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Upper Holocene sea level changes in the West Saronic Gulf, Greece

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ABSTRACT

Along the Peloponnesian coast of the Saronic Gulf and on the coast of Aegina and Poros islands, submerged coastal geomorphological features related directly with submerged ancient coastal constructions, indicate three distinct sea levels. Submerged tidal notches incised on the carbonate basement, beachrocks formed in the intertidal zone and archaeological indicators, such as the ancient harbour installations in Kenchreai and Epidaurus and on Aegina island, the extended coastal buildings and constructions in Agios Vlasis, Psifta and Palaiokastro-Methana, and Vagionia on Poros island, are used to determine the age and magnitude of submersion and the extent of the Upper Holocene marine transgression. By the correlation of geomorphological, historical and archaeological indications three distinct sea levels were identified, at -3.30 ± 0.15 m, -0.90 ± 0.15 m and -0.55 ± 0.05 m. Initial change in sea level occurred definitely after AD 400 ± 100. The intermediate change is dated between AD 1586 and 1839, and the most recent change after 1839. Sea transgression followed a long period of sea level stability, which lasted at least 2200 years, from the Middle Bronze Age to the Late Roman period.

1. Introduction

The West Saronic Gulf, between the east coast of the Peloponnese and the islands of Salamis, Aegina and Poros (Fig. 1a, b), is fragmented by active seismic zones that is considered to have caused footwall uplift and hanging wall subsidence during their successive activations throughout the Upper Holocene (Fig. 2). Sea level changes that occurred in specific coastal locations of these areas are mainly attributed to paroxysmal subsidence episodes connected with strong earthquakes (Scranton et al., 1978; Papanastassiou and Gaki-Papanastassiou, 1993; Noller et al., 1997; Nixon et al., 2009; Dao, 2011; Papanikolaou and Roberts, 2011).

As reported by Scranton et al. (1978), in the bay of Kenchreai on the north side of the Peloponnesian coast of the Saronic (Fig. 1a–c), the submersion of the Roman harbour possibly occurred during three distinct phases, which caused a total sinking of the constructions by 2.30 m. The first phase, which resulted in a submersion by 0.70 m, is correlated with the strong earthquake of AD 77. The second phase coincides in time with the earthquakes of AD 365 and 375, which caused further subsidence by 0.80 m. Finally, the third phase is related to the seismic events of the 6th century AD causing again a subsidence of approximately 0.80 m.

Rothaus et al. (2008) stated that in the coastal area of Kenchreai the excavations revealed level, intact, paved floors, damaged only by later intrusions and no traces of liquefaction, slumping, or lateral spreading were found, implying that the subsidence is almost totally fault-controlled. They consider that the fish tanks of the south breakwater are the only sure dated indication of sinking of the site and up today there is not any other archaeological evidence certainly indicating the number of the co-seismic events that struck Kenchreai. The E–W oriented Oneia fault zone that ends at the bay of Kenchreai (Fig. 2) is an active normal structure with a length varying from 7 km to 9 km and magnitude of earthquake potentials 5.5 R (Papanikolaou et al., 1996; Kranis et al., 2004). The ancient harbour lies in the immediate hanging wall of this fault zone, which according to Papanikolaou and Roberts (2011) may have caused a significant cumulative subsidence during successive activations. The strong earthquakes of AD 365–400, 551, 1756, 1858 and 1928 caused serious damage in the area and their macroseismic effects are associated with this fault zone (Papanastassiou and Gaki-Papanastassiou, 1993; Noller et al., 1997; Papazachos and Papazachou, 1997; Rothaus et al., 2008).

Twenty kilometres south, on the Peloponnesian coast of the Saronic Gulf, in the bay of Korphos (Fig. 1b), Nixon et al. (2009) examined and correlated tidal notches with foraminifera/thecamoebians fossil assemblages found in sediment cores drilled in the salt marsh nearby the village of Korphos and so they produced a sea level curve. They argue that much of 4 m rise in relative sea level

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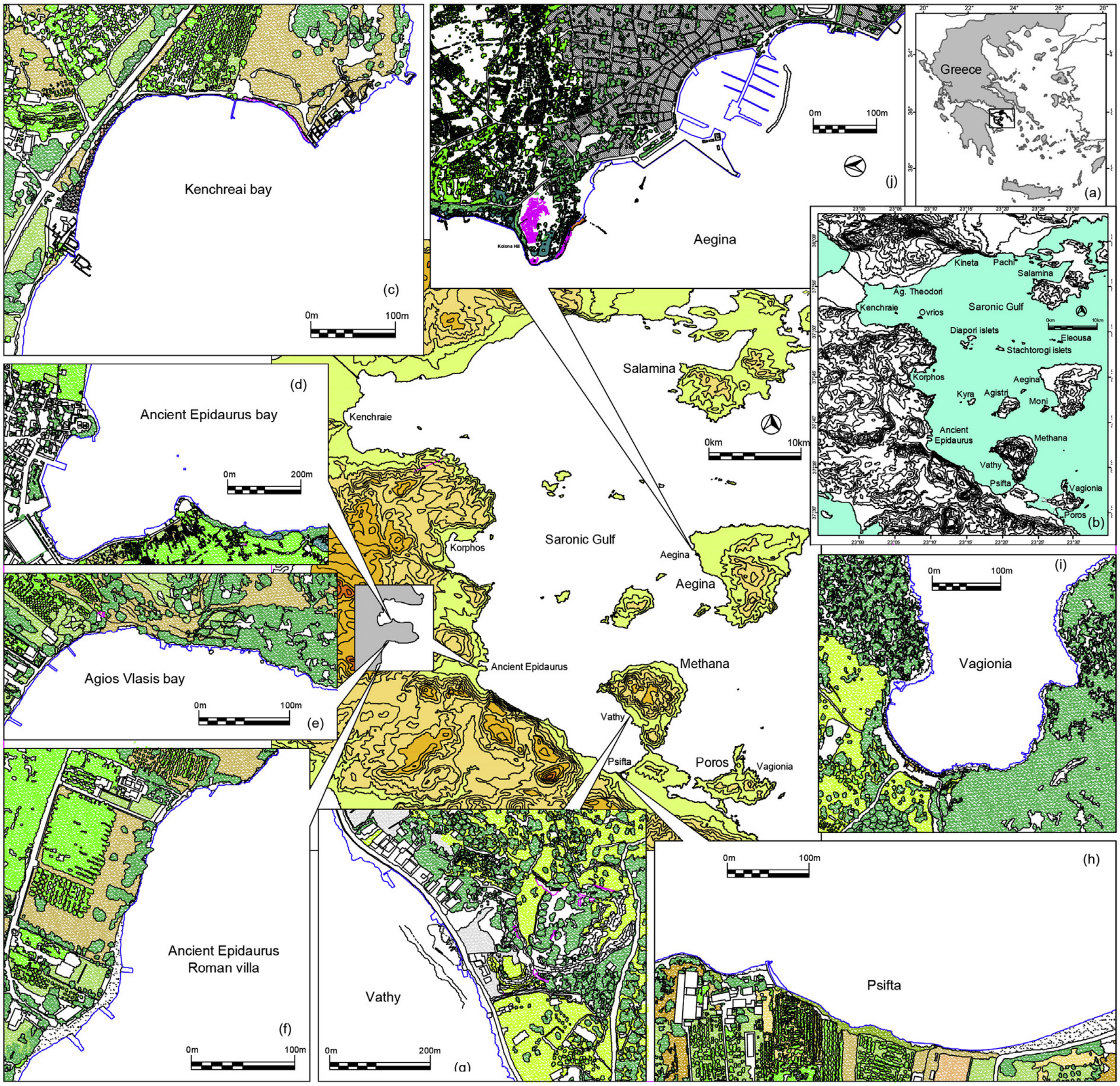

Fig. 1. (a), (b): Location maps of the Saronic Gulf, (c): Kenchreai bay, (d): Ancient Epidaurus bay, (e): Agios Vlasis bay, (f): coast of Epidaurus country villa, (g): Vathy coast of the Methana peninsula, (h): Psifta coast, (i): Vagionia bay on Poros island, (j): seafront of the ancient and modern city of Aegina (after Mourtzas and Kolaiti, 2013).

occurred at Korphos in the last 5500 years during five distinct tectonic phases of subsidence that formed the sea levels of −2.94 m around 5100 BP, −1.74 m ~4400 BP, −1.34 m ~2650 BP, −0.88 m ~1600 BP, and the approximate present level ~400 BP. According to the authors, earthquakes causing coseismic subsidence occur once every 1412 ± 1068 y at Korphos.

Dao (2011) found two submerged beachrock platforms on the coast of Kalamianos Mycenaean settlement, 2.5 km east of Korphos (Fig. 1b). ^{14}C dating of wood charcoal fragments from the younger beachrock phase at −3.50 m to −3.70 m yielded a calibrated age of approximately 1600–1400 BC, slightly earlier than the Late Helladic (1400–1200 BC) potsherds that have been incorporated into it. The older beachrock phase at −5.80 m to −5.90 m comprises well preserved sherds of Early Helladic (2700–2200 BC) jars. The noticeable different rate of sea level change between the two adjacent positions is attributed by Dao (2011) to neotectonic activations of the intermediate faults.

Negris (1904) estimated that the detached west breakwater of the ancient harbour of Aegina on the NW coast of Kolona Hill (Fig. 1b, j), has submerged by 3.70 m since its operation. Knoblauch (1969, 1972) considered that over the last 3800 years sea level has risen by 3.55 m–4.05 m in the ancient harbour of Aegina. He also stated that during the Classical period (482 BC) sea level was at −2.20 m to −2.50 m, whereas in Roman times (*ca.* AD 250) was at −1.60 m to −1.90 m. Mourtzas and Kolaiti (2013) based on geomorphological and archaeological indications defined three distinct relative sea levels at depths of 3.17 ± 0.05 m, 0.97 ± 0.05 m and 0.52 ± 0.05 m. They also attempted to date the sea level changes based on archaeological evidence and historical sources and concluded that the initial sea level change in Aegina occurred certainly after AD 170 and most likely after AD 250, the intermediate change between AD 1586 and 1839, and the most recent change between 1839 and 1999. They first argued for a long period of sea level stability that lasted from the Middle Bronze Age to the Late Roman period.

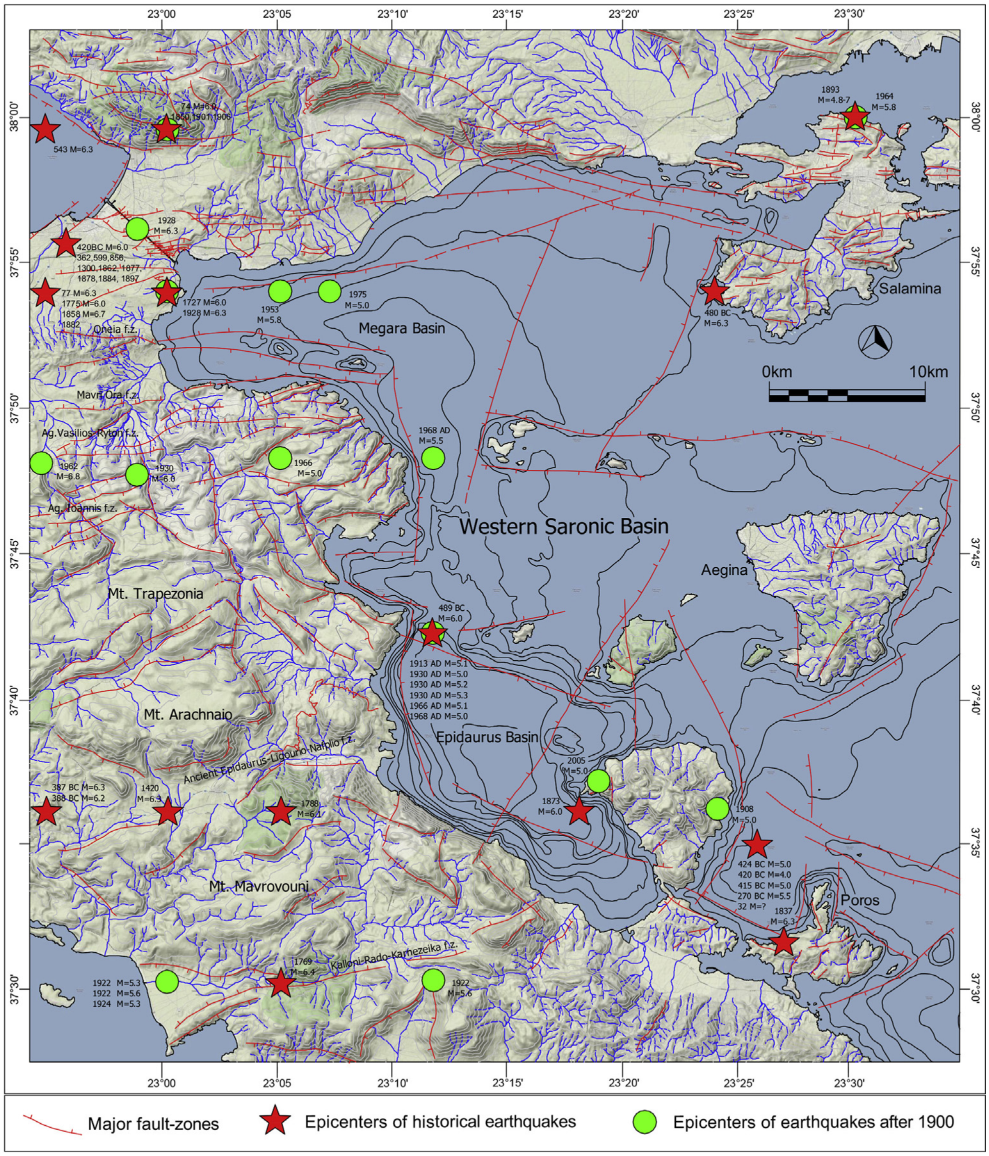

Fig. 2. Seismotectonic map of the Western Saronic Gulf.

2. Geodynamic setting

The basin of the Saronic Gulf forms a complex neotectonic structure in the NW edge of the inner, modern, Hellenic volcanic arc (Papanikolaou et al., 1988; Dietrich et al., 1993). A relatively shallow underwater ridge at its central portion, emerged parts of which are the islands of Salamis, Aegina and Poros, and the peninsula of Methana, demarcates the eastern from the western part of the basin (Fig. 2). This central platform implies the existence of a NNE–SSW trending rupture zone, which is probably the offshore extension of a large thrust belt dominating the adjacent onshore areas (Drakatos et al., 2005). This system marks an important tectonic boundary, dividing the Cycladic blueschist belt to the SE from the Sub-Pelagonian Palaeozoic to Mesozoic carbonate platform to the West. It probably originated as a Tertiary overthrust and experienced a vertical reset during Middle to Late Miocene. Since Early Pliocene it has been reactivated with slight anticlockwise rotation towards a NNE–SSW strike (Dietrich et al., 1993).

The western part of the Saronic Gulf is divided into two sections by a well-defined rupture zone trending E–W, that seems to be the extension of the Corinthian Gulf fault zone (Papanikolaou et al., 1988; Drakatos et al., 2005). The south section is the Epidaurus Basin, WNW–ESE orientated, more than 400 m deep and the northern one is the Megara Basin, E–W orientated, less than 250 m deep (Fig. 2). The WNW–ESE marginal faults at the SW margin of Epidaurus Basin have a throw of approximately 350 m and create a rather symmetric tectonic graben with significant volcanic intrusions within the eastern part of the basin. Both the Epidaurus and Megara basins are demarcated from the West by a N–S fault zone with a throw of more than 400 m parallel to the Peloponnesian coast (Fig. 2). The Megara Basin is a tectonic graben formed by E–W to ENE–WSW marginal faults having a throw of 400 m–500 m. An alternation of horsts and grabens created by E–W to ENE–WSW faults with throws between 200 m and 300 m complement the tectonic structure of the West Saronic Gulf (Papanikolaou et al., 1988).

The neotectonic extensional regime of the area is connected with the thinning of the crust to 20 km in the basin of the Saronic (Drakatos et al., 2005) and the Plio-Quaternary volcanic arc activity, which is distinguished into two major phases (Pe, 1973; Pe-Piper et al., 1983; Dietrich et al., 1988, 1993; Seymour, 1996; Morris, 2000). The volcanic centres of Soussaki, Aegina and Poros belong to the first Pliocenic volcanic activity and the volcanic centre of Methana to the second phase of Pleistocene (Fytikas et al., 1986). The most recent volcanic activity occurred in 230 BC at the NW side of the peninsula of Methana, creating the andesites of Kameni Chora (Fytikas et al., 1986). The volcanic activity today is confined to the hot springs and the fumaroles of Methana and Aegina, which are directly associated with active fault systems (Makris et al., 2004; D'Alessandro et al., 2008).

The entire area of the Peloponnesian coast is characterized by the existence of large fault zones and numerous other second- and third-order faults, which divide it into blocks (Fig. 2), forming large tectonic grabens and horsts (Papanikolaou et al., 1989; Kranis et al., 2004).

The Oneia fault zone at the south margin of the East Corinthian basin (Fig. 2) are seismically active normal faults, mainly trending E–W and dipping to the North with length ranging from 7 km to 26 km (Papanikolaou et al., 1996; Kranis et al., 2004). It demarcates the Oneia alpine mass at the North from the Mavri Ora, Agios Dimitrios, Agios Vasilios-Ryton, Agios Ioannis, Agios Andreas-Ligourio-Metochi, Ancient Epidaurus-Ligourio-Nafplio and Kalloni-Rado-Karnezeika fault zones parallel to it at the South.

Increased seismic activity under a tensional regime with a NNE–SSW direction, is mainly observed at the west margins of the Saronic Gulf (Fig. 2), areas of strong historical and recent seismicity (Makropoulos et al., 1989; Papazachos and Papazachou, 1997; Papadopoulos et al., 2000). In the central ridge of the Saronic Gulf the microseismic activity is related more to the crustal deformation under an 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. Material and methods

Determination of Upper Holocene sea level changes along the coast that border on the West Saronic Gulf was based on the correlation of geomorphological, archaeological and historical data. The present uplifted or submerged position of coastal archaeological sites and constructions, which had a direct or indirect relationship with the coastline in their operation, is used as a sensitive indicator of past sea levels. It also allows determining the vertical direction, magnitude and age of the Upper Holocene changes in the sea–land relationship, always taking into consideration specific restrictions and conditions. The relationship between the ancient construction and a past sea level is the key to the determination of the sea level during its operation. Besides, the historical data derived from ancient literary sources and testimonies contribute to the definition of a "functional level" and sometimes to the decision on the period that the sea level change occurred.

The ancient harbours and coastal installations were mapped using satellite images (Google Earth, 2012, 2013, 2014), high-resolution orthophotos at a scale of 1:500 (Ktimatologio SA), aerial images of the ancient Epidaurus coastal zone (Kritzas, 1972) and the sunken country villa in the bay of Epidaurus (2000/2005, n.a. photograph, <http://www.flying-paradise.com/gallery.cfm>), the detailed mapping of submerged coastal port facilities and buildings of the port of Kenchreai (Scranton et al., 1978), and the mapping of the sea front of Kolona hill in Aegina (Knoblauch, 1969, 1972). Maps were updated during underwater survey, at positions where data accuracy was required to reconstruct past sea levels and to define precisely the "functional level" of the ancient maritime constructions.

Tidal notches and the relevant beachrock phases are also sensitive indicators of Upper Holocene sea level changes in low-tidal range areas, like the Eastern Mediterranean.

Beachrocks are formed in periods of tectonic and eustatic stability of sea level and consequently represent the fossilized section of a former sandy/gravel coast. They are hard coastal sedimentary formations consisting of beach sediments, of both clastic and biogenic origin, rapidly cemented by the precipitation of carbonate cements. The most common type of cement in the Aegean low tide area is the Mg-calcite micritic early cement (Alexandersson, 1969; Dermitzakis and Theodoropoulos, 1975; Kampouroglou, 1989; Neumeier, 1998; Neumeier et al., 2000; Vousdoukas et al., 2007; Erginal et al., 2008; Desruelles et al., 2009; Erginal et al., 2010; Vacchi, 2012). Cementation occurs either in the intertidal or in the swash/backwash and spray zone under complex physico-chemical and biological mechanisms, in periods of low waves and possibly in the presence of meteoric water. Both intertidal and supratidal zones present a similar, indistinguishable diagenesis. The spray (vadose) zone is also part of the supratidal zone where sea water percolates through the beach sand and beachrock cementation is clearly distinguished by crystal arrangement that produce microstalactitic cements (Bernier and Dalongeville, 1996; Neumeier, 1998). The Mg-calcite cement and the intertidal formation of the Saronicos beachrocks is confirmed by Dermitzakis and Theodoropoulos (1975) who first examined the extended beachrock formation along the SE coast of Metopi island in the central part of the West Saronic Gulf.

Numerous observations throughout the Greek coast on the relationship between the beachrocks with both tidal notches and ancient coastal constructions have also 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, 2012a,b,c; Mourtzas and Kolaiti, 2013; Mourtzas et al., 2014). The depth of the base of the seaward end of the beachrock slab coincides with the lower low tide of the respective sea level in which it was cemented, so it can be used as a reliable indicator for the definition of a mean former sea level. The mean sea level during the beachrock formation in 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 for the Saronic Gulf is 0.15 m.

The positive or negative sea level change potentially forms successive beachrock outcrops. Beachrocks have been used by a large number of scholars as accurate indicators of past sea levels for the Aegean low tide area (e.g. Mourtzas, 1990; Fouache et al., 2005; Desruelles et al., 2009; Çiner et al., 2009; Mourtzas, 2010, 2012a,b,c; Dao, 2011; Vacchi et al., 2012; Erginal et al., 2013). Their submerged or uplifted modern position reflects different past sea levels and respective ancient coastlines. The dating of beachrocks is based on archaeological findings and constructions incorporated into or covered by the formation or on their relationship with them. This defines an upper time limit for beachrock formation not exceeding the age of the incorporated or related archaeological constructions and findings (Mourtzas, 1990, 2010, 2012a,b,c; Mourtzas and Kolaiti, 2013; Mourtzas et al., 2014).

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 level, respectively (Pirazzoli, 1986a). The mean sea level that corresponds to each tidal notch formed on the ancient constructions 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.

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 Piraeus, NE of the study area. The maximum tidal range for the time period and the measurement hours was 0.25 m and the difference between mean higher high water and mean lower low water is given at 0.30 m.

After determining the past sea levels positions, various available maps, nautical charts, and bathymetric data (Hellenic Navy Hydrographic Service; Scranton et al., 1978) were used as aids in the palaeogeographical reconstruction of the ancient coastline and the assessment of the type of ancient coastal constructions.

4. Evidence of sea level change on the Peloponnesian coast of the Saronic Gulf

Eight locations were selected along the Peloponnesian coast of the Saronic (Fig. 1), on the basis of the existence of both submerged ancient coastal constructions and geomorphological features indicative of past sea levels associated directly with them. The ancient harbour of Kenchreai at the northern end of the Peloponnesian coast (Fig. 1b, c); the ancient harbour of Epidaurus and the neighbouring "harbour distinct" 30 km southernmost (Fig. 1b, d); the sunken buildings in the northern side of Agios Vlasis bay (Fig. 1b, e) and the submerged country villa, 500 m and 900 m, respectively, south of Epidaurus ancient harbour (Fig. 1b, f); the sunken country villa on the shore of the wetland of Psifta, 20 km south of Epidaurus (Fig. 1b, h); the submerged ancient rock fill and buildings on the coast of the Classical Acropolis of Palaiokastro in today's Vathy village on the western coast of the Methana peninsula (Fig. 1b, g); and finally, the submerged relics of ancient buildings in the bay of Vagionia on the north side of Poros island, 31 km south of Methana (Fig. 1b, i), give a clear idea on the magnitude of submersion and the extent of marine transgression, while enabling their dating.

4.1. The ancient harbour of Kenchreai

The ancient harbour of Kenchreai was the eastern sea gate of ancient Corinth to the Saronic Gulf (Fig. 1c). The small, semicircular basin in the northern end of the bay of Kenchreai occupies an area of 47,000 m^2 and is defined by two, today submerged, natural protrusions (Fig. 3i), which were formed in two breakwaters after the appropriate supplementary works. Among them, at the SE seaward side of the basin, is formed the entrance of the harbour, with an opening of approximately 140 m.

It was built after 146 BC, that is after the invasion of Roman legions and the razing of Corinth by General Lucius Mommius, in the early period of the Roman occupation of Corinth (Scranton et al., 1978) and appears to abandoned around AD 400 ± 25, most likely after a devastating seismic event (Rothaus et al., 2008). Clues for an even later habitation provide the burial of an adult male around AD 675 ± 25, chronology that is documented by the grave offerings. The floor of the tomb is at −0.35 m below the present sea level (Rothaus et al., 2008).

At the base of the north mole, north of the rectangular tower, which according to Scranton et al. (1978) most likely represents the lower part of the base of a lighthouse or watch-tower of Late Roman times, a well-developed beachrock formation occupies the entire length of the narrow coast (Fig. 3ii). It starts at approximately 15 m from the shore and ends in 37 m of it. It consists of cemented coastal deposits of sands and pebbles, as well as archaeological relics, including a large number of potsherds, architectural fragments and building foundations (Figs. 3ii, 4a). At the eastern seaward end of the beachrock, the top is at −2.45 m to −2.70 m and its base at −3.30 m to −3.45 m. The erosion of the intermediate section of the beachrock revealed that it covers part of a paving (Figs. 3ii, 4b). It is most likely a roadway that passed along the shore at this point, now destroyed, which at its northern end was supported by a retaining wall, also incorporated into the beachrock. The retaining wall that is located at a distance of 26 m from the shore, would likely date to the first or second century AD (Scranton et al., 1978). The remains of coastal constructions covered by and incorporated into the beachrock, indicate that the formation of the beachrock slab occurred after their collapse and abandonment, when the sea level was 3.25 ± 0.10 m lower than the present level.

The northern part of the building complex (Fig. 3ii) is referred as the Sanctuary of Aphrodite and is dated from the first to the fourth century AD (Scranton et al., 1978). It comprises a big complex of structures with a central atrium, built by bricks. Its coastal side has been submerged up to −1.85 m in a distance of 11 m–15 m from the shoreline. The foundations and superstructures of the buildings have been incorporated into a younger beachrock phase with a limited development in the NE section of the area. The top and base of the seaward end of the beachrock 11 m offshore are at −0.60 m to −0.90 m, respectively (Figs. 3ii, 4c). The depth of the base of the seaward end of the beachrock, which coincides with the depth of the floor of the well-formed erosion cavity on the foundations of the buildings, indicate a younger sea level at −0.75 m lower than the present level.

The north breakwater that enters the sea in a SSW direction is 100 m long and 35 m wide, approximately (Fig. 3i, ii). It formed by artificial fill of a natural protrusion of the bedrock. The western side of the breakwater surface is elevated relative to the east by 0.15 m–0.50 m for a width of 10 m–25 m. The depth of the breakwater surface ranges from 1.85 m to 2.20 m in the northern end up to the central section and from 3.0 m to 3.30 m in its seaward south end. Remains of buildings are located only at the surface of the elevated western section of the breakwater (Fig. 4d–h), thus indicating that it projected above the sea level at that time by 1.40 m–1.0 m in the north and central part and at least by 0.20 m in the south end (Fig. 3ii), consistent with the definition of a sea level at 3.25 ± 0.10 m lower than at present. If Scranton et al.'s (1978) view that the sea level during the operation of the harbour was 2.20 m–2.30 m lower than the present level was sound, the greater part of the breakwater – approximately 60 m long-should have been 0.15 m–1.0 m below the sea level at that time. To explain the proportionally greater submergence of the breakwater relative to the other harbour facilities, Scranton et al. (1978) attributed it to differential settlement owing to the load of fill or hydraulic undermining or compaction of the loose rock material or wave erosion and material dispersion. However, the underwater survey did not reveal any fill slope failure. Furthermore, the load of fill does not justify settlements of this magnitude even on very soft soils, much less in this case that the fill rests on conglomeratic bedrock.

The south pier has a length of 120 m and a mean width of 50 m (Fig. 3i, iii). On the SE side there are at least five parallel complexes of rooms, with transverse corridors between them, which were interpreted by Scranton et al. (1978) as warehouse buildings. Today they are submerged at −1.10 m to −1.50 m. To the south of the warehouses two apsidal buildings of different construction phases were found. The easternmost was identified with the Sanctuary of the Godess Isis, with the depths of the floors ranging from −0.30 m to −1.10 m. The westernmost and later apsidal structure is an early

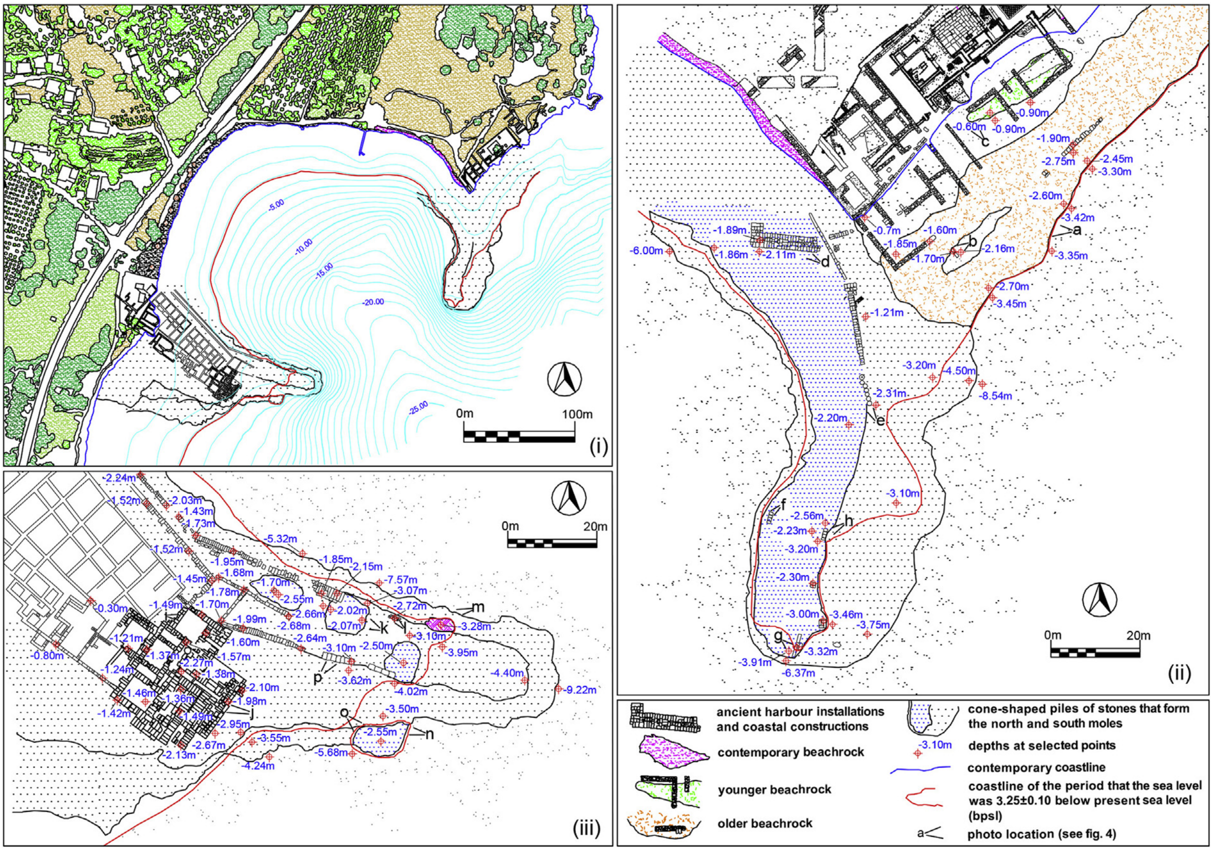

Fig. 3. (i) Plan of the ancient Kenchreai harbour, (ii) north breakwater, (iii) south breakwater.

Christian basilica of the fourth century AD with a narthex and baptistery, which stretches along the contemporary shoreline above the present sea level (Scranton et al., 1978) (Fig. 3i).

At the eastern end of the south pier, which is today submerged at −2.00 m to −2.95 m, SE of the warehouses, is located a construction that comprises four main rectangular paved rooms connected by openings (Figs. 3iii, 4i). The intermediate and westernmost rooms communicate with the sea through so-called "channels" (Fig. 4j) (Scranton et al., 1978). Today the floor, the surface of the superstructure and the bottom of the channels are at −1.45 m, −1.20 m and −2.27 m, respectively. Scranton et al. (1978) interpreted the construction as fish tank (piscinae), and based on this determine an intermediate sea level 1.60 m lower than at present, setting its change from the former level after AD 77. The architectural and structural characteristics of the construction and mainly its plan, the construction with ashlar blocks and not cut into the bedrock, the paved floors, the low partitions, and finally its small depth, differ essentially from these of the known fish tank complexes of the Mediterranean (Nicolaou and Flinder, 1976; Pirazzoli, 1976; Lambeck et al., 2004; Auriemma and Solinas, 2009; Mourtzas, 2012b,c; Anzidei et al., 2013; Morhange et al., 2013) and make the construction unsuitable for keeping and cultivation of fish. The tile ducts (Fig. 4j), which were used in Roman baths to conduct warm air and were found along with Roman pottery of the third century AD within the channels by Scranton et al. (1978), may suggest that the entire construction was a hypocaust under the floor of a Roman bath instead of fish tanks. This consideration discredits the argument of Scranton et al. (1978) for the existence of an intermediate sea level. With a sea level at 3.25 ± 0.10 m in its operation, the floor of the construction and the bottom of the channels were above the mean sea level at that time by 1.80 m and 1.0 m, respectively.

East of the warehouses, the south breakwater is formed by a rocky fill which complements the natural morphology (Fig. 3i, iii). The today underwater ridge enters the sea for 90 m towards the SE and its surface is 35 m wide approximately. The surface of the fill in the north section, 80 m long and 15 m wide, is now submerged from −1.90 m in the western part to −3.10 m in the eastern part, approximately. The surface of the rest of the breakwater up to its eastern seaward end, 23 m long, is at a depth of −4.0 m to −4.40 m (Fig. 3iii). Four successive accumulations of rock fill materials that cover the massive ashlar blocks and are strongly, surficialy, naturally cemented, elevate the surface of the breakwater by 0.50 m–1.0 m (Figs. 3iii, 4k, m–o). The slopes of the fill in their entire length were reinforced by converging retaining walls of ashlar limestone blocks, with their surfaces at a maximum depth of 3.10 m (Fig. 4p). At its NE edge the rock fill is supported by a limestone boulder with its surface at −3.28 m (Figs. 3iii, 4m). The remains of a building on the eastern end of the fill, that consists of stones and potshreds connected together with mortar and today is at a depth of 2.72 m–3.10 m (Figs. 3iii, 4l), indicates that when the then sea level was 3.25 ± 0.10 m lower than at present the surface of the breakwater projected above it by 0.15 m–1.40 m for a length of 80 m.

After determination of the initial functional sea level, the palaeogeographic reconstruction of the ancient harbour of Kenchreai was attempted. The bathymetric maps given by Scranton et al. (1978) were completed by new depths taken in the present survey. In conclusion, during the operation of the harbour, the coast was approximately 50 m wider than at present and the pier and the

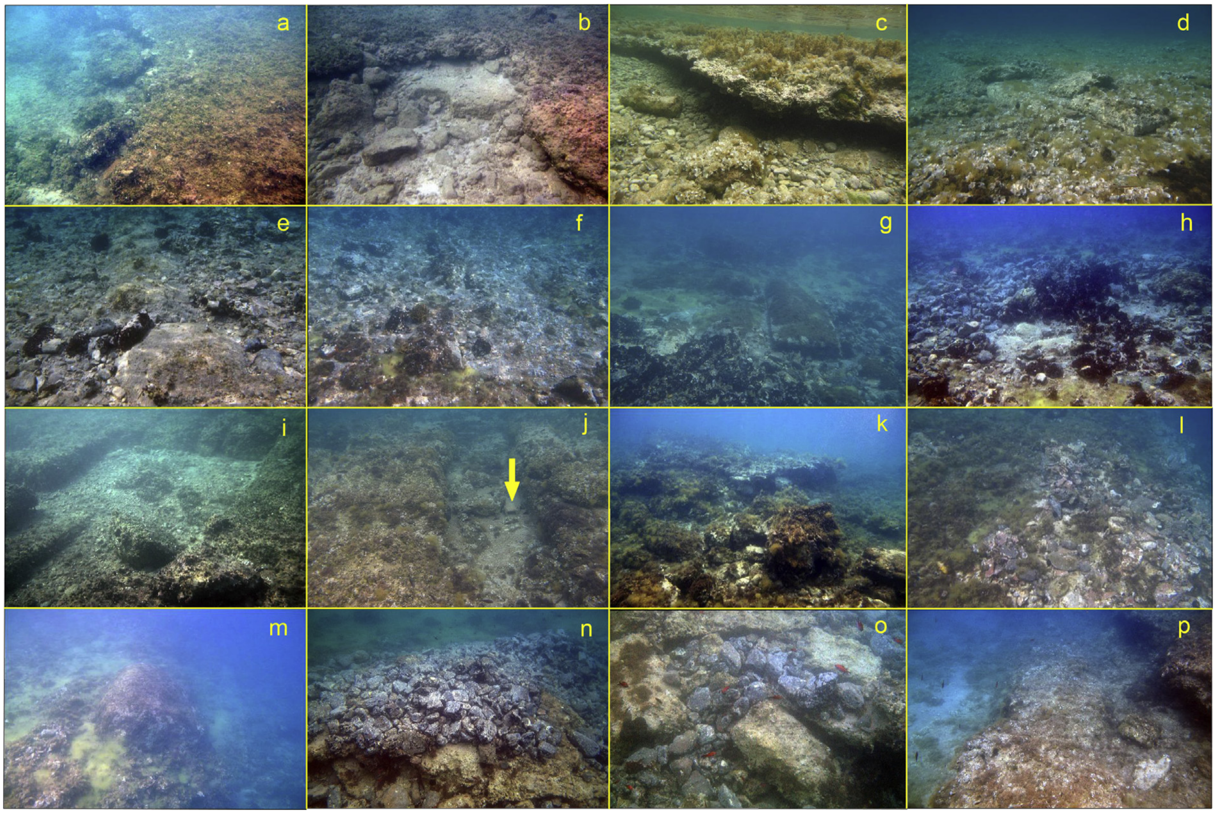

Fig. 4. Underwater views of the ancient harbour of Kenchreai. Coast of the "Sanctuary of Aphrodite": (a) the older submerged beachrock slab at −3.25 ± 0.10 m, (b) the eroded intermediate section of the beachrock that covers part of a paving, (c) the younger beachrock slab at −0.90 m. North breakwater: (d, e, f, g, h) remains of buildings located at the surface of the elevated western section of the north breakwater. South pier: (i) a "pool" of the so-called "fish tank", (j) the so-called "channel" of the "fish tank", the arrow indicates the tile duct, (k, m, n, o) accumulations of rock fill materials that cover massive ashlar blocks and are strongly naturally cemented, (l) remains of buildings located at the surface of the south breakwater, (p) retaining walls of ashlar limestone blocks.

surface of the protective breakwaters were above the then sea level (Fig. 3i–iii).

4.2. The ancient harbour of Ancient Epidaurus

The ancient harbour installations of Ancient Epidaurus (Fig. 1d) consist of two piers, today entirely submerged, situated in the continuations of two natural land protrusions which bound north and south a physical engulfment. The entrance of the harbour, 35 m wide, is located at the eastern side of the ancient harbour basin among the ends of the piers (Fig. 5i).

Since prehistoric times there was already a remarkable settlement in the area of ancient Epidaurus that seems to continue in the Middle Helladic period and its traces to decline in the Myceanean, Geometric and Archaic period. Building remains of the Agora and a small theater of the Hellenistic period confirm the position of the city centre on the Peninsula "Nisi" (Island).

During the roman occupation the city expands on the hillsides, the neck of the peninsula, the northern and southern coasts of both bays, but also further north in today's promontory of Agios Nikolaos. Roman bath and houses, a Late Roman building of the third century AD, parts of walls built of rubble stones connected with mortar that belong likely to a cistern and aqueduct, were found on the south coast of the bay of Ancient Epidaurus with their major part to sink below the sea level (Kritzas, 1972; Proskynitopoulou, 2011). Excavations revealed that the city continues to prosper at least up to the third quarter of the fourth century AD. What is certain is that the city shrank from the end of the fourth century AD, with the decline of the neighboring Sanctuary of Asclepius, very famous in the ancient world. However, some reconstructions seem to have been ocurred by the end of the Roman period, reusing building materials (Proskynitopoulou, 2011).

The rocky fill, that forms the entirely submerged today south breakwater of the harbour, enters the sea for 90 m in an N–S direction (Fig. 5i, Ii). The inland width of the fill reaches 85 m decreasing progressively to the north. The breakwater seems to be divided into three levels:

(a) The lower level comprises piles of stones, 0.30 m–0.50 m in diameter (Fig. 5ii, a), which at the west exposed side has been reinforced by large boulders. At the northern edge of the breakwater eight rectangular blocks have been placed without cement, just as exactly the edge of the northern breakwater of Kenchreai harbour (Fig. 5ii, b). It is likely to form part of the foundation of a signal tower or lighthouse. Their surface is at −4.0 m and the sea bottom at their base at −4.90 m. Further south in the continuation of the blocks, the eastern edge of the breakwater is built for 22 m by rock fills and a stone rubble wall (Fig. 5ii, c). Their surface is at −3.20 m and the sea floor at −3.65 m. Building remains are located at the southernmost part of the western side to a depth of −2.30 m. In the eastern side the surface of breakwater is at −2.35 m to −2.65 m, while the seabed in the respective positions at −2.85 m and −3.65 m.

(b) The intermediate level of the south breakwater forms a terrace at −1.85 m to −2.05 m, with remains of buildings on

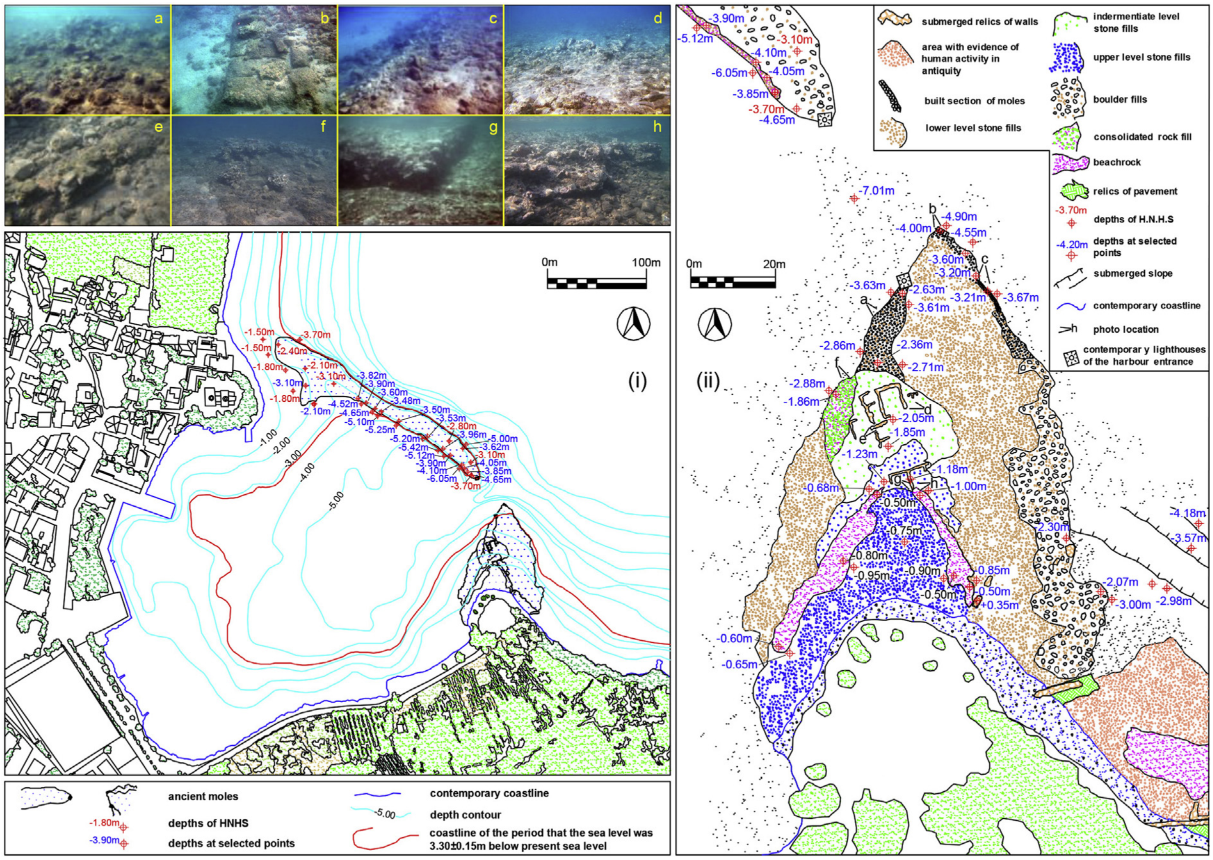

Fig. 5. (i) Plan of the Ancient Epidaurus harbour, (ii) plan of the south breakwater. Top left: underwater views of the south breakwater: (a) rocky fill, that forms the western section of the breakwater, (b) rectangular blocks at the northern edge of the breakwater, (c) the eastern edge of the breakwater consisting of rock fills and a stone rubble wall, (d, e) remains of buildings located at the surface of the two upper levels of the breakwater, (f) the cemented rocky materials of the fill at the eastern end of the intermediate level of the breakwater, (g, h) the beachrock slab which covers the upper terrace of the breakwater and foundations of buildings constructed upon it.

the surface (Fig. 5ii, d, e). In its eastern end the rocky materials of the fill are naturally cemented incorporating numerous pottery shreds (Fig. 5ii, f).

(c) The upper level of the fill also forms a terrace, today at −0.75 m to −1.23 m. The foundations of the buildings on its surface are covered by a younger beachrock phase (Fig. 5ii) of cemented archaeological material with an abundance of pottery shreds. The beachrock top lies at the depth of 0.50 m and the maximum depth of the base is 1.23 m (Fig. 5ii, g, h).

The north beakwater is an entirely artificial structure in the extension of the promontory of Agios Nikolaos, on the north coast of Ancient Epidaurus bay (Fig. 5i). It starts approximately 30 m offshore and follows a slight curve in SE direction for 240 m. It is about 20 m wide and enlarges to approximately 70 m in the inland end. The initial structure of the ancient breakwater seems to have been altered because of the removal of rock blocks from the surface. Part of its top surface appears to preserve only at the edge of the south side for a maximum width of 2.0 m, where rock fill materials of smaller size have been naturally cemented incorporating large ceramic fragments (Fig. 5ii). The depth of the cemented surface, however, which ranges from 3.50 m to 4.10 m because of its lateral position, gives no image of the form and height of the breakwater and therefore is not indicative of the magnitude of sea level change (Fig. 5i, Ii). Moreover, comparing the depths of the present survey with the data of the Hellenic Navy Hydrographic Service (HNHS) for 1982 that give depths to the top surface of the eastern edge of the breakwater between 2.80 m and 3.10 m, results in a differentiation of 1.0 m approximately, which could be attributed to human intervention.

The rock fill and the wall on the NE side of the south breakwater and the level of the fill in its east side, which appears not to have been damaged over time, are reliable indicators of the mean sea level during the operation of the harbour. Considering that sea level was between the top surface of the breakwater and the sea bottom, the level of the breakwater to operate was ranging from −3.15 ± 0.50 m in the NW side to −3.45 ± 0.15 m in the NE side, by the mean functional sea level to be defined at −3.30 ± 0.15 m lower than the present level. The beachrock slab, which covers the foundations of the buildings on the upper level of the rockfill of the breakwater, is associated with a younger sea level at 1.10 m lower than at present. The north breakwater because of human intervention does not provide secure data to determine the sea level. However, based on the bathymetric data of HNHS for 1982 the sea level in the operation of the harbour should be lower than −3.10 m in order the breakwater to be functional.

The palaegeographical reconstruction of the ancient harbour, with the sea level at −3.30 ± 0.15 m, indicates that the basin was significantly smaller and the maximum depth was not exceeding 3.0 m (Fig. 5i).

4.3. The Ancient Epidaurus “harbour district”

The “harbour district” stretches along the coast for 120 m, just east of the south breakwater of the ancient harbour of Ancient

Epidaurus (Fig. 1d) and comprises a complex of submerged buildings (Fig. 6). Originally the buildings were detected in the aerial image (Kritzas, 1972), while Flemming et al. (1973) and Flemming (1978) refer briefly to them, assessing a sea level change of −2.70 m over the last 2000 years. The superstructures of several buildings exceed 1.0 m (Fig. 6d, g, h), whereas extended concrete floors (Fig. 6c), walls and a small tank with hydraulic cement, a ceramic gutter (Fig. 6f) and massive wall similar to the aqueduct that was found on land further south, were identified (Fig. 6a, b). The sunken buildings appear to be linked with the Late Roman bath and the houses that have been excavated in a short distance from the coast at this position (Proskynitopoulou, 2011). The area of human activity during antiquity demarcated by submerged building remains, construction materials of collapsed walls, and numerous pottery sherds and stones has a maximum width of 35 m and develops to a depth of 3.0 m (Fig. 6). The smooth sandy bottom further north is interrupted within 10 m–12 m by an underwater smooth slope, inclined 10° to the NE and then is normalized again. The sea floor at the head of the slope is at a depth ranging from 2.98 m to 3.15 m, whereas at the foot varies from 3.55 m to 4.25 m. The undersea slope demarcates a palaeocoast which corresponds to a mean sea level at −3.35 ± 0.20 m. In the western part of the area, 19 m from the shoreline, the top and the base of a beachrock slab consisting of cemented archaeological material are at −1.11 m

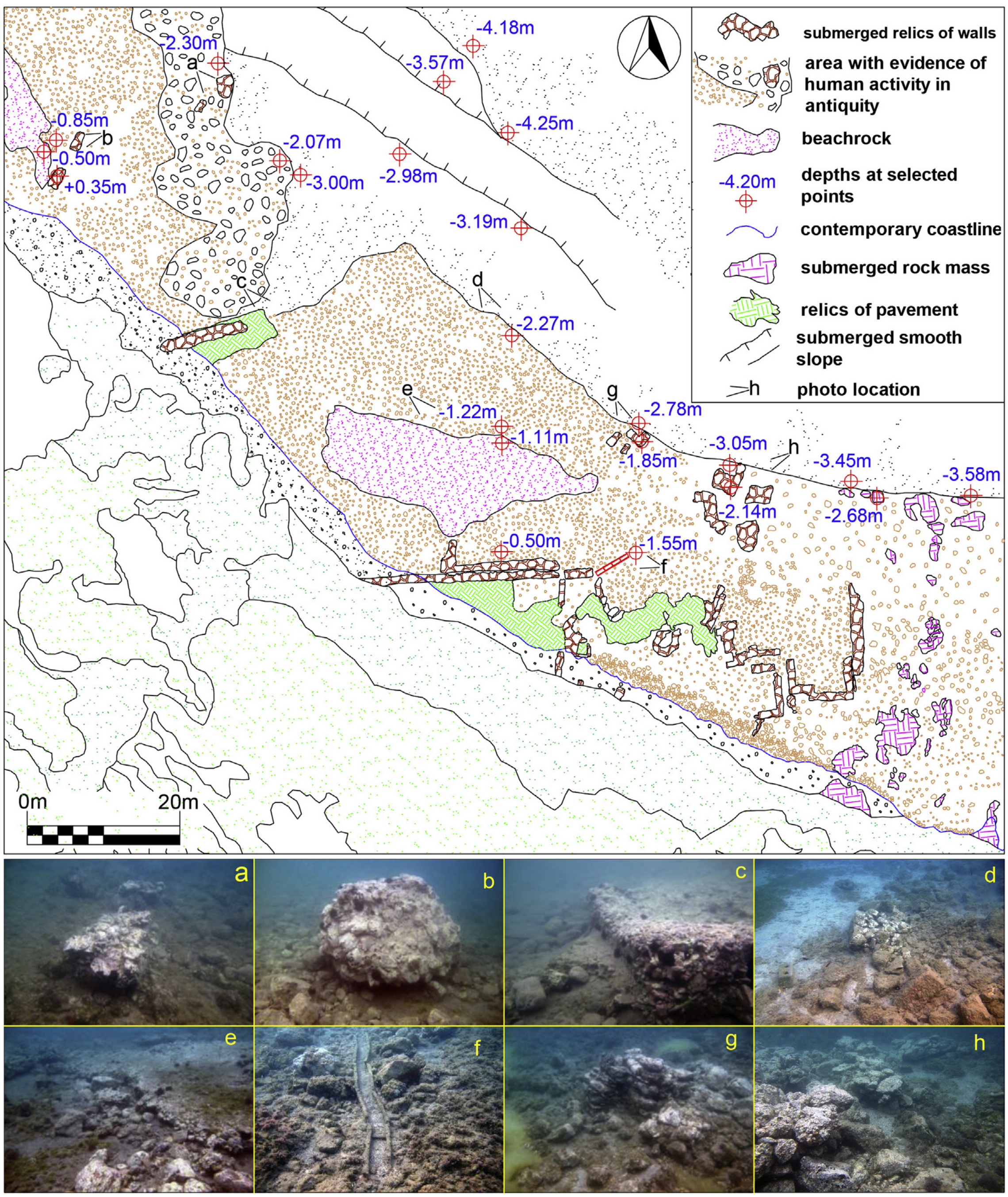

Fig. 6. Plan of the Epidaurus "harbour district". Bottom: underwater views of (a, b) remains of massive walls, (c) extended concrete floor, (d, g, h) superstructures of buildings, (e) beachrock slab, (f) ceramic gutter.

and −1.22 m, respectively (Fig. 6, e). The submersion is analogous to that of the beachrock of the south breakwater and is associated with the more recent sea level that at this location is defined at −1.10 m.

4.4. The submerged coast of Agios Vlasis bay

In the bay of Agios Vlasis, on the SW side of the peninsula “Nisi”, within 400 m south of the harbour of Ancient Epidaurus (Fig. 1e), a large part of the buildings that stretch along the coastline is today submerged below the sea level (Fig. 7).

In a short distance from the shoreline were found on land massive rubble walls of stones and mortar that belong to an aqueduct (Kritzas, 1972). The Late Roman buildings that have been excavated in the same area indicate an expansion of the Roman and Late Roman core of the city of Ancient Epidaurus in the neck of the peninsula and the coast of Agios Vlasis bay (Proskynitopoulou, 2011). The ancient aqueduct ends in a complex of cisterns on the northern coast of the bay and a part of their remains is submerged below the present sea level (Fig. 7d, k). Massive foundation of ashlar blocks and parts of walls made of irregular stones and ceramic tiles connected together with mortar, were found underwater in a

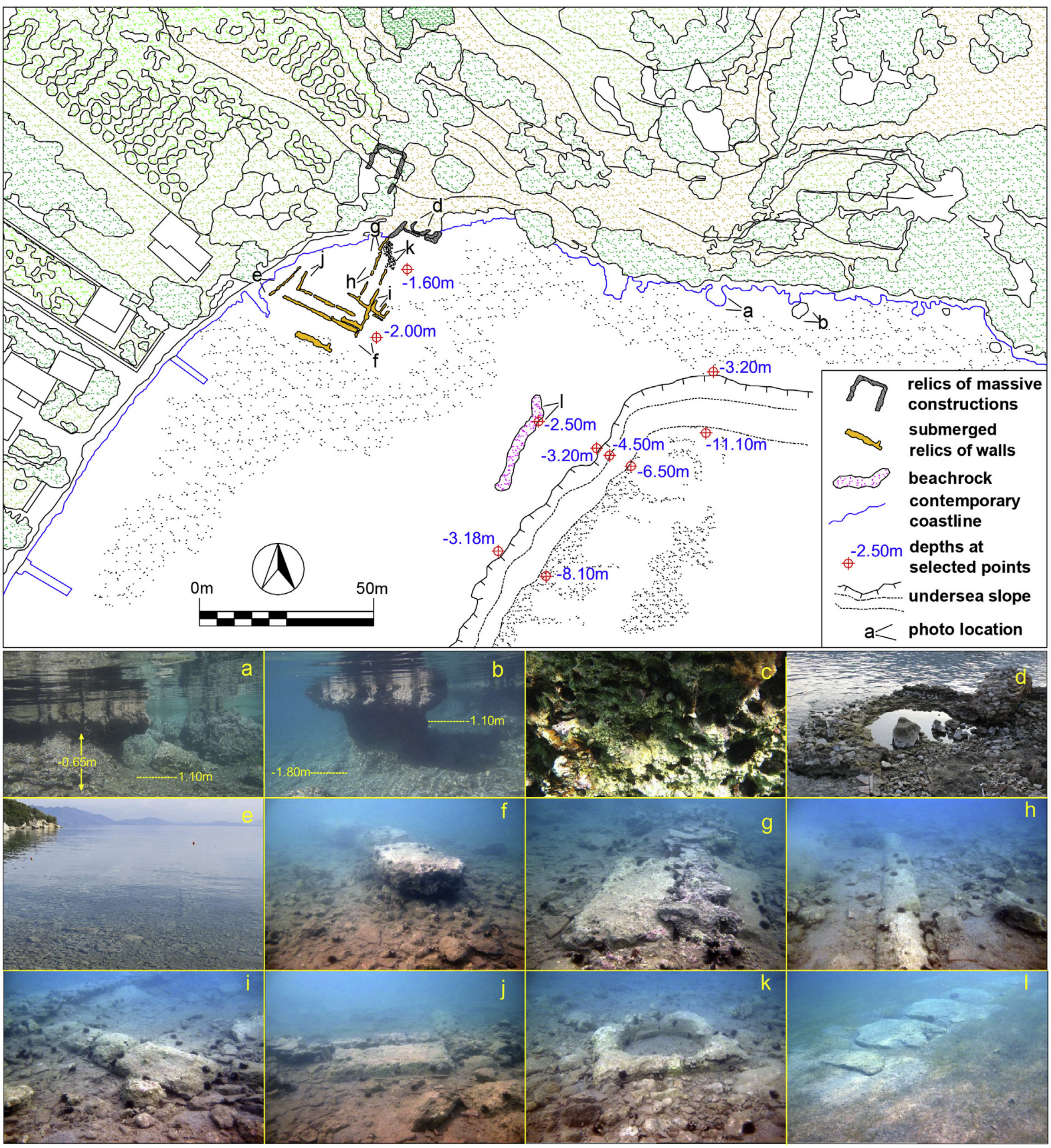

Fig. 7. Plan of the coast of Agios Vlasis. Bottom: underwater views of (a) the tidal notch at a depth of 1.10 m, (b) mushroom shaped rock, (c) bioerosion by endolithic organisms and surface feeders grazing, (d, k) complex of cisterns at the end of the ancient aqueduct, (e, f, g, h, i, j) massive foundations of ashlar blocks and parts of walls, (l) beachrock slab rest on the sandy smooth seabed to a depth of 2.50 m.

maximum distance of 35 m from the shore to a depth of 2.0 m (Fig. 7e–j).

Along the northern steep limestone coast of the bay, has formed a well-developed tidal notch (Fig. 7a). Bioerosion by endolithic organisms and surface feeders grazing seem to have contributed significantly to its formation (Fig. 7c). The tidal notch is monitored all along the rocky coast, whereas "mushroom shaped rocks" have been formed by the former sea level on rocky ledges of the seabed within a short distance from the shore (Fig. 7b). The tidal notch has a height of 0.60 m, inward depth of 0.65 m and its base is at −1.10 m.

Within 90 m from the western coast of the bay, sizeable pieces of a thin beachrock slab rest on the sandy smooth seabed for a length of 30 m approximately to a depth of 2.50 m (Fig. 7l).

Located 100 m from the smooth western coast of the bay and 20 m from the northern coast, an undersea slope inclined 15° to the SE and SW, respectively, interrupts the smooth, almost horizontal, morphology of the sea floor. The seabed at the head of the slope is at −3.20 m, thus demarcating the sandy palaeocoast (Fig. 7). The depth of the seabed at the foot of the slope ranges from 6.50 m to 11.0 m.

4.5. Sunken country villa in the bay of Epidaurus

This large building complex of Roman times was traced to a recess of the slightly curved shoreline in the bay of Epidaurus (Kritzas, 1972), within 700 m south of Agios Vlasis bay, on the so called "Kalymnios" beach (Fig. 1f). It is situated at the southern margin of an extended undersea sandy terrace, which within 400 m from the shore is interrupted by an underwater slope (Figs. 8 and 9a). In 200 m approximately southernmost of the building complex is mentioned the presence of a group of three smaller sunken buildings, most likely houses (Kritzas, 1972).

The building complex appears to be associated with building techniques developed by the Romans in Peloponnese and in the region of Troezen at the end of the 2nd century AD (Vitti and Vitti, 2010). It is also connected with the economic and productive activity of Troezen at the same period, with the exploitation of the terrestrial and marine resources of the region, the salt marshes and tuna fishing, the cultivation of land and grape growing, as well as the quarrying of local stone and logging (Zoumbaki, 2003). Similar villas are found in several locations along the coast of Argolis peninsula, such as: a submerged villa at Fourkari (Skyllaieis) of Late Roman date on the south coast (Frost, 1977, 1988), a villa at Halieis of the 5th and 6th c. AD with remains of a hot bath, which occupied the coastal area of the old townsite and to its establishment belong traces of various brick constructions, now underwater, as is the bath, and numerous poor, anonymous graves (Jameson et al., 1994).

The masonry of the building, which is preserved in several places at the elevation of 1.0 m, is built of rubble stone with tiles and ceramic bricks, irregular, rectangular or triangular in shape, sometimes laid in courses, bonded together with mortar (Figs. 8 and 9b, c, f, g, j). At places it is evident their reuse in a later building phase. The foundation consists of large ashlar blocks, not cemented together (Fig. 9k).

The building complex is located 45 m from the shore, with its main longitudinal axis to be oriented to NW–SE (Figs. 8 and 9a). The maximum length is 47 m, the width reaches 46 m and is divided into 4 subsections. The NW section is an elongated rectangular space of approximately 360 m^2 in area, which in the SW side ends in a large semi-circular arch. It seems that in second use

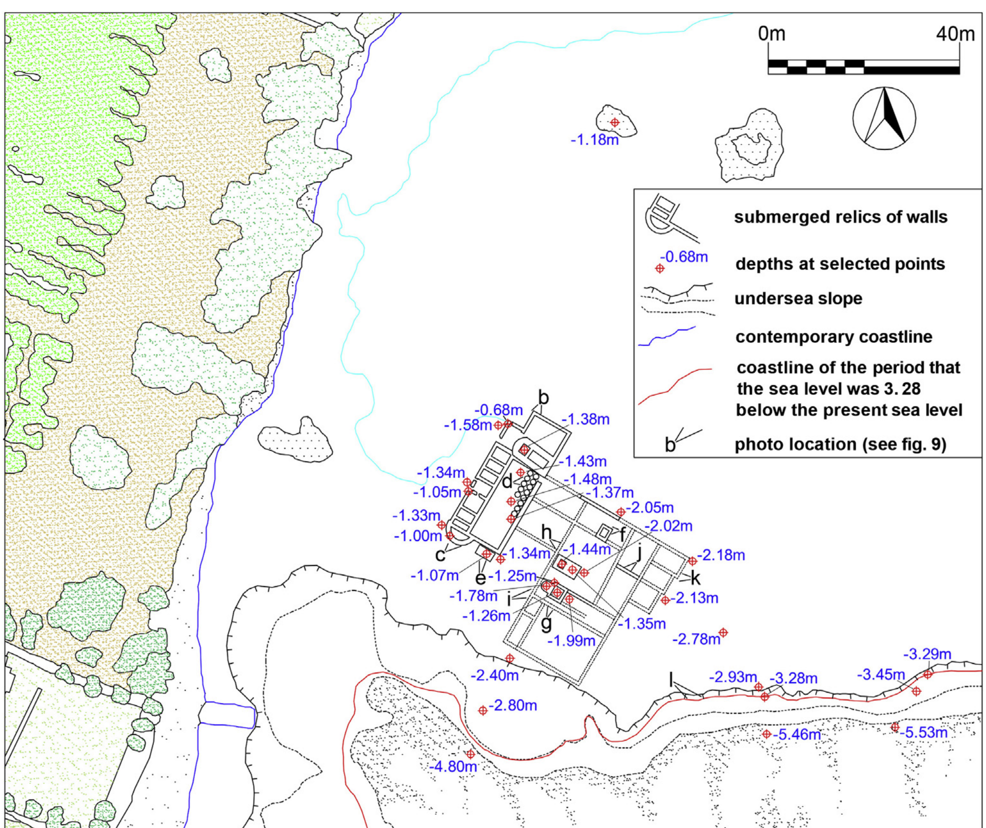

Fig. 8. Plan of the Ancient Epidaurus country villa coast.

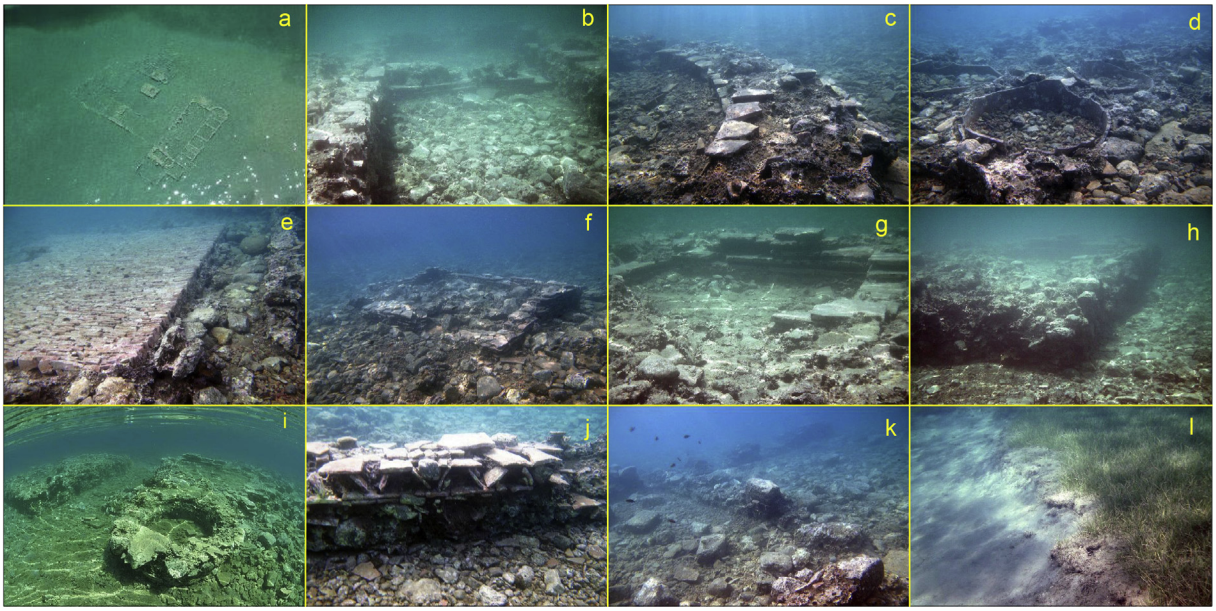

Fig. 9. Views of the Ancient Epidaurus country villa, (a) aerial image of the submerged ruins (2000/2005, n.a. photograph, <http://www.flying-paradise.com/gallery.cfm>), (b) the elongated rectangular space in the NW section of the villa, (c) the semi-circular arch at the SW end of the NW section, (d) jars in two parallel rows embedded in the floor, (e) floor made of bricks, (f) interior walls in the central wing, (g) cistern in the central part of the villa, (i) cistern connected with a well, (h) cistern in the central wing, (j) architectural detail of a wall in the NE section of the villa, (k) the foundation of the NE section built of large ashlar blocks, (l) the head of the slope and the morphological step which corresponds to the palaeocoast.

the west side of this section has been divided into seven uneven small rectangular spaces and a large in the eastern side, which contains thirteen large storage jars in two parallel rows embedded in the floor (Fig. 9d). In the northern side, there is a narrow elongated area, which is separated by a wall in two uneven parts and its south narrow side ends in an arch (Fig. 9c). It seems rather posterior to the second construction phase of the main building, because it has a different orientation and the underlying masonry of the previous phase is distinguished as well. Externally of the SE end of the building, a floor made of bricks connected with hydraulic mortar covers an area of 15 m^2 (Fig. 9e).

Immediately to the east, a building of an area 180 m^2, divided by an interior wall parallel to the external masonry, seems to link the NW wing of the building with this to the east (Figs. 8 and 9a). In the eastern wing of the building approximately 900 m^2 in area, there are two main sizeable spaces in its central and southern part and five smaller peripherally. In the central part of this wing there are two cisterns (Figs. 8 and 9f, h–j), the southernmost connected with a well (Fig. 9i), which likely indicate an artisanal use.

The easternmost buildings seem to be auxiliary rooms not belonging to the outer shell of the main villa building (Fig. 8). Their serrated skew arrangement is likely associated with the passage of an access road.

The building complex is submerged in its NW part at −1.30 m to −1.60 m, whereas in the SE part at −2.20 m. In its south and east part is surrounded by an underwater slope, with the sea bottom at the head of the slope at −2.90 m, the morphological step which seems to correspond to the palaeocoast of −3.30 m and at the sea bottom at the foot of the slope at −4.80 m to −5.55 m (Figs. 8 and 9l).

4.6. Sunken country villa on the coast of Psifta

The building complex is located on the south coast of Epidaurus bay, in the western part of Kalloni bay and 140 m approximately NW of the wetland of Psifta (Fig. 1h). Today is submerged at a depth of 1.75 m–2.27 m, within 50 m from the shoreline (Fig. 10i, ii).

The building masonry of thickness 0.60 m–0.80 m that is preserved in places at the elevation of 0.40 m approximately (Fig. 10a–e), although less elaborate than the villa of Epidaurus, maintains almost the same structural characteristics. It is built of rubble stones, tiles and ceramic bricks bonded together with mortar (Fig. 10c, d).

The complex is divided into two parts and its main longitudinal axis is oriented to NW–SE. The main building of total area 670 m^2 comprises three sizeable rooms, the easternmost of which is accompanied by five, rectangular, smaller rooms in its southern side (Fig. 10ii, f, h). In the western space of the building, five jars of diameter 1.0 m are embedded in the floor in a row along the north wall (Fig. 10ii, g). Two similar jars were also found in the SW part of the eastern area (Fig. 10ii, h). The NE part of the building 170 m^2 in area, projecting from the main structure, consists of five or six rooms, and it seems that were not belonging to the outer shell of the villa (Fig. 10ii, j). Abundant rubble stones scattered around the building in a fairly large radius and a broken column (Fig. 10k) are likely remains of collapsed auxiliary buildings.

The sandy sea bottom inclined slightly to the NE forms an undersea ridge which within 110 m from the shore is interrupted by an undersea slope (Fig. 10i). The seabed at the head and the foot of the slope is at −3.70 m and −6.50 m, respectively. Further east along the coast in front of the wetland as well as easternmost on the coast of the small bay of Valariou, well-developed beachrocks are found within 75 m–80 m from the shore, at the depth of 3.60 m (base) and 3.0 m (top) in their seaward end (Fig. 10k). The beachrock formation, of underwater width 50 m approximately, represents a palaeocoast, which corresponds to a sea level 3.45 m lower than at present (Fig. 10i, l). A younger beachrock phase within 6 m from the shore, with its top at −0.50 m and base at −0.75 m in the seaward end, corresponds to a sea level 0.60 m lower than at present (Fig. 10i, m).

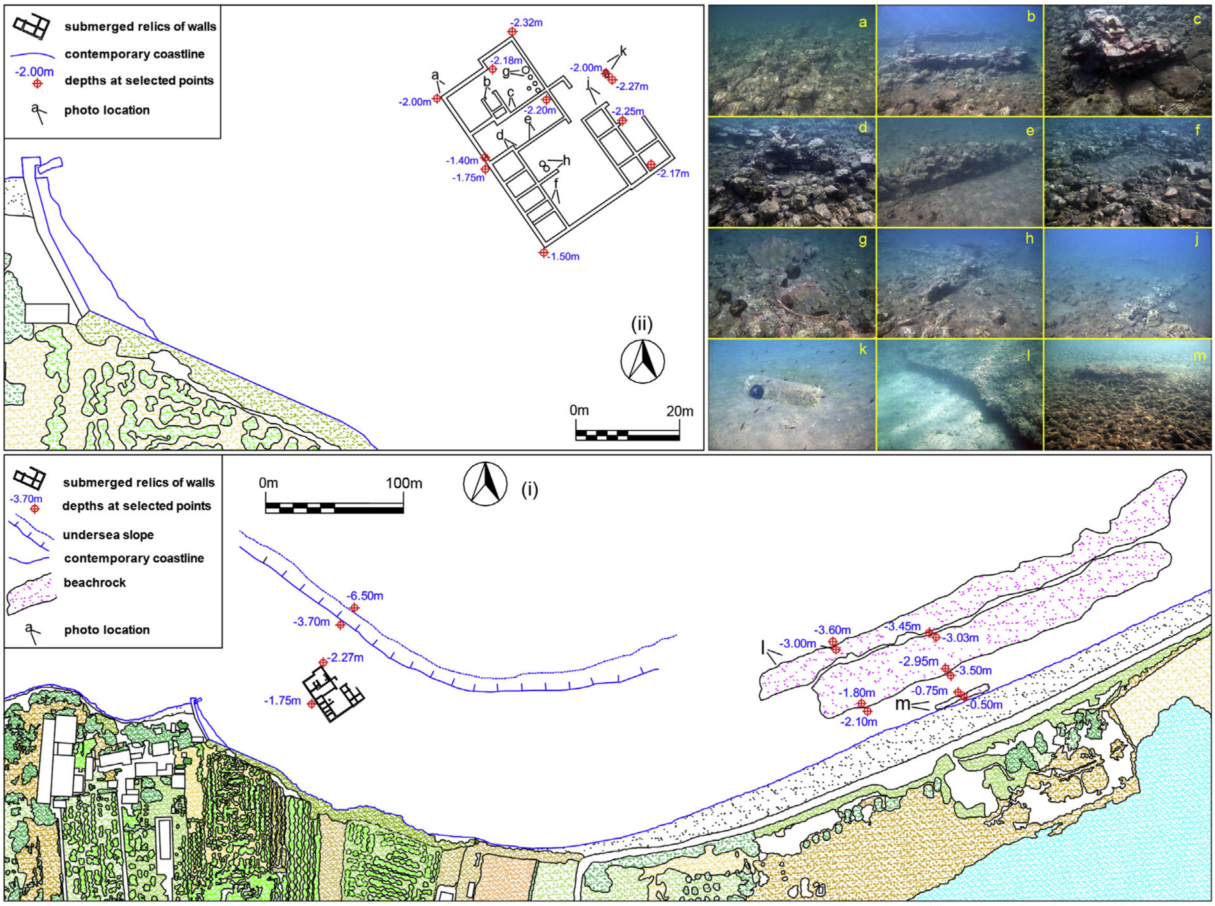

Fig. 10. (i) Plan of the Psifta country villa coast, (ii) plan of Psifta country villa. Top right: underwater views of (a) foundation masonry on the western ending of the villa, (b) walls delimiting a space inside the western room, (c, d) detail of the foundation and the wall structure, (e) wall that separates the intermediate from the eastern room, (f, h) smaller rectangular rooms in the southern side of the villa, (g, h) jars embedded in the floor, (j) the NE part of the building consists of five or six rooms, (k) column piece, (l) beachrock slab of the older phase at the depth of 3.60 m, (m) the younger beachrock phase at the depth of 0.75 m.

4.7. Submerged ancient fill and buildings at Vathy of the Methana peninsula

In the western side of the Methana peninsula, on the south section of the coast of Vathy village (Fig. 1g), below the ancient Classical Acropolis of Palaiokastro, were found an ancient fill, makeshift protective works against waves and later submerged buildings (Fig. 11). Kritzas (1972) stated the existence of a sunken city, whereas Flemming et al. (1973) estimate that the submersion in this location does not exceed 1.0 m from the Classical period to the present.

The first habitation of the area dates back to the Neolithic period and seems to intensify in the Early Helladic Era (2800–1900 BC). During the Late Helladic Era and Mycenaean Age the area was habited by the Ionians who built their settlements slightly higher in the region of Megalochori. In the Classical period the settlement of Megalochori was fortified and the Acropolis of Palaiokastro was built. There are also sanctuaries, tombs, and inscriptions from the Hellenistic and Roman times. Palaiokastro is the main Byzantine centre of the peninsula, as evidenced by the ruins of the medieval ramparts on the ancient fortifications, remains of an Early Christian Basilica nearby and the underground country church of St. Nikolaos eastwards, which dates back to the 11th century (Deffner, 1909; Faraklas, 1972; Catling, 1985, 1986, 1987; Koukoulis, 1986, 1987; James et al., 1996).

The submerged rock fill occupies the entire sea front of the ancient Acropolis, 90 m long and width underwater that reaches 37 m. It seems that has been constructed to gain vital space and expand the narrow zone between the hill and the shore, roughly 40 m wide (Fig. 11). The fill is 2.50 m high and is made of rounded stones, 0.30 m × 0.15 m in average size. In the seaward west ending of the fill, the upper surface is at −2.35 m to −2.75 m and the sea floor at the foot of the fill at −3.47 m to −3.59 m (Fig. 11a). To protect the coastal building against the waves, in the central section of the fill and within 6 m from its seaward ending has been placed a course of ashlar blocks, 0.60 m × 0.50 m × 0.40 m–2.20 m × 0.80 m × 0.40 m in size, coming from the ruins of the ancient fortification (Fig. 11b, b_1, b_2, b_3). The upper surface of the fill in the position of the makeshift protective work is at −2.17 m and the upper surface of the ashlar blocks at −1.65 m. Landwards to the east and for a width of 20 m, the surface of the fill is elevated and today is at a depth of 1.0 m. In the entire length of the fill are observed remains of later buildings, whose masonry is extremely elaborate in the sections that is still preserved up to the elevation of 0.80 m (Fig. 11c, c_1). In the northern side of the buildings a narrow opening bridged with an arch that is built of bricks in the common manner can be dated back from the Roman times to the Byzantine period (Fig. 11c, c_2).

The rocky fill of the Classical period, the later coastal buildings and their protective works, which had been constructed at a functional sea level −3.20 ± 0.40 m lower than at present, seems

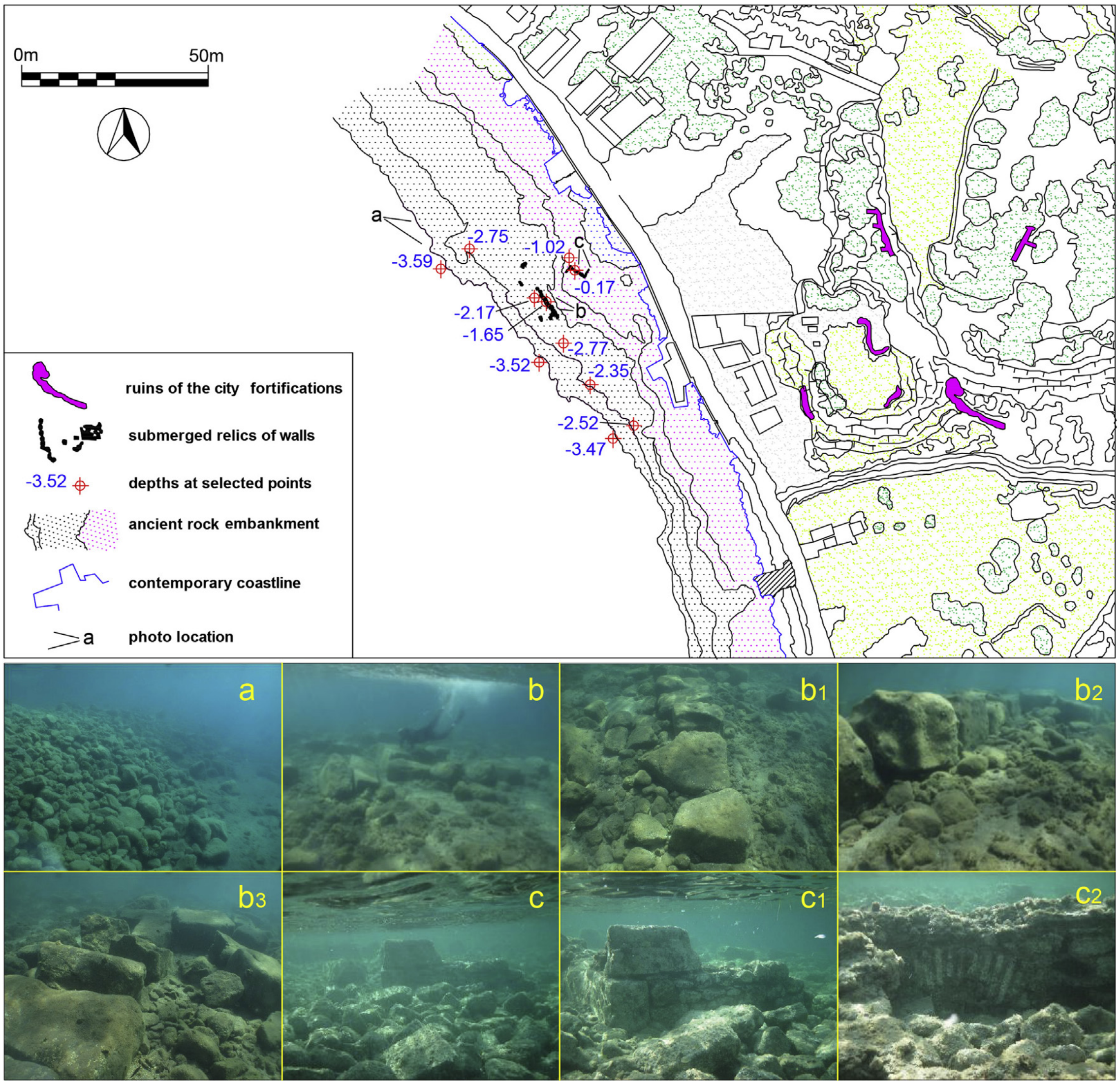

Fig. 11. Plan of the Palaikastro coast, Vathy Methana. Bottom: underwater views of (a) the seaward west ending of the ancient rock fill, (b and details b1, b2, b3) course of ashlar blocks to protect the coastal building against the waves (c and detail c1) remains of later buildings, (c2) narrow opening bridged with an arch in the northern side of the buildings.

that have submerged at the same time by a relative sea level rise subsequent to their construction, likely in the late Roman or even the Byzantine period.

4.8. *Submerged building remains in the bay of Vagionia on Poros island*

The bay of Vagionia on the north part of the island of Poros, is elongated with steep rocky shores and sandy cove (Figs. 1i and 12). It is regarded as the haven of the Sanctuary of Poseidon and the ancient town of Kalavria. The temple, which is built 1 km approximately southward at an altitude of 190 m, dates back to the late 6th – early 5th century BC. The Sanctuary was expanded by the end of the 4th century BC. In the Hellenistic and Roman times its activity continues, while traces of Byzantine pottery are also preserved (Hägg, 2003; Wells et al., 2004, 2008).

Submerged remains of building and traces of habitation were found on the west rocky shore of the bay, on the upper surface of a limestone ridge that enters the sea in a NW–SE direction (Fig. 12a). It is 70 m long and 17 m wide approximately. The upper surface in its SE end is at −4.20 m and the seabed at −4.65 m. Carvings carved into the rock cliff (Fig. 12b), building foundations and segments of their masonry built of rubble stone and tiles bonded together with mortar have been found (Fig. 12c–e). Building traces were tracked down to −3.10 m with the sea floor to be at −3.40 m, thus defining a former functional sea level at −3.25 ± 0.15 m lower than at present. In a distance of about 30 m southeastwards, in front of today's small fishing shelter, were found foundations and elaborate masonry of likely later buildings, which enter the sea for 18 m to the depth of −1.70 m (Fig. 12f–h).

4.9. *Seafront of the ancient city of Aegina*

The extensive ancient harbour installations that stretch along 1600 m of coastline on the seafront of Kolona in Aegina (Fig. 1j) are associated with the great trading and maritime development of the island from the Middle Bronze Age into the middle years of the Classical period. The north harbour is bounded by the north breakwater, the riprap on the then wide sandy coast, the detached west breakwater, and the then uplift morphology of the west end of Kolona Hill (Fig. 13). On the south coast, the harbour installations comprise the fortified closed harbour with the

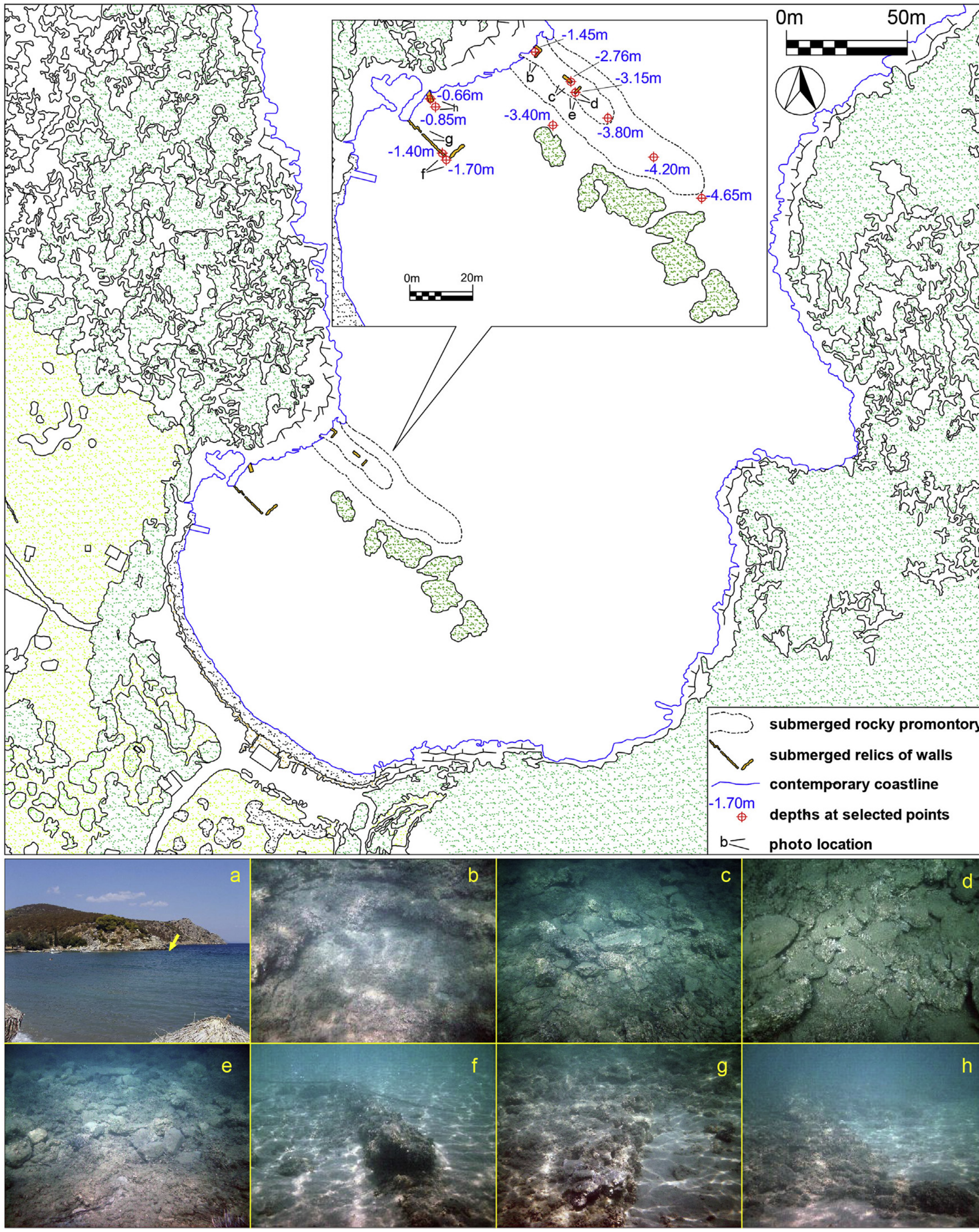

Fig. 12. Plan of Vagionia bay, Poros island. Bottom: views of (a) the submerged promontory location, (b) carvings carved into the rock cliff of the limestone ridge, (c, d, e) remains of building foundations and traces of habitation on the submerged limestone ridge, (f, g, h) foundations and elaborate masonry of likely later buildings.

shipsheds, the commercial harbour, now entirely destroyed by the modern port, the anchorage area bounded by the west breakwater built of cone-shaped piles of stones, the tops of which projected above the then sea level, and the south curved breakwater at its southernmost boundary (Fig. 13) (Mourtzas and Kolaiti, 2013).

The beachrock slab formed on the north coast, with its base and top at −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 harbour" with its base and top at −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 its base at −2.80 m, all refer to an older sea level at 3.17 ± 0.05 m lower than the present one (Fig. 13) (Mourtzas and Kolaiti, 2013).

Two marine notches of aperture 0.20 m–0.25 m have formed along the entire length of the inner and outer faces of the walls of the closed harbour, with their base at depths 1.02 m and 0.57 m, respectively. They correspond to two earlier mean sea levels at 0.97 ± 0.05 m and 0.52 ± 0.05 m lower than at present. The two

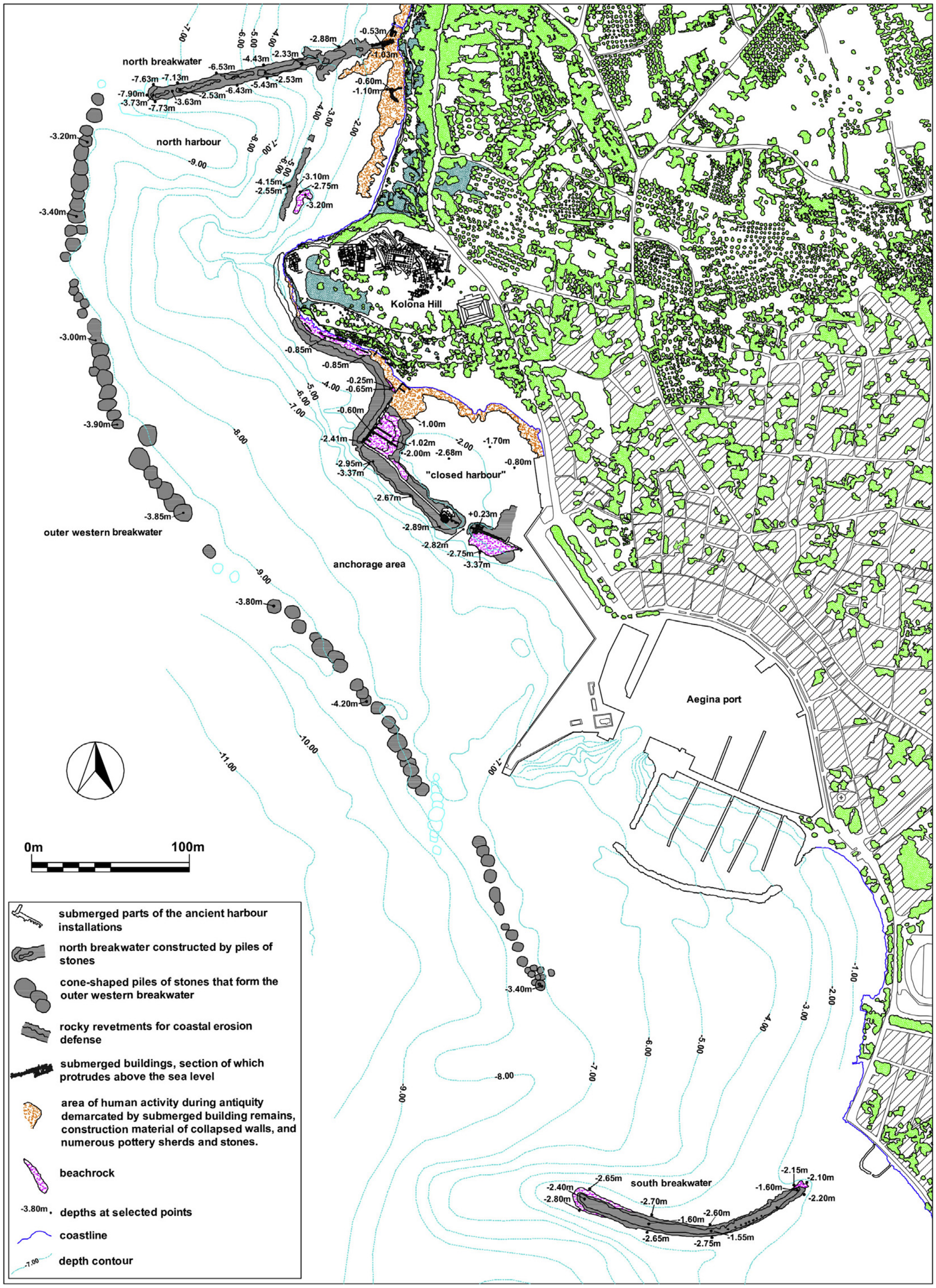

Fig. 13. Plan of the seafront of the ancient and modern city of Aegina (after Mourtzas and Kolaiti, 2013).

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 harbour basin. The superstructure of the wall and the shipsheds has been incorporated in it. The younger and shallower beachrock phase has formed along the entire length of the SW coast of Kolona Hill. It consists of archaeological materials and has incorporated the superstructure of the coastal wall. In its seaward end, the base is at −0.65 m to −0.85 m and the top at −0.25 m below the sea surface (Mourtzas and Kolaiti, 2013).

On the basis of geomorphological and archaeological indications, three distinct sea levels have been defined, at the depths of 3.17 ± 0.05 m, 0.92 ± 0.10 m and 0.47 ± 0.10 m. The dating of the changes, according to archaeological evidence and historical sources, shows that the initial sea level change in Aegina occurred certainly after AD 170 and probably after AD 220. The intermediate change is dated between AD 1586 and 1839, and the most recent one between 1839 and 1999. Sea transgression followed a long period of stability of the sea level, which lasted at least 2100 years, from the Middle Bronze Age to the Late Roman period (Mourtzas and Kolaiti, 2013).

5. Discussion

The submersion of tidal notches and beachrock slabs, the assessment of a functional level of ancient constructions and the relationship between the palaeocoast and the ancient coastal constructions in each study area, led to the definition of three distinct sea levels along the western coast of the Saronic Gulf at −3.30 ± 0.15 m, −0.90 ± 0.15 m and −0.55 ± 0.05 m (Fig. 14).

The submerged beachrock slabs of the northern coast of Kenchreai, Aegina and Psifta with their base at the depth of 3.25 ± 0.10 m, 3.17 ± 0.05 m and 3.60 m respectively, correspond to the lower sea lever at −3.30 ± 0.15 m. This stand was also determined by the functional level of the ancient constructions, which was defined at −3.30 ± 0.15 m in the area of the south mole of the ancient harbour of Epidaurus, at −3.35 ± 0.20 m in the neighboring “harbour district”, at −3.30 m in the country villa of Epidaurus, at −3.20 ± 0.40 m on the coast of the ancient Acropolis of Palaiokastro in Vathy of the Methana peninsula, and finally at −3.25 ± 0.15 m in the bay of Vagonia on Poros island.

Based on the depth of the later beachrock phase and the erosion cavity formed on the ancient buildings of Kenchreai by 0.90 m, the beachrock slabs at the south mole of the ancient harbour of Epidaurus and the “harbour district” by 1.23 m, the tidal notch on the rocky coast of Ag. Vlasis bay by 1.0 ± 0.10 m and the depth of the lower tidal notch that has been formed on the port installations of the ancient harbour of Aegina at −1.0 m, was determined the intermediate sea level at −0.90 ± 0.15 m lower than at present. The later sea level at a depth of −0.55 ± 0.05 m corresponds to the higher tidal notch formed on the harbour installations of the ancient harbour of Aegina and the later beachrock phase of Psifta, both found at the same depth. The dating of the three distinct sea levels is grounded in the age of the ancient sunken constructions and on their relationship to geomorphological indicators that are indicative of past sea levels.

The older mean sea level at −3.17 ± 0.05 m, which in Aegina is dated from the Bronze Age (ca 1800 BC) to AD 250, seems that remained stable throughout this time period of 2100 years (Mourtzas and Kolaiti, 2013). The ancient sunken fill in Bathy of the Methana peninsula is certainly connected with the Classical Acropolis of Palaiokastro, but also with the later submerged buildings, likely of the Byzantine period. Finally, the sunken ruins on the north coast of Poros are indirectly dated back between the 6th and 4th century BC.

The sea level change by 2.40 m, from −3.30 ± 0.15 m to −0.90 ± 0.15 m, appears that occurred in the Late Roman period, by the end of the 4th century and probably later in the 6th century AD. The sunken coastal buildings and the port installations of Kenchreai harbour are dated back to AD 400 ± 25, whereas there is evidence for even later habitation of the area up to AD 675 ± 25 (Rothaus et al., 2008). The port installations of the ancient harbour and the coastal buildings of the “harbour district” in Epidaurus, and the coast of Agios Vlasis refer to the Late Roman period until the third quarter of the 4th century AD (Proskynitopoulou, 2011). The construction of the building complexes in Epidaurus and Psifta, which are characterized as country villas, seems that is associated with the economic and productive activity and the building techniques developed by the end of the second century AD (Zoumbaki, 2003; Vitti and Vitti, 2010). Similar sunken country villas on the

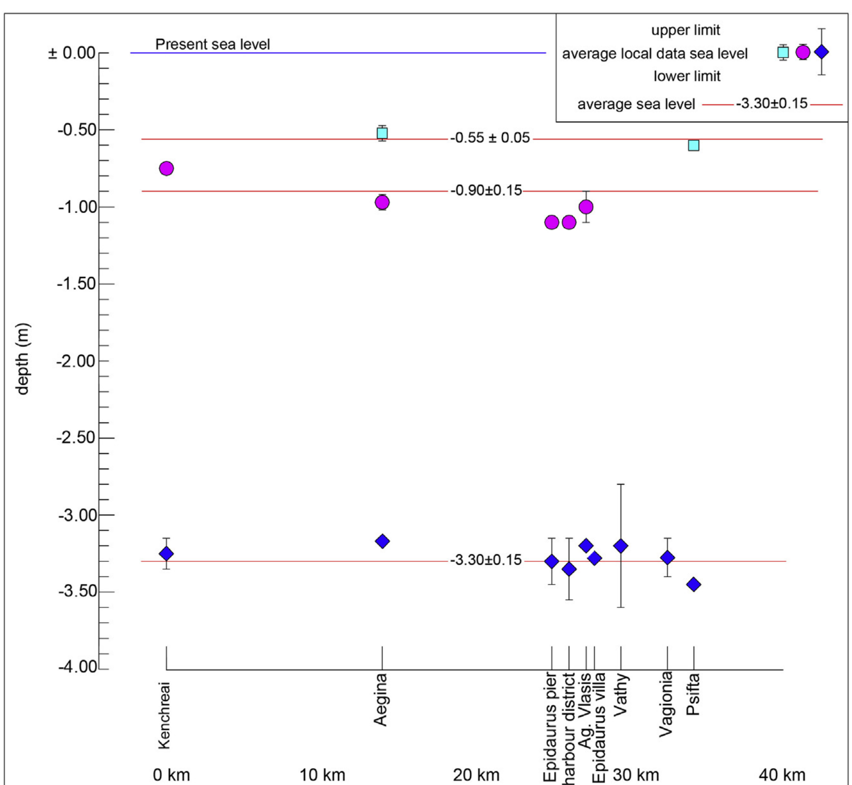

Fig. 14. Correlation between the average local sea levels.

coast of the Argolic peninsula, a few kilometres southwards, are dated back to the Late Roman period of the 5th and 6th century AD (Frost, 1977; Jameson et al., 1994).

The later sea levels of −0.90 ± 0.15 m and −0.55 ± 0.05 m were dated only on the coast of Aegina. According to historical data, it was concluded that in 1555 the sea level was lower by 1.0 m than the present level and corresponded to the sea marine tidal notch of −1.00 m. It was also established that the relative change in sea level by 0.35 m, as results from the tidal notches of −1.02 m and −0.57 m, likely occurred between 1555 and 1839. Finally, the most recent relative sea level change by 0.55 m, seems to be related with the period between 1839 and 1999 (Mourtzas and Kolaiti, 2013).

To summarize, the sea level of −3.30 ± 0.15 m remained stable in the period between the Middle Bronze Age and the end of the 4th century AD, possibly even in the 6th century AD. The change in sea level that followed formed a later sea level at −0.90 ± 0.15 m. This stand was maintained until its change by 0.35 m approximately, which occurred between 1555 and 1839. This latest sea level at −0.55 ± 0.15 m changed between 1839 and 1999, thus forming the present sea level (Fig. 15).

These conclusions appears to be in flat contradiction to the findings of Nixon et al. (2009), who reported the presence of five tidal notches up to the depth of 2.94 ± 0.16 m along the rocky limestone coast south of the salt-marsh of Korfos, giving a maximum age of 5000 BP to the deepest of them. The systematic underwater survey, however, revealed the existence of a tidal notch clearly formed at a depth of 0.40 m that goes all along the coast and a wave cut platform with relatively rough surface, 5.0 m–8.0 m wide, which is formed at a depth of 2.70 m–3.50 m. An underwater cliff, approximately 2.0 m high, demarcates the wave cut platform from the adjacent sea bottom at −5.40 m to −5.60 m.

The systematic survey of Dao (2011) on the coast of Kalamianos, 2.5 km east of the previous location, where is found an Early to Late Bronze coastal archaeological site, confirms the conclusion of our study on the stability of sea level at −3.30 ± 0.15 m throughout this period. Dao (2011) identified two peculiar, of limited extent, beachrock slabs at the depths of 3.50 m–3.70 m and 5.80 m–5.90 m that he dated to 1640 cal y BC to 1400 cal y BC and 2800 cal y BC to 2200 y BC, respectively. Traces of ancient quarrying activity that were tracked down during the survey in the north side of the east coast of the cape, although can be often confused with the structures of the limestone bedrock, it seems that reach in a distance of 50 m approximately off the shore to a depth of 3.55 m, a depth similar to that of the later beachrock described by Dao (2011).

Comparison between our curve of relative sea level change in the West Saronic and the curve of Nixon et al. (2009) for Korfos, the curves resulting from the composition of the data of Knoblauch (1969, 1972) for Aegina and Scranton et al. (1978) for Kenchreai, and the glacio-hydro-isostatic and eustatic corrected curve developed for Peloponnese by Lambeck and Purcell (2005), reveals substantial differences. Knoblauch (1969, 1972) and Scranton et al. (1978) determine the past sea levels initially interpreting the operation of the port facilities and then assessing their functional level, based exclusively on archaeological evidence. Therefore, the differences are due to different approach methodologies which lead to different assessments, often significant, on the sea level stands, their duration and dating, and the timing and rates of their change. As shown in Fig. 15, the curve of the relative sea level change in the West Saronic which was drawn in the present study, is systematically below the glacio-hydro-isostatic model of Lambeck and Purcell (2005). In addition, whereas the glacio-hydro-isostatic curve follows a continuous upward change in sea level over time, our curve includes shorter or longer periods of sea level stability, over which the respective coastal geomorphological indicators were formed. Furthermore, the differences in elevation and age of sea levels are significant. What is, however, the most important differentiation is the extremely long period of stability in

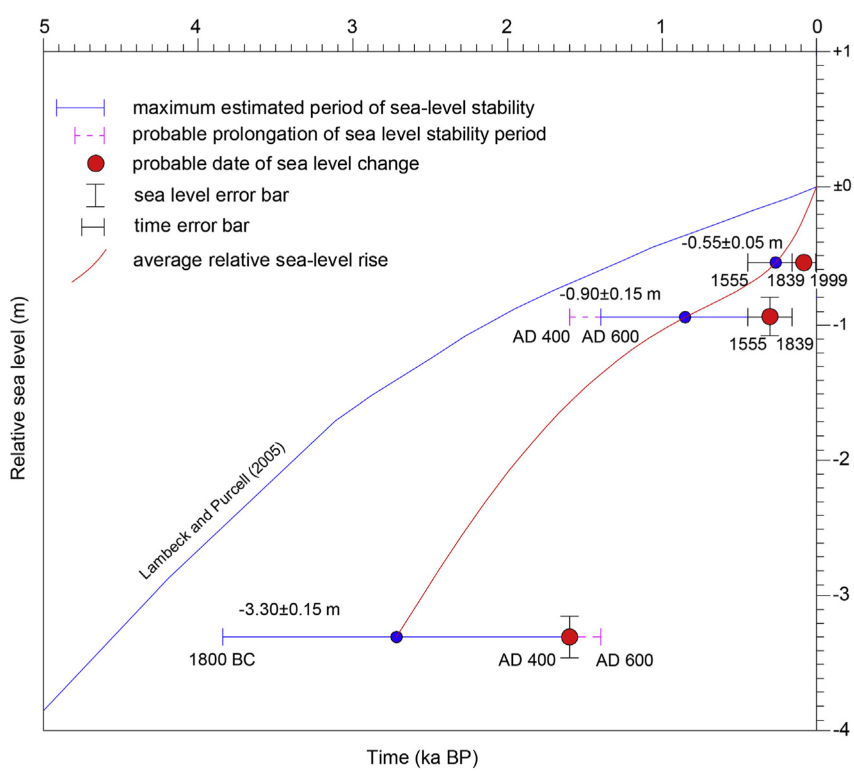

Fig. 15. Relative sea level for the West Saronic Gulf compared with the predicted sea level curve for Peloponnese of Lambeck and Purcell (2005).

sea level, of at least 2200 years approximately, during the prehistoric and historic period.

The long-term stability of the relative sea level followed by an abrupt rise in such an extensive area cannot be connected with the local tectonism, specific fault zones and seismic events. These changes concern the wider area of the Saronic Gulf and a greater section of the earth crust including the east Peloponnesian coast.

These large scale recent vertical tectonic deformations of the coast and especially the initial, appear to be associated with the mobility of the highly complex collision tectonics of the Hellenic Arc, in a relatively short time period between the middle of the fourth and the middle of the sixth century AD, called by Pirazzoli (1986b) “early Byzantine tectonic paroxysm”. It is a period of intense tectonic coseismic activity during which a substantial part of the Greek Coast and Asia Minor and more widely the entire Levant coast from Hatay in Turkey to Syria and the Lebanon, were displaced.

In the compressive front arc and extensive back arc stress regime of the Hellenic Arc, large crustal blocks bordering by E–W and NNW–SSE strike-slip and oblique to normal faults, were found in a process of redefining an adjustment position to tectonic forcing.

6. Conclusions

The submersion of coastal geomorphological indicators related to past sea levels, the assessment of the functional level of dated ancient constructions and the relationship of palaeocoasts with ancient coastal installations, aided in defining and dating three distinct sea levels along the coast of the West Saronic Gulf at -3.30 ± 0.15 m, -0.90 ± 0.15 m and -0.55 ± 0.05 m. It was also established a long period of stability in sea level during the prehistoric and historic antiquity, which lasted at least between 1800 BC and AD 400 $\pm$ 100. A rapid sea level rise followed in the last 1600 $\pm$ 100 y with two short sea level stands intermediately, initially by 2.40 m and then by 0.35 m between 1555 and 1838. The final change by 0.55 m occurred between 1839 and 1999. The uniformity of the submersion throughout the coast of the West Saronic indicates the absence of tectonic displacements along the extensive seismically active fault zones and therefore indicates a unique tectonic behavior of a single extended fragmented block of the lithosphere of an area at least 2550 km^2 over the last 3000 years.

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