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THE ROLE OF BEACHROCK FORMATIONS IN THE EVOLUTION OF EMBAYED COASTAL ZONES OF ATTICA (GREECE) IN RELATION TO SEA LEVEL RISE. THE CASE OF KALYVIA BEACH ZONE (***)

ABSTRACT: KOUTSOMICHOU I., POULOS S., EVELPIDOU N., ANAGNOSTOU CH., GHIONIS G. & VASSILOPOULOS A., *The role of beachrock formations in the evolution of embayed coastal zones of Attica (Greece) in relation to sea level rise. The case of Kalyvia beach zone*. (IT ISSN 0391-9838, 2009).

The coastline of Attica incorporates a great number of pocket beaches, which are characterised further by the presence of extensive beachrock formations. The present study concerns the evolution (past, present and future) of the Kalyvia beach zone, located at the western coast of Attica and at a distance of 42 km from the city of Athens. The subaerial part of the beach zone consists of mixed materials (mainly sand, granules and gravel), while extensive beachrock formations exist on its shoreface. The beach is exposed primarily to southern wind-induced waves, the largest of which (offshore wave height up to 6m and period >11sec) begin to break at about 8 m of water depth and have a run-up capability of approximately 1.5 m. Most of the subaqueous part of the Kalyvia beach zone is lithified, as the beachrocks extend from the shoreline down to >8 m of water depth. This part of the beach zone may be subdivided further into three units: the deeper one (water depths >7m), the middle (depths 5-6.5 m) and the upper unit (from 4 m depth up to the shoreline). This almost continuous presence is related to the gradual sea level rise during the upper Holocene (past 6.000 years), indicating also a relative climatic stability and/or homogeneity during this period, although some morphological and structural differences in the beachrock indicate changes either in the rate of sea level rise or in the prevailing climatic conditions. Over the last decades, human activities and constructions have deprived the beach of hinterland sediment supply, changing, therefore, its sedimentological character. During this period, beachrocks have played a 'protective role' stabilizing and reducing substantially the retreat of the beach zone, which on the basis of the landward boundary displacement of the beachrocks has been estimated to be in the order of 30cm per year from 1969 to 2005. This retreat is attributed to the marine erosion of the sediment that used to cover the upper beachrock formations, in combination to the sea-level rise (approx. 18 cm over the past century) and the lack of sediment supply. Moreover, this degradation of the Kalyvia beach zone is expected to be intensified by the potential future sea level rise (approximately 38 cm for the year 2100).

KEY WORDS: South Attica (Greece), Coastal Geomorphology, Beachrock, Coastal erosion.

INTRODUCTION

The coastline of Attica is characterised by the presence of a large number of bays of various dimensions, separated by headlands, which inhibit exchange of sediment between them. Extensive beachrock formations are present in many beach zones formed in bays associated with alluvial plains, e.g. in Anavyssos, Kineta, Kalyvia Bay, Varkiza Bay and in many other sites, either in Greece (e.g. Leondaris, 1986; Plomaritis, 1999; Neumeier & *alii*, 2000; Anagnostou & *alii*, 2005; Fouache & *alii*, 2005; Belias, 2007; Vousdoukas & *alii*, 2007). or the rest of the world (e.g. Russel, 1959; Gewelt & Fierro, 1984; Cooper, 1991; Rey & *alii*, 2004).

Beachrocks are hard, rocky formations, originating from the cementation processes of the beach material (sand and gravel); the latter process is related to the precipitation of carbonates (calcite or aragonite) induced either by physicochemical or biological factors with the first to be associated often with the mixing of fresh and marine (saline) waters. Beachrock formations may occupy large parts of the surf zone and may even extend beyond the breaking point (Russell & McIntire, 1965), while their outcrops may act as barriers trapping the sediments involved in the longshore

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littoral drift, creating accumulation and erosion patterns, similar to those formed by hard coastal protection works (Cooper, 1991). The same author has further suggested that beachrocks may be characterised as long-term sediment sinks, the formation of which may result in significant coastline changes and claimed that beachrock presence may: (i) reduce (neutralise) the movable volume of littoral sediment through lithification; (ii) alter the longshore sediment supply and littoral circulation patterns in a manner similar to that expected by the construction of groins; and (iii) complicate further the diagnosis and prediction of beach morphodynamics under present and future climatic changes.

The aim of the present study is to examine the evolution of the Kalyvia beach, as a representative of the beach zones that have formed within small bays of the Attica coast and are characterized by the extensive presence of beachrock formations, in relation to the sea-level rise; the latter has been recognized as one of the main factors responsible for the general picture of retreating shorelines along the European (including the Mediterranean) coast (Eurosion, 2004). In respect to the time scale, this work covers the period from the middle-upper Holocene to present time and to the next century, during which a mean sea-level rise of 38 cm has been predicted by the IPCC (2007) report.

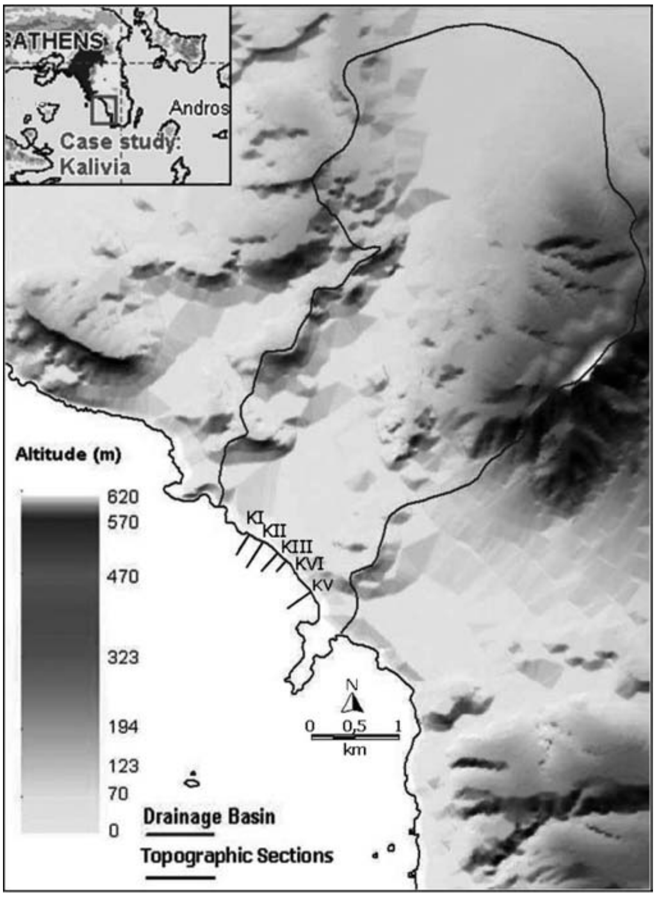

FIG. 1 - Morphology of the study area and locations of the 5 principal topographic cross-sections. In the upper left frame is the geographical location of the study area.

GEOGRAPHICAL SETTING

The Kalyvia beach is located in the homonymous bay, which belongs to the southwestern coast of Attica (fig. 1), at a distance of 40 km from Athens. It is 1.2 km long and 15 to 50 m wide, with an average width of 35 m. It is formed on the coastal side of a low-lying alluvial plain which is intersected by an ephemeral stream draining an area of approximately 19.15 km^2 and relatively low relief (maximum elevations <700 m) (fig. 1).

The coastal study area belongs geologically to the Attico-Cycladic metamorphic zone and in particular to the lower metamorphic «Attica unit» (Papanikolaou, 1986) which is intensely deformed with initial structures of NE-SW direction and sequential ones of NW-SE direction (Mariolakos, 1972; Mariolakos & Papanikolaou, 1973). It consists of a large mass of marbles, frequently dolomites, and of amphibolitic and mica schists, with thin intermediate marble horizons. Mafic-ultramafic metamorphic rocks are found inside the schists. In low-altitude areas one may find Holocene beach formations and torrential deposits, Quaternary old and new alluvial fans and talus fans.

The part of Attica region that belongs to the Attico-Cycladic massif could be regarded as a region of limited neotectonic activity (since early Pleistocene); this is supported by the Cyclades Plateau (the core of the Attico-Cycladic massif) which has been recognised as an aseismic region by McKenzie (1972), Morelli & *alii* (1975) and more recently by Papazachos (1990) and Hejl & *alii* (2002).

Therefore, the eustatic sea level change seems to play the principal role in the evolution of the Attica coast. According to the published sea level curves for the Mediterranean sea (Pirazzoli, 1991; Lambeck, 1995) the onset of glacial melting, shortly after the last glacial maximum (LGM), until its termination approximately 6000-6.500 years BP, shows that the sea level has risen rapidly (up to 15 mm/a), however, at variable rates. Subsequently, it has been rising continuously but at a rate lower than 1 mm/year, reaching its present level. The majority of the archaeological data (i.e. Negris, 1904) and recent eustatic models provided by Lambeck (1995, 2000) for the Aegean region, indicate that the sea level was 5-6 m and 1.5-2 m below its present level at 5.500-6.000 and 2.000 year BP, respectively. Furthermore, the IPCC report of 2007 has documented an average increase of sea level of 18 cm globally for the period 1890-1990, attributed primarily to the greenhouse effect and predicted a further rise of 38 cm for the year 2100.

DATA COLLECTION AND METHODOLOGY

Aerial photographs as well as a satellite image were used for the digitization per chronology of elements such as land use, human intervention in the region, coastline alterations and the geographic extent of the existing landforms.

The aerial photographs were orthorectified and imported to a GIS by georeferencing. The necessary coordinates and ground control points (GCPs) were derived from the topographic maps of the area and the trigonometric points of the region. The same process was applied to the satellite image.

Each aerial photograph was digitised in order to extract the corresponding coastline per chronology. A separate GIS layer was constructed for each chronology, in order to facilitate the study of the coastal zone changes, by comparison of the different layers. The landform changes are also shown on the information layers, while the layer which corresponds to the data from the satellite image shows their current extent.

The initial information concerning the land use and human intervention was taken from the topographic and cartograms of the area. Stereo-pairs of the aerial photographs were used for the stereoscopic observation of the area, which permitted the distinction and delineation of the different land use types, even in inaccessible areas, and the detailed assessment of human constructions. A different map was produced for each chronology, which, upon insertion into the GIS, gave new information layers. The above-mentioned data were enriched and supplemented by field observation. Special emphasis has been given to the mapping of the beachrock formations along the shoreline and underwater. Besides the geospatial depiction of the acquired elements, a rich database was created to host the necessary categorised information which would become the primary data for the following analyses. The geospatial depiction of the information layers was used to develop all the necessary thematic and cartographic material of this study.

Subaerial and subaqueous morphology and sedimentology have been studied along five topographic cross sections (fig. 1), along which 29 sediment and 10 beachrock samples have been collected. For the underwater part, the fieldwork was supported by the scuba diver group of the Hellenic Centre for Marine Research. A differential GPS was used for positioning.

The grain size analysis and classification of the collected sediment samples was carried out according to Folk's (1980) procedure and nomenclature.

The average and maximum possible wave conditions (height, period, wave run-up and depth of closure) that could affect the shore zone of the Kalyvia Bay have been estimated on the basis of predicted values of offshore significant wave height and period according to CERC (1984). The required wind data were taken from the Wind & Wave Atlas of the Northeastern Mediterranean Sea (Athanassoulis & Skarsoulis, 1992). The wave-run up and depth of closure estimates for the highest approaching waves are given by the equations (Komar, 1998):

Equation 1 $$h_c = 2{,}28\, H_s - \frac{H_s^2}{gT^2}$$

Equation 2 $$R = 0{,}36\sqrt{g}\, S\, \sqrt{H_s}\, T$$

where, H_S is the significant wave height, T the wave period, h_c the closure depth, R the wave run-up, S the beach slope (tan) and g the acceleration of gravity (9.81m s^{-2}).

RESULTS

The subaerial part of the Kalyvia beach zone has a mean width of 35 m (from the shoreline to the Athens-Sounion road). Its sediments consist mostly of sand and pebbles, while in places the anthropogenic interference is profound, i.e. a tennis court, a summer bar and three aqueducts that drain the low-lying hinterland area. Moreover, as shown in the old map of 1887 (fig. 2), the backshore of the Kalyvia beach zone hosted a line of discontinuous sand dunes, which are not present today. Most probably, this could be the result of the construction of the Athens-Sounion road in the early 1960s, partially on the sand dune field. On the NW end of the Kalyvia beach zone, one can find the mouth of an ephemeral stream whose bed has been stabilized with concrete. In addition, along the embankment of the Athens-Sounion road, there are three aqueducts that drain the landward low-lying area. In front of the shoreline towards the sea, there are beachrock benches with an emerged surface that reaches a width of 15 m. The submarine morphology of the area is generally very smooth with gentle slopes (2-3 degrees). On both ends of the beach (north and south) due to the presence of two islets at 100 m and 200 m from the shore respectively, a sedimentary shadow has been formed, which results to very shallow waters (<3.5 m). In contrast, the rest of the nearshore zone, especially towards the centre of the area, reaches depths of up to 10 m.

The results of the grain size analyses and their statistical elaborations are presented in table 1. In general, the subaerial sediments vary from sand to pebbly sand, having medium to poor sorting, especially those located at the upper part of the beach zone; this is attributed to the fact that the waves usually do not reach the upper part of the beach and to the various human interferences, which may artificially add material of different origin, size and sorting. The subaqueous samples, collected from 'sandy patches' in between beachrock formations are thinner (Mz: 0.2-2.8 φ, mainly >2φ) and better sorted (σ_I>0.5). The fact that the

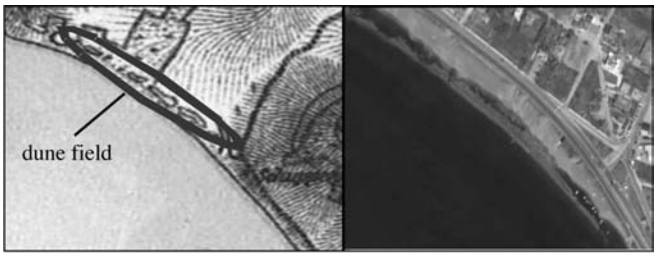

FIG. 2 - The dune field in the von Zieten 1887 map (left) and the beach zone including the Athens-Sounion road in the 2007 satellite image (right).

TABLE 1 - Results of the granulometric analysis of the sediment samples (Sediment sampling along the topographic sections KII, KIII and KIV)

Sample	Position of sampling	Mz (φ)	σ_i (φ)	sorting	Sediment texture
KII-1	Sea	2.70	0.57	Medium	S
KII-2	Sea	2.70	0.58	Medium	S
KII-3	Sea	2.30	0.67	Medium	S
KII-4	Sea	0.89	0.52	Medium	S
KII-5	Sea	0.64	0.60	Medium	S
KII-X1	Land	-1.50	0.63	Medium	S
KII-X2	Land	-2.72	0.93	Medium	gS
KII-X3	Land	-2.32	1.62	Poor	gS
KIII-1	Sea	2.30	0.74	Medium	S
KIII-2	Sea	2.28	0.51	Medium	S
KIII-3	Sea	2.31	0.56	Medium	S
KIII-4	Sea	0.41	1.15	Poor	S
KIII-5	Sea	0.19	0.86	Medium	S
KIII-X1	Land	1.2	0.72	Medium	S
KIII-X3	Land	1.94	0.47	Good	S
KIV X2	Land	-0.48	2.32	Very poor	gS
KIV X3	Land	0.28	1.10	Poor	S

subaqueous sand is better sorted than the subaerial one is attributed to the wave action. However, the subaqueous sand is not as well sorted as expected, because it has been trapped in cavities in front, beside and on the top of the beachrocks.

The incoming waves are induced by winds blowing from W, SW and S directions, with their characteristics dependent on the corresponding fetch lengths, as shown in table 2. On an annual basis, the most common waves are caused by winds with speeds <16 knots, blowing from W (10.06%), SW (7.29%) and S (6.02%) directions. The corresponding wave heights are between 1 m (W and SW) and 2.6 m (S). These most frequent waves break at water depths between 1.3 and 3.3 m, being able to move bottom sediments up to 6m of water depth (closure depth) and having a run-up capability from 0.2 to 0.6 m (tab. 3). The

TABLE 2 - Frequency (f), wave period (Tp) and significant height (Hs) of the incoming waves

Wind speed U (knot)	South (F = 248.5 km) f (%)	Tp (m)	Hs (s)	West (F = 38.5 km) f (%)	Tp (m)	Hs (s)	Southwest (F = 49.6 km) f (%)	Tp (m)	Hs (s)
1-3	0.67	0.77	0.02	0.85	0.79	0.02	0.8	0.79	0.02
4-6	1.68	2.47	0.19	2.12	2.47	0.19	1.63	2.47	0.19
7-10	2.04	4.74	0.69	3.21	3.61	0.57	2.26	3.93	0.65
11-16	1.63	8.07	2.57	3.88	4.36	1.01	2.6	4.74	1.15
17-21	1.10	9.27	3.91	2.09	5.01	1.54	1.60	5.44	1.75
22-27	0.44	10.27	5.35	1.19	5.55	2.10	0.86	6.04	2.39
28-33	0.25	12.00	6.00	0.52	6.06	2.75	0.33	6.59	3.13
34-40	0.08			0.13	6.56	3.49	0.07	7.13	3.97
>41	0.03			0.02	7.04	4.32	0.01	7.65	4.91

TABLE 3 - Closure (h_c) and breaking (d_b) depths and run-up (R) capability of the incoming waves

Wind speed U (knot)	South (F = 248.5 km) h_c (m)	d_b (m)	R (m)	West (F = 38.5 km) h_c (m)	d_b (m)	R (m)	Southwest (F = 49.6 km) h_c (m)	d_b (m)	R (m)
1-3	0.05	0.03	0.01	0.05	0.03	0.01	0.05	0.03	0.01
4-6	0.43	0.24	0.05	0.43	0.24	0.05	0.43	0.24	0.05
7-10	1.57	0.88	0.19	1.30	0.73	0.13	1.48	0.83	0.15
11-16	5.85	3.29	0.63	2.29	1.29	0.21	2.61	1.47	0.25
17-21	8.99	5.01	0.89	3.49	1.97	0.30	3.97	2.24	0.35
22-27	12.16	6.85	1.15	4.78	2.67	0.39	5.43	3.06	0.45
28-33	13.66	7.69	1.43	6.25	3.53	0.49	7.11	4.01	0.57
34-40				7.93	4.48	0.59	9.01	5.08	0.69
41-47				9.81	5.54	0.71	11.15	6.29	0.82

maximum expected wave conditions are induced by the S winds, reaching periods and heights of up to 12s and 6 m, respectively (tab. 2). These storm waves start to break at a water depth of 7.7 m and result in a closure depth of 13.7 m and a run-up of approximately 1.5 m (tab. 3).

The extensive beachrock formations are continuously present from the beach face down to 9 m of water depth covering the total length of the beach zone. Figures 3 and 4 reveal that the beachrock formations may be subdivided into three different units: the lower one (depth >7.5 m), the middle (from 5 to 6.5 m of water depth) and the upper and more recent unit from 4 m depth to the shoreline. All three units appear broken at places, with the upper one being the most stressed (fig. 5). In terms of their microstructure, examination under the electronic microscope has shown (fig. 6) that in the case of the upper (more recent) beachrock unit the micritic cement grows up to microcrystalline, yet it doesn't form well around the grains and in the pores. In the middle beachrock unit almost all grains are vested with cement, in the form of one or two layers (of cement generations). The first layer is the same as in the upper unit; the second layer is well developed, microcrystalline with the peaks of the crystals directed towards the pores. In the oldest beachrock unit the cement forms large-sized (50-60 μm), well-developed carbonate crystals (rhombohedra); these crystals could be the result of re-crystallization of pre-existent microcrystalline cement. This sedimentological variation of the cement material of the different beachrock units indicates some variations of the prevailing hydrological and possibly climatic conditions; these may be further related to changes in seawater temperature, different mixing between fresh groundwater and nearshore seawater and changes in the rates of sea-level rise.

A comparative analysis of the aerial photographs of 1969, 1988, 1996 and the satellite image of 2004, shows that the landward limit of the upper beachrock formation retreats (fig. 7) with rates that vary from 0.2 m/a (1969-1988) up to 0.4 m/a (1988-1998) (tab. 4). This indicates clearly that the beach zone of the Kalyvia Bay is under erosion, which is partially inhibited by the presence of beachrocks.

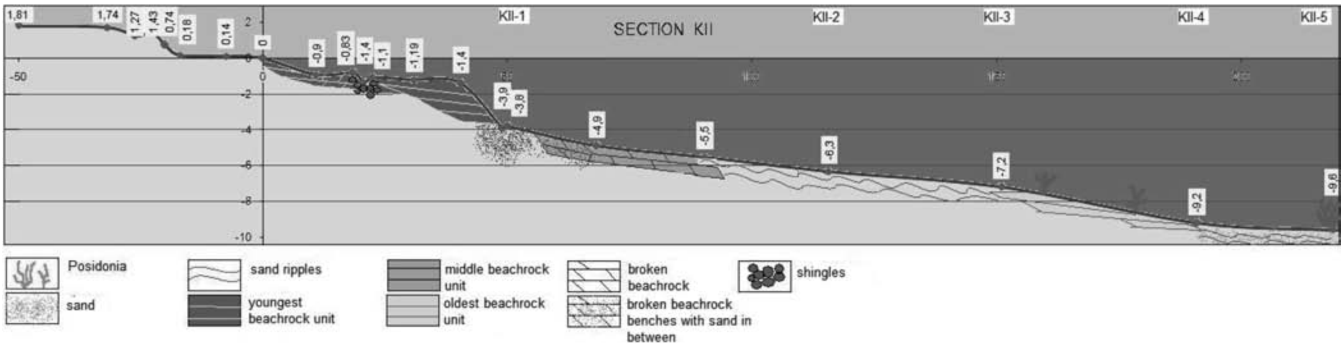

FIG. 3 - Topographic section KII and sediment sampling positions (KII-1, 2, 3, 4, 5) with schematic depiction of the sea bottom surface layer.

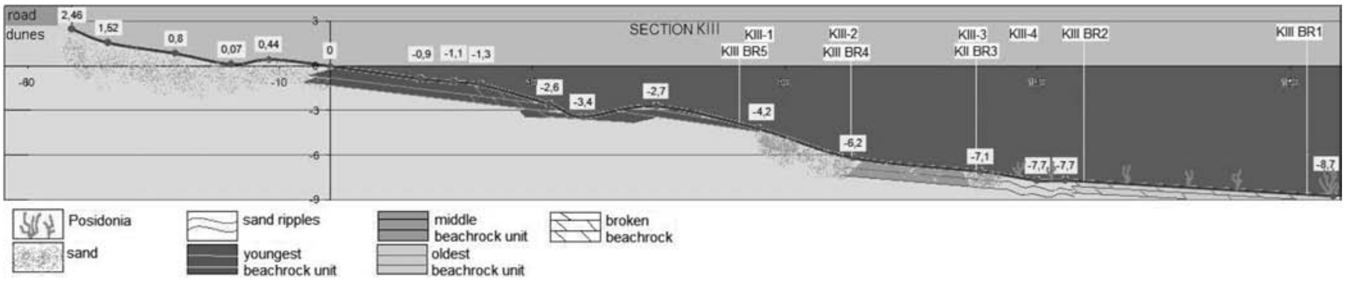

FIG. 4 - Topographic section KIII and sampling positions for sediment (KIII-1, 2, 3, 4, 5) and beachrocks (KIII BR1, 2, 3, 4, 5) with schematic depiction of the sea bottom surface layer.

TABLE 4 - Statistical data for the coastal retreat derived from beachrock mapping (measurements taken at the centre of the shore where the retreat is maximum)

Years	1969-1988 (19yrs)	1988-1998 (10yrs)	1998-2005 (7yrs)	1969-2005 (total 36 yrs)
Retreat (m)	4.1	4.7	2.7	11.5
Retreat ratio (m/yr)	0.2	0.5	0.4	0.3
Percentage over total retreat (%)	35.6	40.6	23.8	100.0

DISCUSSION

The subaerial part of Kalyvia beach zone consists of mixed material (mainly sand, granules and gravel), with extensive beachrock formations on its shoreface.

The beach zone is exposed primarily to southern wind-induced waves with the largest waves beginning to break at a water depth of 8 m and with a run-up capability of approximately 1.5 m.

The subaqueous part is characterized by the presence of beachrock formations, which may be further subdivided

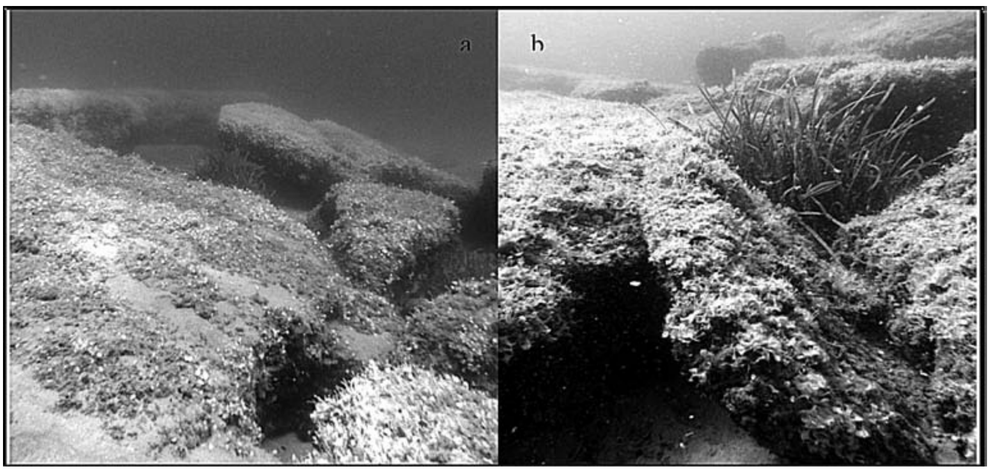

FIG. 5 - Broken beachrock at water depths of 2 m (a) and 1.5 m (b).

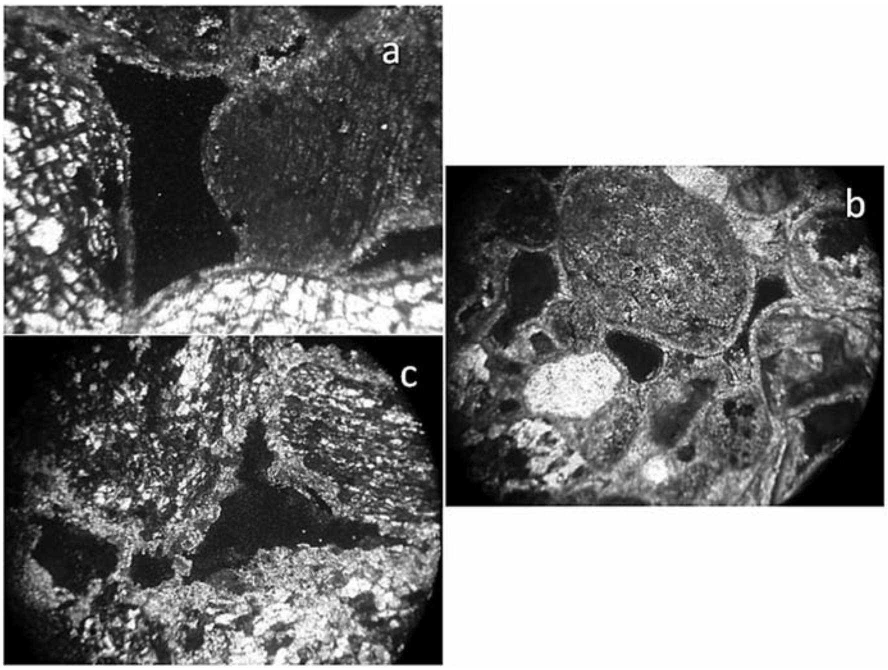

FIG. 6 - Electronic microscope photos of the microstructure of the different beachrock units of the Kalyvia beach zone: upper (a), middle (b) and lower (c).

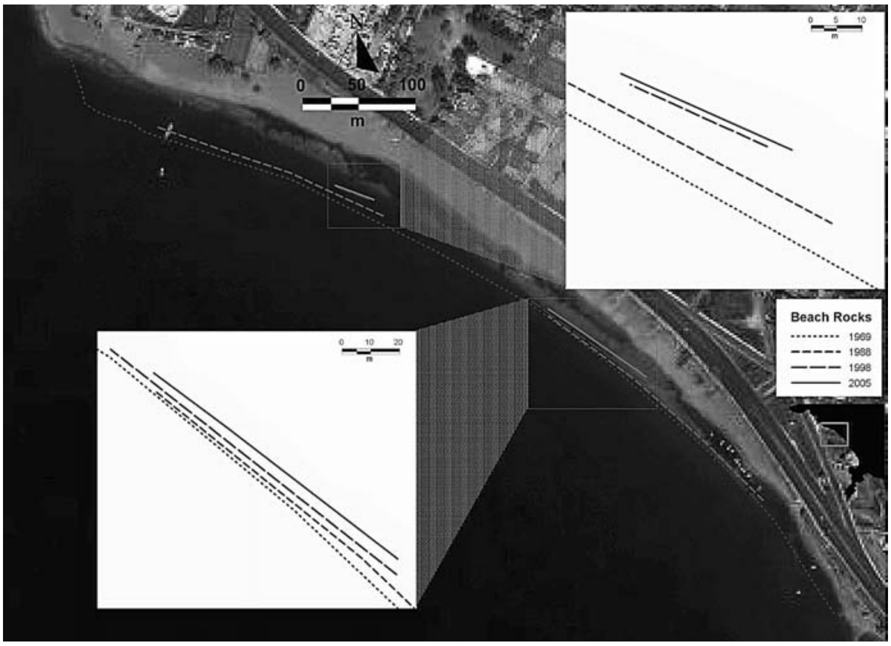

FIG. 7 - Map showing the retreat of the coast, derived from the mapping of the landward boundaries of the sequential beachrock formations, from 1969 to 2005.

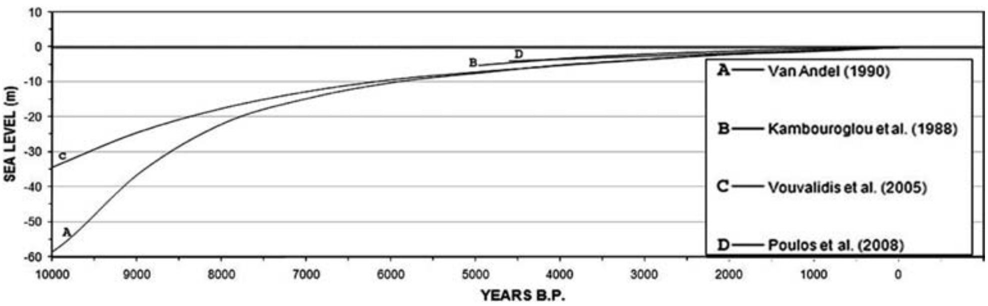

FIG. 8 - Curves of sea-level rise during the last (Holocene) transgression in the case of the Attiko-cycladic plateau (abstracted from Poulos & *alii*, 2008).

into three units: the deeper (water depths >7 m), the middle (depths 5-6.5 m) and the upper unit (from 4 m of depth to the shoreface).

This almost continuous presence is best related to the gradual sea level rise during the upper Holocene (past 6.000 years), indicating also a relative climatic stability and/or homogeneity during this period. However, some morphological changes and changes in the internal structure of the beachrock indicate differences in the rate of sea level rise and/or the prevailing climatic conditions. Moreover, their presence in the form of three units, shows that there might have been changes in the rate of sea-level rise induced by climatic variation, e.g. Little Ice Age (Grove, 1988) and possibly by some kind of neotectonic activity (Flemming, 1978; Pirazzoli & *alii*, 1982; Pirazzoli, 1986). Their present-day morphology is the result of the erosion induced by the wave activity.

The morphological map of 1887 (fig. 2) reveals that during the past centuries the Kalyvia beach zone was well-formed, while the prevailing environmental conditions favoured the formation of sand dunes, which can be seen on the aerial photograph of 1945 (fig. 9). The sediment budget must have been quite stable while coastal conditions continued to favour the formation of the upper unit of beachrock, with its sub-aerial part covered by the unconsolidated beach material (mostly sand); the latter conclusion is supported by the absence of beachrock in the map of 1887. Since the middle 1990s beachrock formations occupy the shoreface (fig. 9, 10); this is due to the combined result of the wave activity, which removes the unconsolidated beach cover, and the dramatic reduction of supply of terrestrial material. The latter is mainly induced by the human intervention, especially during the last 70 years, which altered the beach zone sediment budget through, for example, the construction of the Athens-Sounion road (1960s) along the dune line, the regulation of the natural drainage system of the nearby hinterland area and some other recent constructions, such as a tennis court.

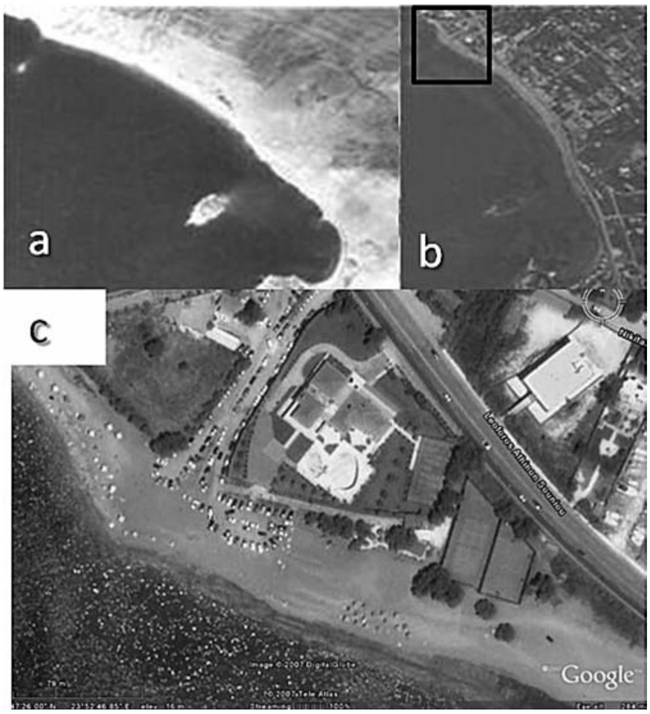

FIG. 9 - The Kalyvia beach zone as shown (a) in the aerial photo of 1945, (b) in the satellite image of 2005 and (c) the satellite image of 2007 (area within frame in 9b).

Nowadays, the beachrocks, despite restricting the sediment exchange between the backshore and the nearshore zone, contribute to the stabilization of the coastline by protecting it from the erosive wave action, since their resistance to erosion is significantly greater than that of the unconsolidated beach material. However, as has been shown above (fig. 7), their landward boundary is retreating, over the past 35-year period, by 30 cm per year, on average.

FIG. 10 - The Kalyvia beach zone as shown in the photograph taken in 2006.

This retreat is attributed to the marine erosion of the upper beachrock formations in combination with sea-level rise (approximately 18 cm over the past century, according to the latest IPCC 2007 report) and the aforementioned lack of terrigenous sediment supply. Moreover, this degradation of the Kalyvia beach zone is expected to be intensified in the future due to the predicted (potential) sea-level rise of some 38 cm (for the year 2100).

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