignoring its protective riprap. To explain its functionality, he was forced to shift the construction date of the "closed harbor" 1318 years later than that of the north breakwater and also to increase the sea level from 1.35 m to 1.55 m higher than the functional level of the north mole. Finally, in his dating of sea level change, Knoblauch (1969, 1972) does not take into account the contemporary depth of the west breakwater in relation to the testimony of Pausanias, and he completely ignores the existence of the south breakwater. Based on the above, it is clear that the differences in the curves that were derived from Knoblauch's data (1969, 1972) and the present study is because of inverse approach methodologies, which led to different estimates of sea level stands, duration and dates.

The Lambeck and Purcell (2005) model presents the glacio-hydro-isostatic and eustatic contributions to relative sea level change. Any differences between the sea level data and the model theoretically can be attributed to the local seismo-tectonic factor. We observe that the curve for Aegina that was derived from the present study is systematically lower than that of glacio-hydro-isostatic model. Moreover, whereas the glacio-hydro-isostatic curve shows a continuous sea level rise over time, the curve from the present study indicates short or long periods of stability in the relative sea level, during which the corresponding coastal landforms were formed. Additionally, the elevational and chronological differences in relative sea level are significant. However, the most important difference is the extremely long period of stability in relative sea level of at least 2200 years. It should be noted that this stability is also found across the Saronic Gulf, on the tectonically fragmented and seismically active coast of the Peloponnese (Kolaiti and Mourtzas, submitted).

The glacial isostatic adjustment model for the Late Holocene in the central Mediterranean presented by Evelpidou et al. (2012) indicates that the relative sea level in the study area 2000 years BP was ca. 0.45 m lower than the present one. Their estimates differ significantly from those of the present study (Fig. 7). These divergences, according to their model, are attributed to tectonic deformation, with the exception of the eustatic rise of the sea level over the two last centuries, which is widely accepted.

The long-term stability of the relative sea level followed by an abrupt rise on the coast of Aegina cannot be connected with the local tectonism, specific fault zones and seismic events. These changes concern the wider area of the Saronic Gulf and, most likely, a greater section of the Earth's crust, including the east Peloponnesian coast. They are likely linked with deformation processes that occurred in the Hellenic Arc during a period of major tectonic events, called the "Early Byzantine tectonic paroxysm" by Pirazzoli (1986b).

10. Conclusions

The extensive harbor installations on the seafront of ancient Aegina in front of Kolona Hill, a significant part of which is well preserved below the present sea level, enhance one of the largest artificial harbors of antiquity.

The submerged beachrock from cemented archeological material, the marine tidal notches that have formed on the surface of the ancient harbor and maritime constructions, and the currently submerged parts of ancient constructions that had a direct relationship with past sea levels, allowed the definition of three different relative sea levels, at depths of 3.17 m ± 0.05 m, 0.97 m ± 0.05 m and 0.52 m ± 0.05 m lower than the present depth.

The dating of past sea levels, based on archeological evidence and historical sources, refers to an abrupt rise in sea level toward the end of the Late Roman period. It occurred in three distinct phases of submersion, initially by 2.20 m, then by 0.45 m and finally by 0.50 m. The initial sea level change occurred after AD 170, when Pausanias visited Aegina. We concluded that this change occurred after AD 400 ± 100 on the opposite Peloponnesian coast of the Saronic Gulf, based on archeological evidence. According to historical sources, the two successive sea level changes date to AD 1586–1839 (the intermediate) and AD 1839–1999 (the most recent).

Sea transgression followed a long period of stability of relative sea level, which lasted at least 2200 years, from the Middle Bronze Age (ca. 3900 yr BP) until the Late Roman period (ca. 1700 yr BP). The paleogeographical reconstruction of the coast and the ancient harbor installations for this period revealed an extensive anchorage area and three inner artificial harbors: the north harbor on the north coast of Kolona Hill, the “closed harbor” in the north part of the south coast, and the commercial harbor to the south, today completely destroyed by the modern port.

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