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Formation & evolution of the Ververonda Lagoon (Porto-Heli Region, SE Argolic Gulf) during historical times, on the basis of geophysical data and archeological information

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with 10 figures and 3 tables

Summary. The scope of the present contribution is to investigate the formation and evolution of the Ververonda 'lagoon' that belongs to the South Argolid peninsula (Porto Heli region) during the last transgression (Holocene) period. This is achieved by utilising existed information and the production of the appropriate supplementary data; the former refers to geology, seabed morphology and stratigraphy, relative sea-level rise and archeological evidences, while the latter involves in-situ coastal geomorphological mapping, analysis of surficial sediment samples, the collection of a sediment core and the application of geophysical techniques (e.g. electrical resistivity). On the basis of the interpretation of all the above information, it has been found that the Ververonda lagoon was formed after the 2nd century A.D. and has kept its lagoonal hydrological characteristic until the middle of the 20th century when two artificial channels permit exchange of water with the open bay. During the late Mesolithic period (ca. 6,000 years BC) the lagoon was coastal land with the bay of Ververonda being mach smaller in size. At the end of the Early Helladic period (some 2,000 years BC) the sea has invaded the inner part of the Ververonda Bay, covering most of the current lagoonal area. The sea have continued to rise, not necessarily with a stable rhythm, reaching a level of approx. 2 m below its present stage at Roman period (2,000 BP). At this period the lagoon was deeper while the ephemeral streams discharging along the northern side of Ververonda Bay (including the present lagoonal coast) provided substantial sediment influxes. Thus, over the last 2,000 years when sea-level was rising slowly, marine processes had formed gradually the barrier that separated eventually the inner part of the Bay forming the Ververonda lagoon; this process is estimated to have been concluded some hundred years ago. Human interference during the second half of the 20th century destroyed its lagoonal hydrological character by establishing free-communication with the open bay waters, through two artificially dredged channels.

Key words: Holocene transgression – sea level rise – lagoon formation

1 *Introduction*

The Ververonta Bay belongs to the Southern Argolid Peninsula that in ancient time called also Akte. The bay at its inner part incorporates a transgressive lagoonal-type of formation, whose existence has been reported in literature since 16th century (Kiros 1990). Nowadays, it is called the Ververonda lagoon, although it has lost its typical lagoonal hydrologic character after the opening of the second channel in 1970's via which communicates with the open Argolic Gulf. The Ververonda 'lagoon' is separated from the Porto Heli Bay by a strip of land with relatively low-relief, where the homonymous port exists since the 18th century. Although the lagoon and the associated bay have not been investigated, in detail, they belong to a broader region i.e. the Southern Argolid Peninsula, which has attracted the attention of intensive archeological and geophysical surveys; this happened primarily due to the presence of the Phrachti Cave, to the north,

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and secondarily to the existence of the classical city and port of Halieis (the word means fishermen in ancient Greek), which is among the most extensive submerged ancient cities in Mediterranean (JAMESON et al. 1994).

The present investigation focuses upon the formation and evolution of the Ververonda 'lagoon' during Holocene on the basis of geophysical (i.e. sedimentological, oceanographic, morphotectonic) data together with the available archaeological information concerning the broader region of the southern Argolid peninsula and its nearby islands; these information extend back to upper Palaeolithic period (prior to 10,500 years BC).

2 *The study area*

2.1 *Geological/geomorphological setting*

The Ververonda lagoon and the homonymous bay belong to the southern end of the Southern Argolid peninsula (Fig. 1), which is bordered to the north by a mountainous region lies in between the Argolic and Saronic Gulf including the Dhidima (maximum elevation 1,113 m) and the Adheres (588 m) ranges. The southernmost peninsula consists mainly of rounded hills with maximum elevations just above 100 m, intersected by many small and a few larger valleys. In particular, the country to the north of Ververonda 'lagoon' slopes gently and is intersected by many small, short and shallow valleys of ephemeral streams (see Fig. 1).

The 'lagoon' is separated from the open Bay by a beach barrier formation, while the remaining part of the coast of the western part of the southern Argolid peninsula is characterised by the presence of cliffs, a few tens of meters high, with some pocket beaches consisting of coarse material (shingles and cobbles), while beaches with relatively finer material (granules and sand) are present in front of some stream valleys (JAMESON et al. 1994).

Geologically, the southern Argolid peninsula belongs to the Pelagonian isotopic zone and is characterized by two main strike slip faults, located at the area of Dhidhima Range, while the Ververonda and its surrounding area seem to be controlled by two normal faults trending NW-SE and deeping to the NE (Fig. 2). Although tectonic activity is present during Neogene (VAN ANDEL et al. 1993), the absence of any significant tilting of the Late Quaternary alluvial deposits (late Pleistocene and Holocene) indicates its minimal contribution in landscape changes. The Dhidhima range consists of Triassic-lower Jurassic limestones, dolomites and marbles, whilst the Adheres range is formed by flysch formations (mainly shales and sandstones). The southernmost of the peninsula, including the area of Ververonda and Porto-Heli, is covered by the so-called Peloponnesian conglomerate of Plio-Pleistocene age (Fig. 2).

Furthermore, late Quaternary alluviation (upper Pleistocene to Holocene) has been identified in Southern Argolid formed by the colluvium that has accumulated on lower slopes by slope wash, or the slow creep of the soil mantle (VAN ANDEL et al. 1986) and includes usually debris flow, stream flood and overbank loam deposits. The major stages of this alluviation separated from each other by periods of landscape stability include: (i) the Loutro alluvium (with three sub-units: lower-middle-upper) prior to 35,000 BP, (ii) the Pikrodafni alluvium (4,500–3,000 BP); (iii) the Flamboura alluvium (50 BC–1,700 AD) with two sub-units (lower-upper); and, (iv) the Kranidhi alluvium formed from 1,700 AD to present.

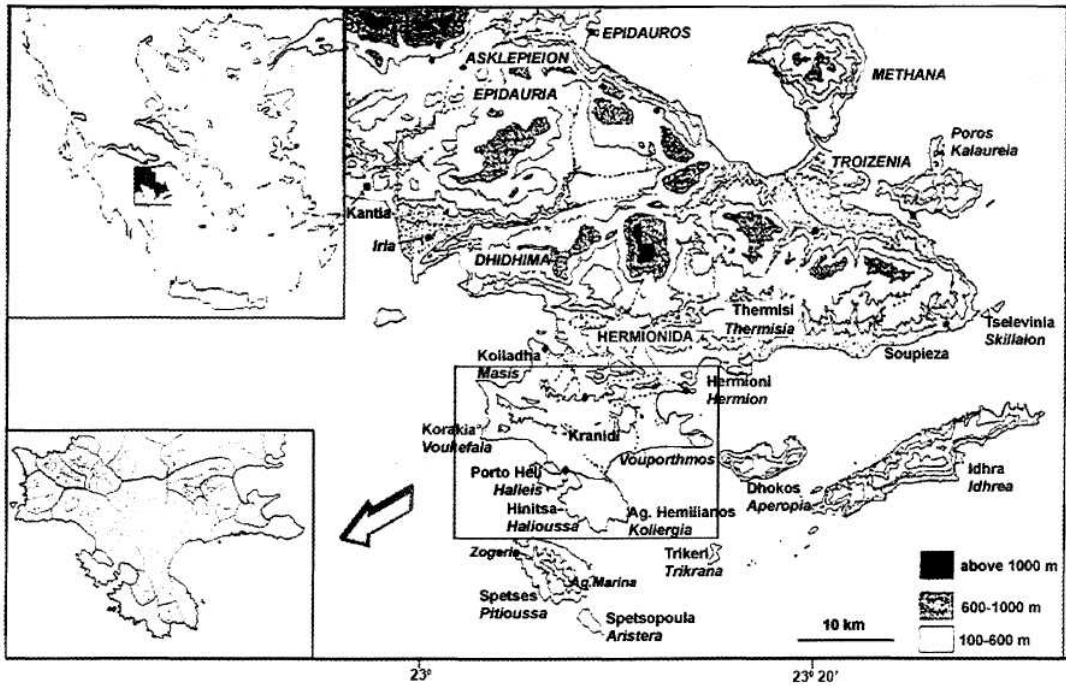

Fig. 1. The southern Argolid peninsula, within the centered box, is the study area whose valley network is shown on the lower-left box (the figure is a synthesis of figures abstracted from JAMESON et al. (1994)).

2.2 *Modern and palaeoclimatic conditions*

The current climatic condition is typically Mediterranean with cool – moist winters and dry-hot summers. The mean annual rainfall is cerca 500 mm and the temperature 18 °C (10 °C in January and 27 °C in July) (PERRY 1981). Humidity tends to be higher in summer ranging from 40 % to 100 %, while in winter snowfall occurs usually at altitudes higher than 600 m (Dhidhima and Adheres). In winter, winds are mainly from NW and W and rarely from the SE. During the summer period and especially in July and August the Etesians (northerly and northeasterly winds) dominate the southern Argolid peninsula; in addition, daily sea breezes alter with winds, which come from the hinterland at night.

The climate during at least the late Holocene period was assumed to be rather unchanged and similar to the current one. Recent works including those of CAMBELL et al. (1988), BIANCHI & MCCAVE (1999) have shown that global climate during late Holocene was rather unstable. BAR-MATTHEWS et al. (1998) investigating the climate of the eastern Mediterranean region with the use of cave deposits also proved the aforementioned climatic instability. This climatic variability is usually associated with warmer (more humid) and colder periods lasting from few decades to hundreds of years. On Fig. 3, it can be seen that during the last interglacial period (last 18,000 years) global air temperatures varied from -4 °C up to +1 °C, compared to present day mean annual temperatures. Thus, an early (proimo) climatic optimum c.13,000 years BP and the cooler

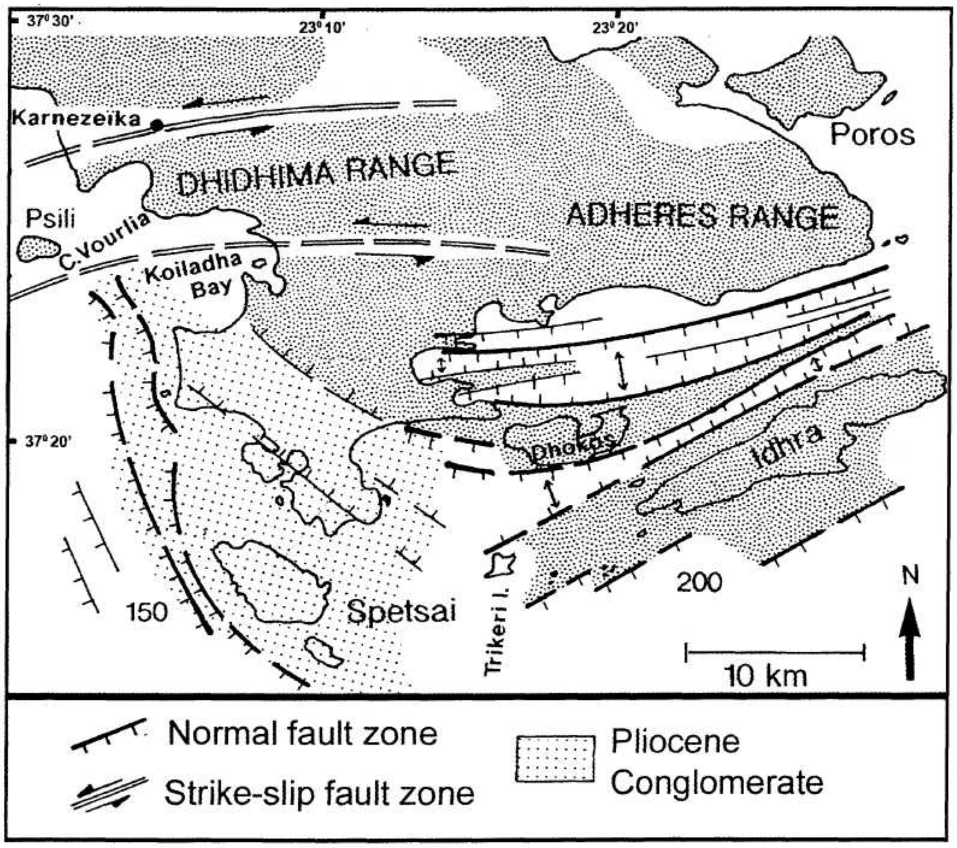

Fig. 2. Main geological/tectonic characteristics of the broader area of the South Argolid peninsula (originally from VAN ANDEL et al. (1993)).

and drier period (Younger Dryas) in between 11,000 and 10,500 years BP, have been identified. Furthermore, during the past 9,000 years, when the range of temperature variation was in the order of ±1 °C relative to its current value, the following distinctive climatic periods have been developed: a cooler period (about 8,000 years BP), followed the middle Holocene climatic optimum occurred 4,500–5,500 years BP, while another cooler period took place in 4,000–2,000 years BP, followed by the Medieval Warm Period (2,000–1,000 years BP). The most recent cooler period, the so-called Little Ice Age, started in the 14^{th} century AD and terminated in the beginning of the 19^{th} century (prior to 1850).

Furthermore, the warm periods of Holocene climate are usually well-correlated to wet periods. On the basis of ^{14}C dating in foraminifera, associated with high sediment accumulation in the SE Mediterranean off Israel coastline, two major humid phases have been identified by SCHILMAN et al. (2001). The first phase 3,500–3,000 years BP, which coincides with the period in between the middle Holocene Climatic Optimum and the followed cooler period (later than c. 2,700 years BP) having its peak at ca. 3,000 years BP. The second warmer period identified in 1,700–1,000 years BP belongs to the Medieval Warm Period (MWP) taking place prior to a rather dry period from ca. 2,000 to 1,700 BP.

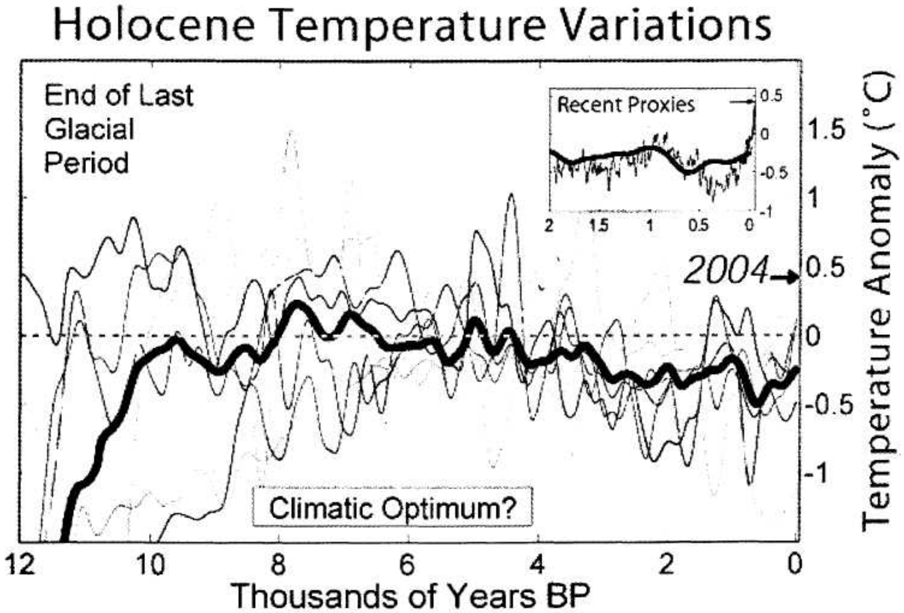

Fig. 3. Deviations of air temperature from the mean temperature of the last 12,000 years (originally from (http://www.globalwarmingart.com/wiki/Image:Holocene_Temperature_Variations_Rev_png).

2.3 *Sea-level rise and sub-bottom Holocene stratigraphy*

It is well known that first phase of rapid sea level rise (although not at a constant yearly rate) concluded 5,500–6,000 years BP, i.e. the period of Holocene Climatic Optimum. During this first phase the sea rose from ca. 120 m to a few meters below present sea level (bpsl), e.g. LAMBECK (1996), DAI PRA & HEARTY (1991), RIEDEL (1996) POULOS et al. (2008) and/or close to its present stage (KAYAN 1991). It is also accepted that during Holocene sea level in the eastern Mediterranean was never significantly higher than today (e.g. KELLETAT 2005). Besides, the rise of the sea level was not continuous, but interrupted by brief still-stands or even reversals; this may be related to Holocene climatic variation characterised by relatively warmer and colder periods, as mentioned earlier. Moreover, on the basis of numerous drowned ruins from antiquity it has been recognized that the sea level in the eastern Mediterannean has been rising since at least the last 2,500 years (if not earlier) in an amount of more than 2 m (e.g. KELLETAT 2005; RIEDEL 1996).

Although tectonic rates are expected to be insignificant for the period of early Holocene, with the exception of the early Byzantine paroxysmic phase in 1,350 BP (PIRAZZOLI 1986) compared to rates of sea level rise, on Fig. 4 the sea level curves of RIEDEL (1996), ANDRES & WUNDERLICH (1991) referred to the eastern Mediterranean have been plotted together with the global curve of ROHDE (2008) and the curve provided by JAMESON et al. (1994; fig. 3.26) for the Porto-Heli region; the latter is based on datings of archaeological artifacts selected from the ancient submerged port of Halieis, incorporating though any localized tectonic activity.

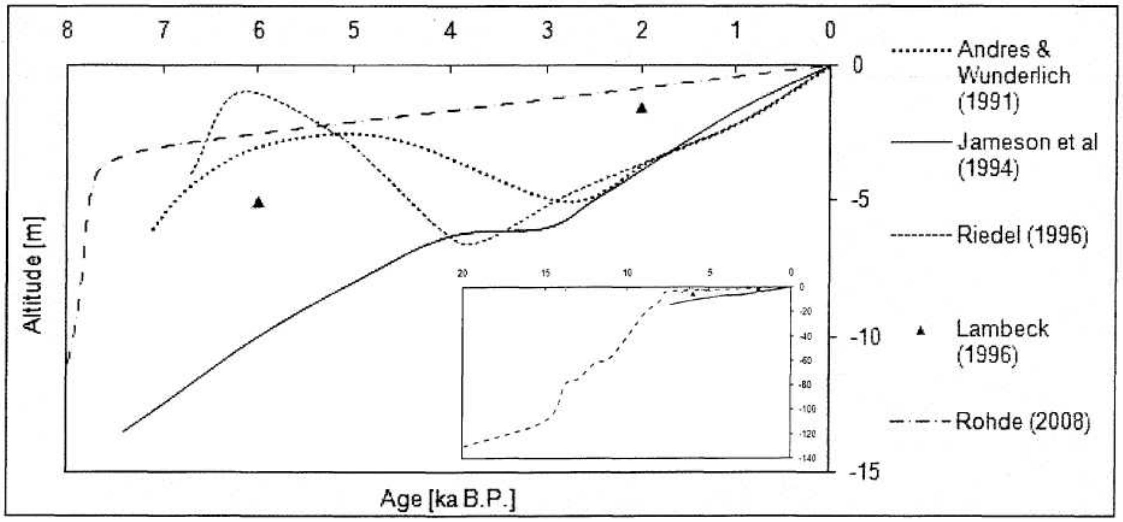

Fig. 4. Sea level curves referred to eastern Mediterranean Sea by RIEDEL (1996), ANDRES & WUNDERLICH (1991), to the Aegean Sea by POULOS et al. (2008) and LAMBECK (1996; stages at 6,000 and 2,000 years BP) and to the Porto Heli Bay by JAMESON et al. (1994).

In conjunction with sea level rise during the Holocene, the sub-bottom high-resolution seismic reflection profiling data has revealed the transgressive character of coastal evolution with the early postglacial shores lying seawards of those of today (JAMESON et al. 1994; VAN ANDEL et al. 1986); this has been attributed also to the relatively low sediment supply due to the absence of major river systems debouching along the South Argolid peninsula. In accordance to that the thickness of the sediment above the basal transgessive surface (identified in the Koilada Bay by VAN ANDEL et al. 1986) is generally less than 2 m thick, except in bays where much higher fluvial influxes are expected to be accumulated. Thus, upon the identification of distinctive sub-bottom reflectors (a to d) and their correlation with the upper Holocene alluviation phases, whose thickness together with corresponding (estimated) ages of formation derived from the nearby Koiladha bay and presented on Table 1, the following phases of deposition can be identified: (i) the Kranidhi phase:

Table 1. Distance below present sea level and corresponding time- period of formation of post-transgessive acoustic reflectors (a, b, c & d) in Koiladha bay (after JAMESON et al. 1994).

Acoustic Reflector	Distance below present sea level (m)	Estimated time period of formation (years BP)
bay floor	2–3	
a	3	1,700 – ?1,300
b	5–6	3,500 – 1,700
c	7–8	ca. 4,000
d	9–10	ca. 5,000

from bay floor to reflector a; (ii) the upper Flaboura phase: in between the reflectors a and b; the lower Flaboura phase: in between reflector b and reflector c; and, (iv) the Pikrodafni phase: from reflector c to reflector d.

3 *Collection and analysis of geophysical data*

For the needs of the present investigation the data set includes detailed topographic reconstruction, identification of sedimentological characteristics from the near (sea)shore bed of Ververonda Bay, the lagoon floor and along a short sedimentary core. In addition, stratigraphic information is extracted from electric resistivity measurements at selected locations. All the locations of the various sampling sites are shown in Fig. 5.

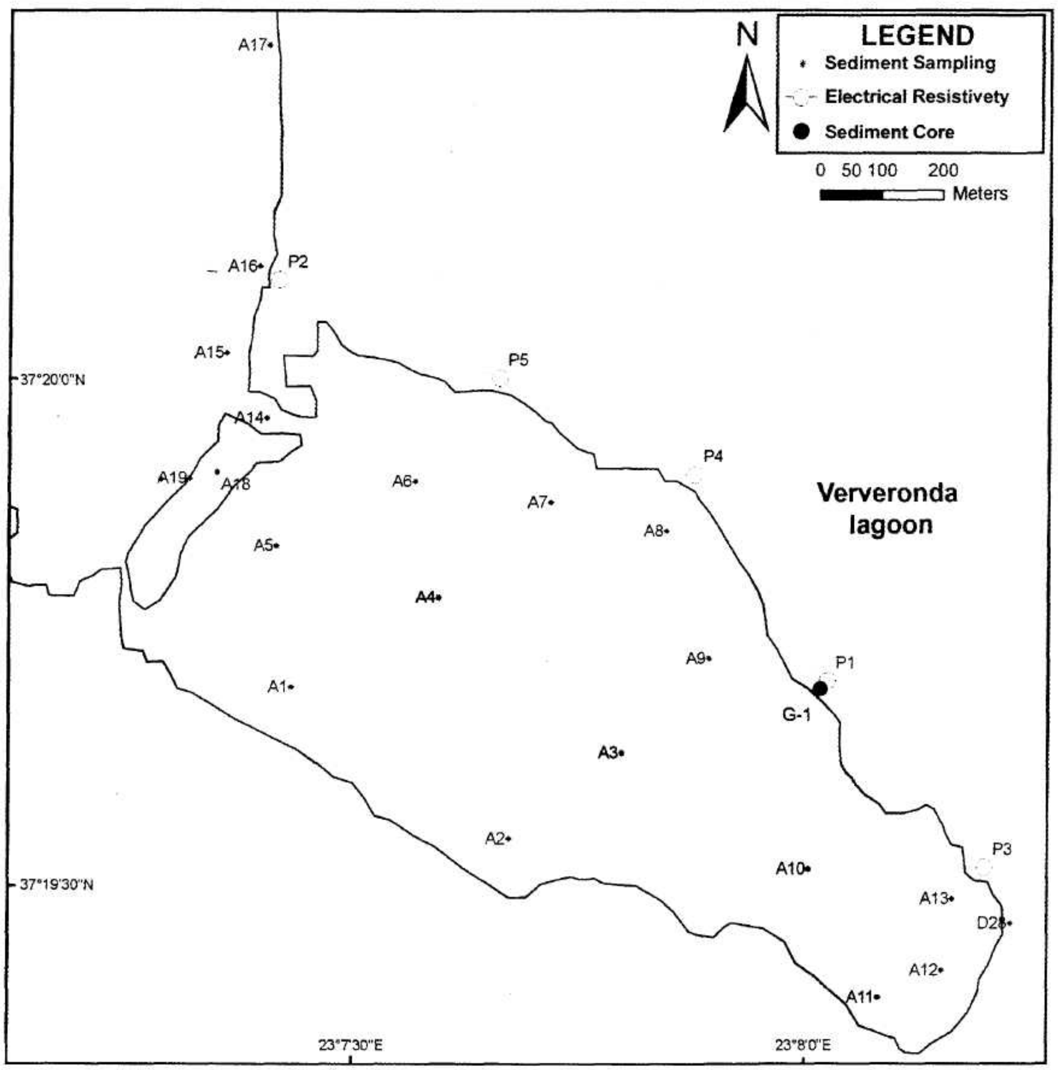

Fig. 5. Locations of sampling positions of geophysical data (A: surficial sediment samples, P: electrical resistivity positions, G: sediment core, boxes indicate subaqueous photography).

The selected surficial sediment samples and those along the sediment core (obtained with the use of an Cobra vibrocorer) have been analyzed granulometrically by dry-sieving (fraction >0.0625 mm) and being named according to FOLK's (1974) nomenclature.

Five (5) Vertical Electrical Soundings (VES) were carried out in the northern part of the lagoon, in order to investigate the stratigraphic structure of the subsurface geological formations. All soundings were performed by applying the Schlumberger array configuration. Maximum current electrode spacing (AB) reached up to 300 meters. Current electrode spreading operation met difficulties due to the dense vegetation and district construction (streets, residences, fences, etc). A Terrameter SAS300B with Booster (ABEM) was used for these measurements. The geophysical data were processed by applying the automatic method of ZOHDY & BISDORF (ZOHDY 1989) and the commercial software packages IX1D (v3) of Interpex (2006).

For the geomorphological mapping of the study area, topographic diagrams (1:5,000) published by the Hellenic Army Geographical Service (H.A.G.S.) were used together with 4 rectified charts (scale: 1:10,000) obtained from the Hellenic Ministry of Agriculture. A digitized terrain model was built combining all these maps with the use of GIS (ArcMap 8.3) function, named "cut and fill". Supplementary information concerning coastal elevations obtained with the use of a surveying total station, while depth soundings provided by a portable echo-sounder (ZODEX).

A series of underwater photographs of the nearshore seabed and, in particular, of the subaqueous beachrock formation have been taken with the use of an OLYMPUS Camedia 740 digital camera.

In the absence of wave records, offshore wave characteristics have been estimated using wind data obtained from the Wind & Wave Atlas of the Eastern Mediterranean Sea (ATHANASOULIS & SKARSOULIS 1992). Thus, the significant wave height (H_s) and the peak period (T_m) of the wave spectrum, are calculated for the dominant fetch directions (NW, W and SW), using the deep-water ($d/L < 0.25$; d: water depth and L: wave length in deep waters), wave forecasting equations for the fetch-limited case (CERC 1984):

$$H_s = 5.112 \cdot 10^{-4} \cdot W \cdot F^{0.5} \tag{1}$$

$$T_m = 6.238 \cdot 10^{-2} \cdot (W \cdot F)^{0.33} \tag{2}$$

where, W is the wind stress (m/s) related to the measured wind speed (U) through the equation $W = 0.71\,U^{1.23}$, F is the fetch in m, while the prediction of both H_s and T_m is based upon the assumption that wind blows over the sea surface for a sufficient time for the generated waves to obtain their maximum height under the given fetch limited conditions. Following, the significant period (T_s) is given as 0.95 T_m. Subsequently, wave run up of the storm (highest waves) have been calculated by applying KOMAR's (1998) equation:

$$R = 0.36 \cdot g^{0.5} \cdot S \cdot H^{0.5} \cdot T \tag{3}$$

where, S is the tangential of the beach slope.

4 *Results and Discussion*

4.1. *A synthesis of the existed archaeological information, in relation to climatic variation and sea level stands for the southern Argolid peninsula*

Most of the archaeological information concerning the period from upper Palaeolithic (40,000–10,500 BC) through Mesolithic (10,500–6,800 BC) to Neolithic (6,800–3,200 BC) period is based upon a wide range of raw materials and artifacts that have been found primarily at Franchthi Cave and secondarily in other sites of Southern Argolid peninsula, such as the Koilada, Iliokastro and Ermioni. During the upper Palaeolithic the various artifacts from the Franchthi cave show a typical picture of a short-term camp used by small groups of foragers. At that time, the sea level was approximately 35–40 m lower than it is today (CHAPPEL & SHACKLETON 1986) and a wide coastal plain surrounded the Argolid peninsula was covered by a steppe of grass and sagebrush, with patches of trees (JAMESON et al. 1994). In the Mesolithic period, although hunting was still important, as it is revealed by the use of stone tools, for the Franchthi people, the seafood was added to their diet, while they are evidences for the use of fishing boats. During this period the sea level has risen to approximately -20 m deteriorating the coastal plains (JAMESON et al. 1994); it is referred also that the distance between the Franchthi cave and the sea was reduced from 6–7 km to about 1 km. During the Neolithic period, the first phase of sea level rise is concluded with the Argolid coastline to obtain almost its present shape. All the archeological evidences show that the landscape turned slowly to a cultural transformed landscape, accompanied by a distinctive increase in habitants. During the Early (3,200–2,150) and Middle (2,150–1,600 BC) Helladic period, an overall reduction in settlement density occurred in the broader area of Southern Argolid; this maybe related to the decreasing trend of air temperature (see Fig. 3). A significant expansion of settlement in the area occurs during the Late Helladic (Mycenaean, 1,600–1,100 BC); this is attributed to a relative still-stand in sea level, as stated by JAMESON et al. (1994) for the ancient port of Halieis, despite the fact that this period is characterised by a decreasing trend in air temperature (see Fig. 3). During the subsequent Geometric and Archaic Period (1,050–510 BC), the climate was rather stable although relatively colder. In this period, the most important sites are Hermion, Mases and Halieis; the sanctuaries at Hermion and Halieis together with the shrine at Mases were the principal cult centers of that epoch. The area continuous to flourish from the Early to Middle Classical Period (510–420 BC), favored by warmer weather conditions and possibly not affected from the last local transgressive phase, as shown by JAMESON's et al (1994) local curve (Fig. 4). During this period, the city of Halieis was established (in 479 BC) with its associated port to play a major role during the upper Classical period. The following rise in air temperature during the Late Classical /Early Hellenistic Period (420–300 BC) was accompanied by a great rise of sites, mostly in the hinterland of the Southern Argolid peninsula, where 38 settlement areas have been reported by KIROS (1990). Surprisingly, the city of Halieis declined at the second half of the 4th c. BC and was abandoned; this is attributed to the deterioration of its port due to sea level rise and/or being the consequences of an earthquake (at 3rd c. BC) as referred by KIROS (1990). More or less the situation remains unchanged during the Hellenistic period (323–30 BC) while in the middle of the Roman Period (30 BC–300 AD) a dramatic reduction in settlement sites (only 17 small sites could be identified) occurred, mostly during the first half of the 2nd c. AD; this is associated with a decreasing trend in air temperature, to some earthquake activity (although there are not information) and/or to socio-economic reasons. Not substantial residential change during Late Roman-Early Byzantine Period (140–350 AD) has been reported, indicating that the area did not affected substantially by the Byzantine paroxysmic tectonic phase that affected substantially the Hellenic arc (PIRRAZOLI 1986). In addition, Pausanias, who visited Greece in the third quarter of the 2^{nd} c. AD provides a good description of the ancient coastal topography of the Southern Argolid peninsula, although it is not based on personal observations. In his description, he refers to the presence of five islands as somebody sails around the coast of the southern Argolid peninsula, from the Koilada bay towards the Ermioni bay; these area (for locations see Fig. 1): Aliousa (the small island at Xinitsa inlet), Pytiousa (Spetses), Aristera (Spetsopoula), Trikrana (Trikeri), Aperopia (Dokos) and Hydrea (Hydra). Furthermore, Pausanias, in his description, does not mention at all the presence of Ververonda lagoon, although he has referred adequately to the ancient city of Halieis by saying that it was abandoned with its port to be surrounded by a shallow muddy area. Subsequently, during the Medieval Period (400–1,600 AD), which is characterised as a warm period, settlements are found only in the hinterland (e.g. along the Fournoi, Ermioni, and Poikrodhafni valleys and on the Iliokastro plateau), while pre-existing coastal establishments and associated ports such as those of Ag. Marina in Pityousa (Spetses), at Skinto in Dokos (Aperopia) and the Ermnion in Ermioni Bay do not exist due to sea level rise of about 2 m from the Minoan period, when they had flourished (KIROS 1990).

4.2. *Geophysical data*

4.2.1 *Coastal Geomorphology*

The various morphological observations are presented on the 3-D terrain model produced with the interpretation of the rectified topographical charts orthophotoxartes in Fig. 6. It can be seen that the maximum depth of the lagoon, which covers an area of approximately 1.3 km^2 is no more than 2.7 m, while its bathymetry is rather uniform. The beach-barrier that separates the lagoon from the open bay waters has elevations <2 m, which are similar to those observed along the beach zone located at its north side. The northern coast of the lagoon is related to a rather even and gently sloping alluvial plane, which represents the biggest part of its catchment area (in total some 9.4 km^2).

Nearshore bathymetry is characterised by a gently sloping bed with beach rock formations being present along the total length of the beach face. Underwater photographs reveal that beachrock formations are quite steep being in between 0.4 m and 1.6 m of water depth (see Fig. 6 and photos in Fig. 7). In addition, beach rock formations have been observed at water depths of 2.3–2.5 m (Fig. 7) but only in front of the alluvial plane and not in front of the beach barrier. This indicates that the formation of the beach rocks is related to aquatic aquifer of the alluvial plane and the existence of lagoon (prior to its artifial connection with the open water bays). The nowadays observed two channels, the first and the oldest one with depth of approx. 1.2 m at its SE opened when the lagoon was used for fish-farming prior to 1970's, while the second and more recent one (opened in 1970) has a depth of 2.5 m that is similar to that of the lagoon bed. Following the construction of the second channel, which included the removal of the beachrocks, the lagoon has obtained hydrological characteristics similar to those of the open Ververonda Bay waters.

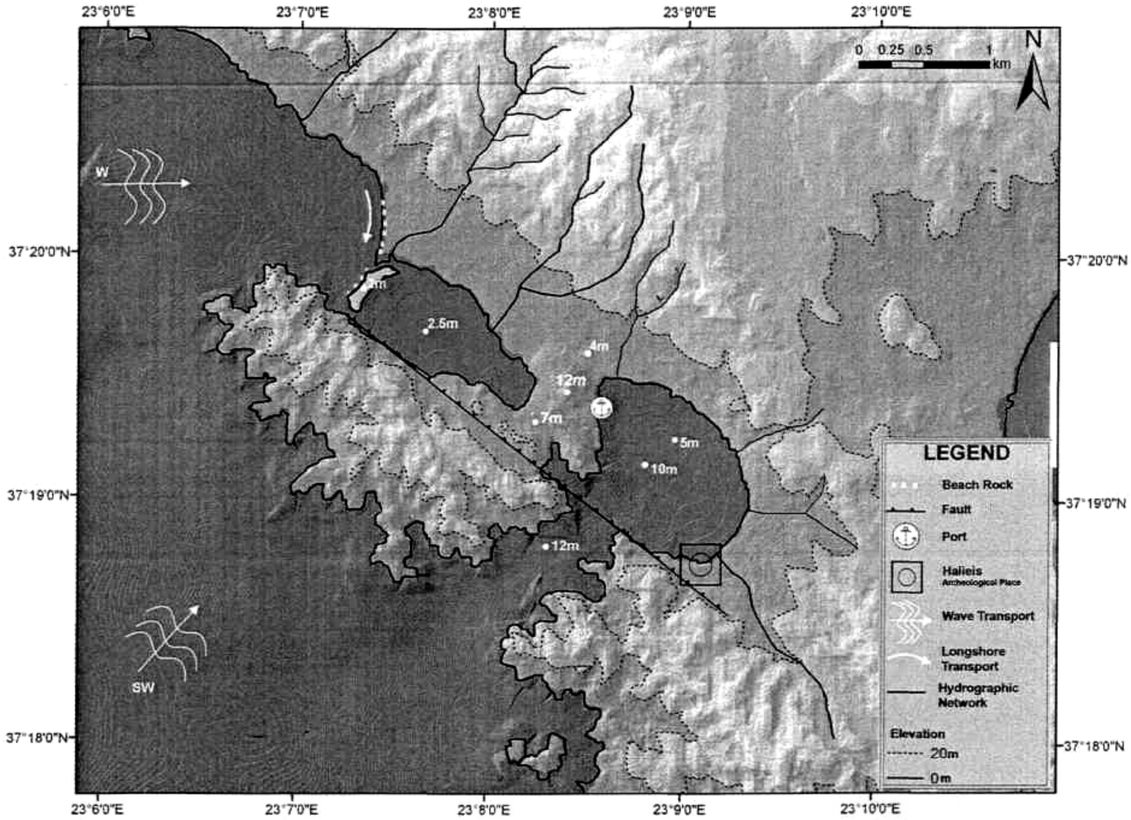

Fig. 6. Geomorphological characteristics of the Ververonda lagoon and its surrounding area.

Along the northern lagoonal bank and the Ververonda Bay debouch some ephemeral streams (see Fig. 6) that providing some amounts of terrigenous material which are the products of erosion of the Holocene alluvial plane. On the basis of sediment yield for the Mediterranean region of <250 t/km^2 (WOODWARD 1995) an amount of no more than 1000 tones may be transported annually from its catchment towards the coast.

4.2.2 *Sedimentological investigations*

On Table 2 the gravel, sand and mud (silt + clay) percentages of the surficial sediment samples are presented together with their classification according to FOLK's (1974) granulometric nomenclature. As it can be seen, the material of the beach barrier (being consisted mostly of gravel and coarse sand) is similar to that of which the beach zone in front of the alluvial plain is consisted. The nearshore sediment is sandy in water depths larger than 1.5 m. The lagoonal bed material is characterised by the abundance of mud (mostly clay) while sand percentages are <25%. This granulometry denotes the terrestrial origin of the fine-grained material (fine sand and mud)

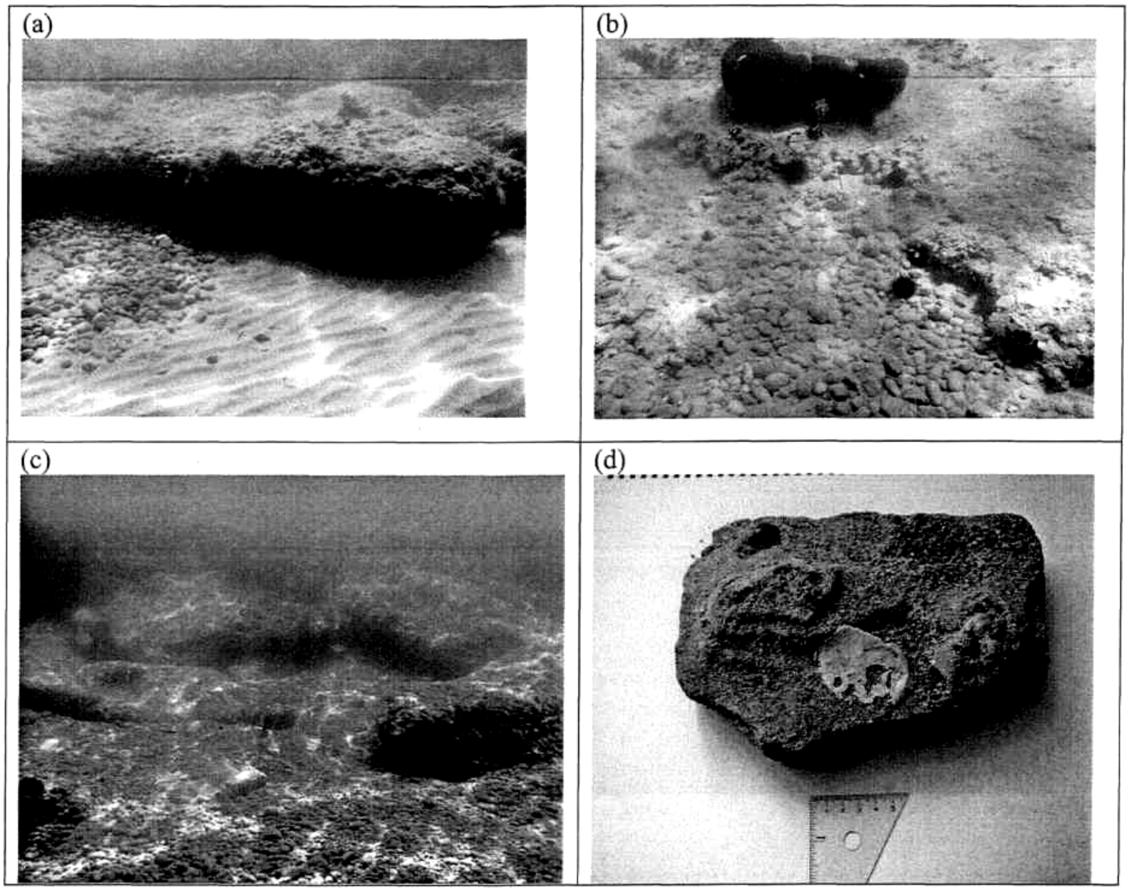

Fig. 7. Beachrock photographs. (a) underwater photo from the almost vertical face of the beach rock formation at position A (see Fig. 2); (b) underwater photo of the beachrock at the beach barrier (depth = 1 m) at location B; (c): flat beach rock formation on the seabed at location C and (d) a piece of beach rock from the upper formation with an ostracode sell.

whilst the coarser material in the size of coarse, sand and granules are of biogenic origin (mostly shells). Sandy material within the lagoon is more abundant behind the beach barrier and at the banks of the two artificial channels.

The description of the short core (3 m in length) is given in Fig. 8. The material along the core is characterized, generally, by the abundance of muddy material, which includes in places some pebbles (mostly angular) showing a terrestrial origin. Moreover, the first half of metre consists of a dark redish mud with pebbles, followed down to 1.2 m by a yellowish layer that includes angular gravels (<2 cm in diameter). This rests on top of a layer that extends down to 2.5 m of core length also muddy with some angular granules similar to the upper layer. The last part of the core 2.5–2.9 m consists of debris deposit. The granulometry and the overall texture of the core material reveal the terrestrial deposition of core material, which have the characteristics of stream flood and overbank (possibly) loam deposits.

Table 2. Percentages of gravel, sand and mud content of the surficial and along the sediment core samples (for locations see Fig. 5).

Sample	Gravel	Sand	Mud	Folk (1974)	Sample	Gravel	Sand	Mud	Folk (1974)
A1	0.00	17.69	82.31	sZ	A15	11.19	88.34	0.47	gS
A2	0.00	15.90	84.10	sZ	A16	0.00	99.72	0.28	S
A4	0.00	21.22	78.78	sZ	A17	59.91	40.09	0.00	sG
A5	0.99	47.89	51.12	sM	A18	52.56	47.41	0.03	sG
A6	0.00	22.12	77.88	sZ	A19	7.17	92.57	0.26	gS
A7	0.00	20.27	79.73	sZ	A20	1.24	98.58	0.18	S
A8	7.72	43.34	48.94	gM	S1	21.94	19.3	79.27	gM
A9	26.09	49.34	24.57	gmS	S2	10.84	21.37	65.22	gM
A10	0.00	22.97	77.03	sZ	S3	25.64	19.71	52.68	gM
A11	0.00	16.79	83.21	sZ	S4	4.72	13.82	79.27	g(s)M
A12	0.00	54.56	45.44	zS	S5	29.83	9.43	58.83	gM
A13	0.00	15.45	84.55	sZ	S6	63.58	7.87	27.3	mG
A14	26.05	72.11	1.84	gS	S7	48.3	17.04	33.42	mG

4.2.3 *Landscape stratigraphy (electrical resistivity)*

The geophysical investigation with the application of the electrical resistivity method reveals the presence of two distinctive almost horizontal layers (Fig. 9) with respect to measured resistivity values that terminates to the E/SE at the Plio-pleistocene Argolid conglomerate. The lower formation with resistivity values between 2.3 and 3.5 Ohm.m was detected below the 5–7. This formation is considered to represent permeable land sediments fully with sea water; its texture should present high porosity and lack of muddy material. In contrast, the upper formation with much higher values of electric resistivity (about 13–20 Ohm.m) is considered to represent an impermeable land formation containing brackish water. On the basis of the core description, the material of the upper unit is reach in mud, while the water content is related to the surrounding surface aquifer. In addition, if not both layers at least the upper (i.e. up to a depth of approx. 5–7 m) has been deposited in a terrestrial depositional environment which may be related to the Kranidi and partially to upper Flamboura allouvial formations (as described in section 2).

4.2.4 *Wave climate*

The Ververonda Bay is exposed principally to the W and secondarily through reflection on the Argolid coast to SW wind-generate waves, whose main characteristics are presented on Table 3. The most frequent waves come from the SW while the highest waves come from the SW due to the larger fetches. The associated wave run up from the highest waves are approx. 1 m which maybe increased by storm surge several tens of centimeters; this value shows that high waves can cover most of the seaside of the beach barrier and may reach the top of the beach zone, which is to the north of the beach barrier and in front of the alluvial plane, indicating that they are, at least partially, under hydrodynamic (wave) control.

As the Bay of Ververonda faces to the W, the flux of wave energy (P) should induce a longshore sediment transport from the NW towards the SE; this is able to transfer the terrestrial material that is debouched by the ephemeral streams discharge along the northern coast of the Ververonda Bay, contributing, therefore, to the formation of beach barrier that eventually have been formed the homonymous lagoon. The highest approaching waves break at 3–4 m of water depth and are capable to move bed sediment up to a depth of 6 m.

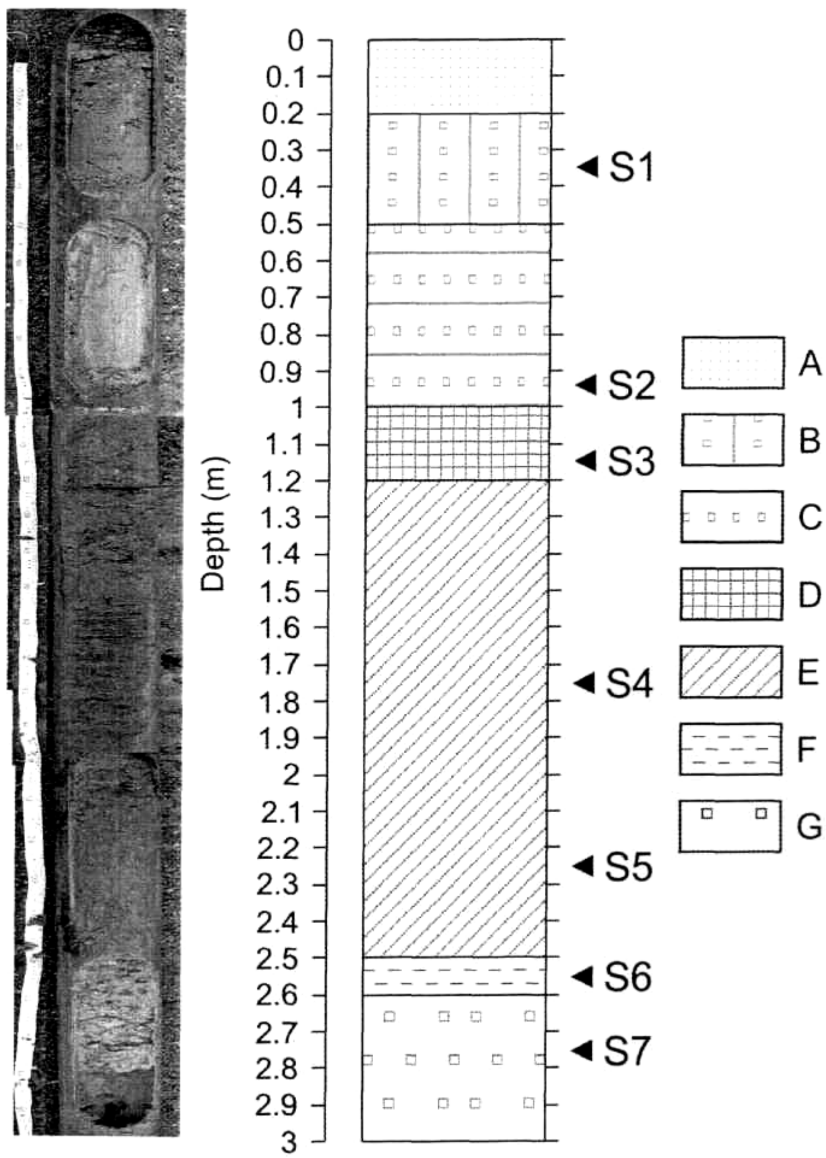

Fig. 8. Core description. A: human deposits (mostly road material), B: reddish mud with some pebbles, C: yellowish mud, D: reddish sandy mad, E: light yellow gravelly layer and G: light yellow sandy-gravel liquefied layer; S1–S7: sediment samples.

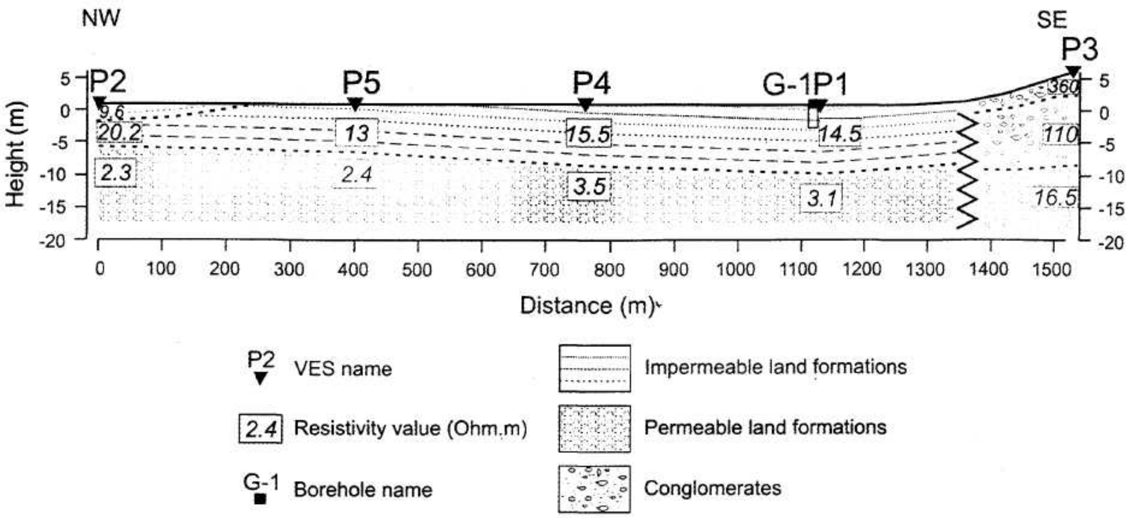

Fig. 9. Landscape stratigraphy on the basis of electrical resistivity along the northern bank of the Ververonda lagoon (for location see Fig. 5).

Table 3. Wind-generated offshore wave characteristics approaching the Ververonda Bay.

	U knot	Ua m/ sec	feq %	Tp (sec)	Hs (m)	Hc (m)	Hb (m)	Db (m)	P (W/m)	R (m)
West (fetch: 28,000 m) – annual frequency of occurrence 3.3%										
Mean	13.50	8.65	0.82	3,73	0.74	1.68	0.82	0.95		
High	37.00	29.89	0.01	5.62	2.56	5.81	2.61	3.28		0.81
total									1489.78	
Southwest (fetch: 30000m)- frequency of occurrence 3.6%										
Mean	13.5	8.65	0.77	3.82	0.77	1.74	0.85	0.98		
High	37.0	29.89	0.028	5.75	2.65	6.01	2.71	3.39		0.84
total									1954.16	

5 *Concluding remarks for the Formation and evolution of the Ververonda 'lagoon'*

The formation of the Ververonda 'lagoon' is associated primarily with the relative rise of sea level, the accumulation of sediment and the nearshore hydrodynamics. With respect to eustatic sea level rise according to CHAPPEL & SHANKLETON (1986) at 10,000 BP (early Mesolithic) sea level was ca. -29 m bpsl, to reach -10 m bpsl during Neolithic period (4–5 ka BP) and at -6 m bpsl in Early Helladic (2,500 BP). Furthermore, from the local curve provided by JAMESON et al (1994) sea level was considered to be about 5 m bpsl for the period 1,700–3,500 BP and 2–3 m bpsl. ca. 1,600 BP; these latter values may include any tectonic local displacement as they are based upon dating of artifacts for the Halieis region.

Nearshore coastal bathymetry during transgression should be quite different to that shown today due to deposition of transgressive sedimentary sequences. On the basis of seismic (acoustic) obtained from water depths >10 m the average sediment thickness above basal transgressive surface at Port Heli embayment found to be vary in between 2 m (for water depths >20 m) and 4 m (for water depths <20 m). Assuming that the seabed up to 50 m bpsl was covered by water during the past 10,000 years indicate a rate of deposition in the order of 0.2–0.4 mm/yr (VAN ANDEL & LIANOS 1983); this rates are regarded as rather small and attributed to the lack of any significant river system. On the other hand, these rates maybe much higher (>1 mm/yr) along the coastline (water depths <5 m) and nearby the mouth of the various ephemeral streams (see Fig. 1). Thus, in the Koilada bay, where water depths are <5 m and in accordance to the values presented on Table 1, the thickness of upper Holocene deposition reaches the 10 m for the last 5,000 years; this corresponds to a rate of approx. 2 mm/yr being attributed to terrigenous sediment influx, marine coastal erosion and nerashore sediment transport.

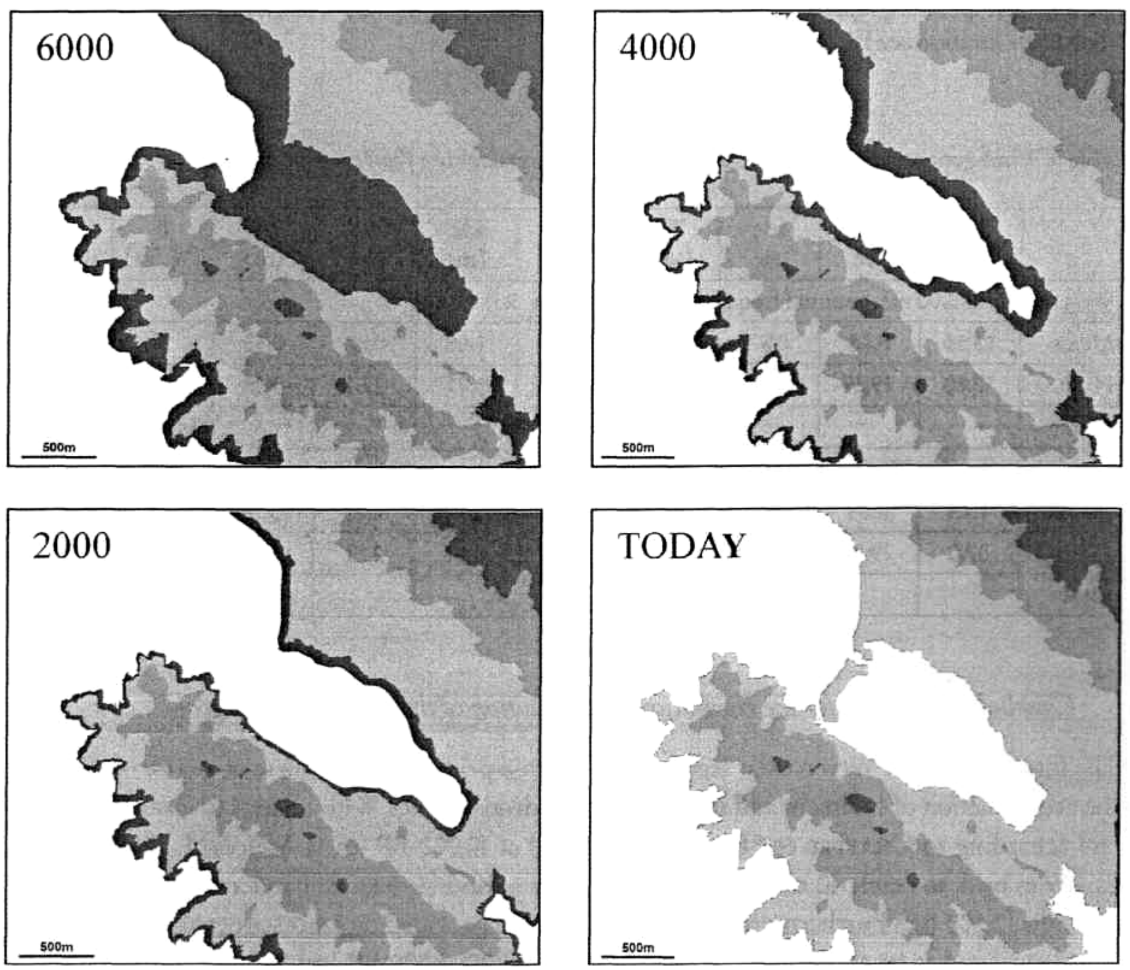

Fig. 10. Conceptual reconstruction of the Ververonda Bay coastline from the Mesolithic period up today.

On the basis of the values of relative sea level rise and rate of accumulation of terrestrial sediment in the nearshore area, the palaeogeography of the Ververonda Bay and the nearby Porto Heli coastal region is presented on Fig. 10 for the last 8,000 years BP, assuming insignificant tectonic vertical displacements (e.g. <0.5 m). During the late Mesolithic period (ca. 6,000 years BC) the lagoon did not existed with the bay of Ververonda being much smaller in size. After a period of 2,000 years, at the end of the Early Helladic period (some 2,000 years BC) the sea inundated the inner part of the Ververonda Bay, covering most of the current lagoonal area. The sea continued to rise, not necessarily with a stable rate, to approx. 1–2 m bpsl at Roman period (2,000 BP). At this period the lagoon was deeper while the ephemeral streams being disharged along the northern side of Ververonda Bay (including the present lagoonal coast) were providing substantial sediment influxes. Thus, over the last 2,000 years when sea-level was rising slowly, marine processes had formed gradually the barrier that separated eventually the inner part of the Bay forming the Ververonda lagoon; this process is estimated to have been commenced formed after the 2nd c. AD and concluded some hundred years ago. The lagoon has kept its lagoonal hydrological characteristic until the middle of the 20th century, when two artificial channels permitting massive exchange of water with the open bay destroyed its lagoonal hydrological character transforming it into sea conditions.

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