A morphological study of a reef with beachrock characteristics in association with the recent evolution of the Ammoudara beach zone (Heraklion, Crete).

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ABSTRACT

The morphological characteristics of a coastal reef that is observed along the Ammoudara beach (6 km to the west of the city of Heraklion, Crete) are investigated in relation to the sedimentology and modern evolution of the adjacent beach zone. The reef has a length close to 4 km, a mean width close to 35m and is located at a distance of 60 m from the shoreline at an average water depth of 2.6m, while the seaward water depth exceeds 3m. Its height above the seafloor exceeds 80 cm, reaching in places less than 0.5 m from the sea surface. It has two layers; the lower one which consists of fine grained (sandy) material and is approximately 40 cm thick and the upper layer, around 30 cm thick, consisting of relatively coarse-grained material (gravel and sand). Moreover, on the surface of the upper layer, runnels are observed, whilst distinguished cross bedding, similar to that observed in aeolian deposits, exists within the bottom layer. The reef is not present in front of the active mouths of the rivers Gazanos and Xiropotamos which debouch in the coastal area of Ammoudara. The western end of this submerged reef is attached to the beach face, exhibiting the characteristics of a typical beach-rock formation. On the basis of the above, it is concluded that the reef under investigation it is a submerged beach rock which indicates the position of a former coastline that is now submerged due to a relative sea level rise of approximately 0,5m.

Key words: Beach rock, Holocene, sea level rise, Ammoudara, Crete.

ΠΕΡΙΛΗΨΗ

Στη εργασία αυτή εξετάζονται τα μορφολογικά και ιζηματολογικά χαρακτηριστικά ενός παράκτιου ύφαλου, που παρατηρείται κατά μήκος της παραλίας της Αμμουδάρας (6 km δυτικά της πόλης του Ηρακλείου Κρήτης) σε σχέση με τη σύγχρονη εξέλιξη της παρακείμενης παραλιακής ζώνης. Ο ύφαλος έχει μήκος περίπου 4 km, μέσο πλάτος περίπου 35m και εντοπίζεται σε απόσταση 60 m από την ακτογραμμή και σε μέσο βάθος 2,6 m. Ο ύφαλος αναπτύσσεται 80 cm κάτω από την επιφάνεια της θάλασσας φτάνοντας κατά τόπους τα 0,5m. Ο ύφαλος αποτελείται από δύο στρώματα, ένα κατώτερο πάχους περίπου 40cm που συνίσταται από λεπτόκοκκο (αμμώδες) υλικό και το ανώτερο, πάχους περίπου 30cm, που αποτελείται από σχετικά χονδρόκοκκο υλικό (άμμος και χάλικες). Επιπλέον, στην επιφάνεια του ανώτερου στρώματος παρατηρούνται αυλακώσεις ενώ το κατώτερο στρώμα εμφανίζει σταυρωτή στρώση, παρόμοια με αυτή που παρατηρείται σε αιολικές αποθέσεις. Ο ύφαλος δεν αναπτύσσεται μπροστά στα στόμια των ποταμοχείμαρρων Γαζανός και Ξυροπόταμος οι οποίοι εκβάλλουν στην παραλία της Αμμουδάρας, ενώ το δυτικό άκρο του βυθισμένου υφάλου είναι σε επαφή με το μέτωπο της παραλίας, εμφανίζοντας έτσι χαρακτηριστικά τυπικού ακτόλιθου. Με βάση τα παραπάνω συμπεραίνεται ότι ο εξεταζόμενος ύφαλος έχει ένας βυθισμένος ακτόλιθος, υποδεικνύοντας έτσι τη θέση μιας παλαιότερης ακτογραμμής και τη σχετική ανύψωση της θαλάσσιας στάθμης

Λέξεις κλειδιά: Ακτόλιθος, Ολόκαινο, θαλάσσια στάθμη, Αμμουδάρα Κρήτη.

Τομέας Γεωγραφίας & Κλιματολογίας, Τμήμα Γεωλογίας & Γεωπεριβάλλοντος, Ε.Κ.Π.Α., Πανεπιστημιούπολη, Ζωγράφος, 15784

1. INTRODUCTION

Beachrocks are nearshore formations developed by the rapid cementation of the beach sediments by carbonate material in the intertidal zone (Bathusrt, 1971; Milliman, 1974). Even though beachrocks have been found mainly in tropical and subtropical areas (Russel, 1959), in recent years they have been observed to be formed, in temperate latitudes and non-tidal seas, such the northern coast of the Mediterranean Sea (Alexandersson, 1972). In Greece, beachrock formations have been reported in many areas and many papers describing them have been published (e.g. Roubanis 1971; Dermitzakis and Theodoropoulos, 1975; Leontaris, 1986). These formations vary from tiny patches of cemented sand to areas of hundreds of meters wide and up to a few kilometres long, with their thickness varying from less than 0.5m to more than 2m. The cementation process takes place between the high and low waters marks, although in some cases it may continue farther onshore under unconsolidated beach material (Russell and McIntire, 1965). Their surface presents erosional features such as cracks, runnels, potholes, etc. Beachrock formations have a 5°-15° gradient, whilst in many cases they follow the general dip of the beach (Moore, 1973; Badyukovar and Svitoch, 1989).

Nowadays, beachrocks have been used as relative sea-level indicators (e.g. Fouache et al., 2005), although dating them is difficult due to lack, usually, of sufficient material to allow radiocarbon dating.

The purpose of the present study is to examine the morphological and sedimentological characteristics of the Ammoudara beach zone and, in particular, of the reef that lies parallel to its shoreline and within its nearshore zone, in order to determine if this reef is a beach rock formation and, as such, an indicator of a former shoreline.

2. STUDY AREA

The beach zone of Ammoudara is located in the northern coast of Crete, being 2 km west of the city of Heraklion. The study area has a length of 6.1 km, an E-W direction and width up to 60m (Fig.1). On the landward side it is bordered by an area of active sand dunes with width more than 60m and low height (<3 m), which are stabilised from vegetation. Material is supplied to the sand dunes by the northern winds and is eroded by the high waves during storm events. The inland part of the dune field area includes a low-lying region formed by fluvial illuviation. Moreover, some parts of this region present elevations either very close to the sea level or even lower.

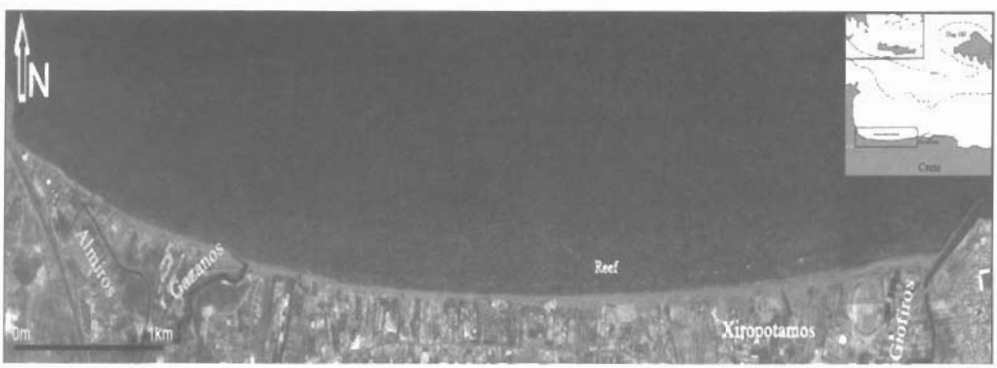

Figure 1. – Satellite image of the study area, showing the reef, rivers Gazanos, Xiropotamos and Giofiros and the carstic well of Almiros (Image source: Google Earth, 2003). The location of the study area is shown in the inset.

The area is exposed mainly to wind generated waves of N, NE and NW direction, with the NW wind to be the dominant one annually (annual frequency 28.89%), whilst on a monthly basis is the most frequent with the exception of the period November to January, when north waves are prevailing. The highest expected waves exceed the 6m in height and the 11 sec in period (Athanasoulis & Skarsoulis, 1992). These high waves are capable to mobile surface sediments (closure depth) up to water depths of more than 11 m (Ghionis et al., 2004).

The Ammoudara beach zone hosts the mouths of three small rivers (Fig. 1), the Gazanos, the Xiropotamos and the Giofiros with catchment areas of 192 km^2, 35 km^2 and 279 km^2 respectively. Freshwater measurements from the Hellenic Public Power Corporation have shown that the Gazanos and Giofiros rivers have a mean annual water discharge of 15.6×10^6 m^3 and 21.6×10^6 m^3, respectively. Moreover, the karstic source of Almiros exists in the region (Fig. 1) at an altitude of 4 m and at a distance of 1 km from the coastline. Its discharge is between 4 m^3/s (in the summer) and 70–80 m^3/s (in the winter), after periods of heavy rainfalls in the Psiloritis mountain (Maramathas and Boudouvis, 2005).

Furthermore, in the Ammoudara beach zone is located the main tourist activity of the city of Heraklion and that has resulted to the distraction of the dune field by the constriction of tourist facilities and parking spaces. Also to the edges of the beach zone there is the electricity power plant of the Heraklion city, to the west and to the east the exit of the biological waste treatment plant sewer exits in inside river Giofiros, whose exit has been directed towards east by a jetty.

One of the main characteristics of the Ammoudara beach zone is the rocky reef that lies parallel to the shoreline at a distance of about 80 m and has a width ranging from 15 m up to 20 m.

3. MATERIALS AND METHODS

For the geomorphological mapping of the study area, two topographic diagrams (1:5000) published by the Hellenic Army Geographical Service (H.A.G.S.) and a geological map of the area (scale 1:50,000), published in 1989 by the Institute of Geological and Mineral Exploration (I.G.M.E), were used.

The morphodynamic measurements included representative shore-normal profiles along the beach zone (see Fig. 2), which were extended from the sand dunes to the depth of 5m. Beach elevations and slopes were measured with the use of topographic rods and GPS, whilst depth soundings (at distances of every 5 m) were taken with the use of a portable bathymeter (Zodex echo-sounder) up to the water depth of 5 m. Furthermore, surficial sediment samples were collected along the profiles and analyzed according to Folk's (1974) procedure, the location of the sediment samples are showed in figures 4, 6 and 8. Finally, a series of underwater photographs have been taken with the use of an Olympus Camedia 740 digital camera. The beach profile locations, as well as the locations of the photographs are shown in Figure 2.

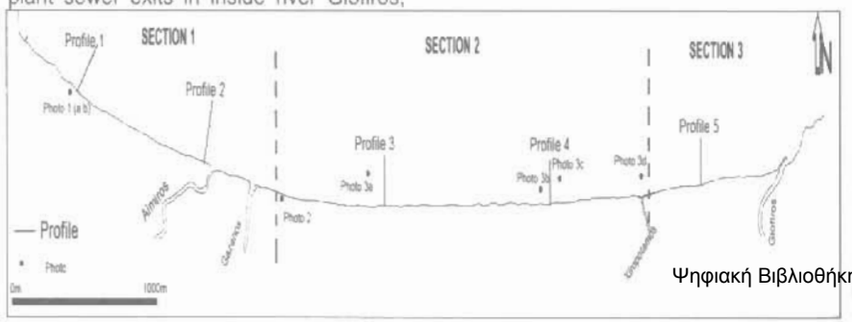

Figure 2. Locations of topographic profiles and underwater photographs.

4. RESULTS AND DISCUSSION

The landward limit of the beach zone of Ammoudara is the field of sand dunes, which are at distances from 30m to 60m from the coastline and have heights between 2.2m and 2.8m. Beach cusps were observed along the beach, with widths of 1m, lengths up to 1.5m and heights of 30cm; these were accompanied farther landwards by storm cusps with lengths ranging between 17m and 40m. The beach zone gradients vary between 1% and 20%, with the larger values corresponding to sand dune foreheads and to the beach face. A reef which lies 80 m offshore and parallel to its central and eastern part, having a total length close to 4 km, a mean width of about 35m and starts at an average water depths of 1.5m, whilst, at its seaward side, water depths exceed 3m. Its height above the seafloor exceeds 80 cm, reaching in places less than 0.5 m from the sea surface.

Based on the presence or absence of the nearshore reef, the orientation of the coastline and the overall morphological and sendimentological characteristics, the coastal zone of Ammoudara can be subdivided in three sections (Fig. 2): (i) The western section, 2500m in length, which begins at the west end of the beach and ends to the east of the mouth of R. Gazanos, including the mouth of Almiros; in this section the reef does not exist; (ii) The middle section, which begins 600m eastwards of the mouth of Gazanos, extends 2300 m in length and ends at the mouth of the River Xiropotamos; in this section the reef is present and parallel to the coastline; and (iii) The eastern section lying between the mouth of the River Xiropotamos and the mouth of the River Giofiros, which is the natural east end of the beach; this section has a length of 1100m and the reef is present in the nearshore zone.

Western section 1.

In the first section, the subaerial and the parts of the profiles had similar characteristics. The land department has width from 11 m , that is the minimum width for the entire beach zone, up to 40 m (profile 1). The sand dunes are located at an average distance of 25m from the coastline. The beach face gradient is between 4° and 6° (profiles 1 and 2). Close to the mouth of the River Almiros the gradient increasing to 8° - 10°.

Along the coastline, there is a typical beachrock formation (Fig. 3) with an exposed thickness of 40cm and a width of 4m to 25m. At the mouth area of the River Almiros, this formation does not exist, whilst its presence is terminated at the mouth area of the River Gazanos and it does not re-appear again. Its absence in front of the river mouths is explained by the high energy of the river flow that does not allow the formation of a beachrock. Seawards of the beachrock, the sea bed gradient changes to 6° up to the depth of 1.5m with the exception of Profile 2 (Fig. 4), where it remains constant to the depth of 3m, after which it changes to 4° to become almost level farther offshore.

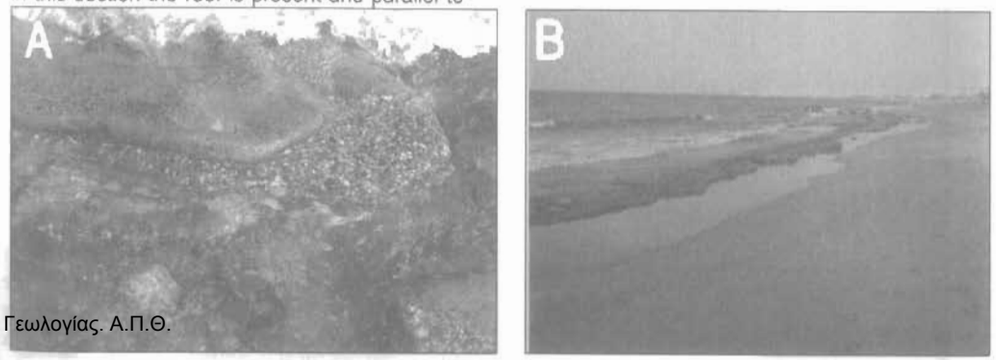

Figure 3 - Typical beach rock formation in the area of Profile 1 (A: close plan view; B: along the beach face of section 1)

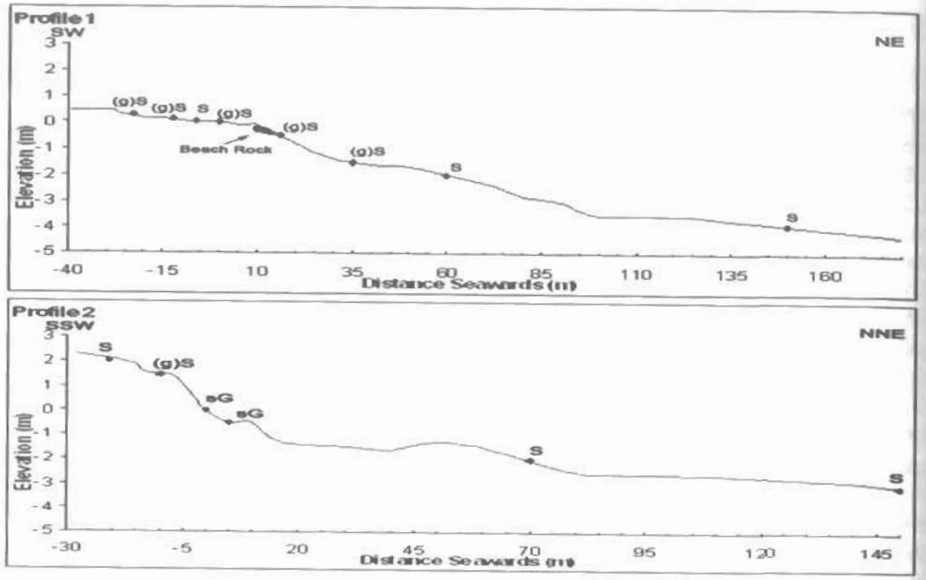

Figure 4- Beach zone elevations along profiles 1 and 2 (for locations see Fig. 2) and sediment classification (Folk, 1974) taken across each profile. [(g)S = slightly gravely Sand; S = Sand, sG = sandy Gravel].

Sendimentologicaly, this section is characterized as slightly gravely sand ((g)S), while there are areas with coarser material. An exception to this is the mouths of Almiros and Gazanos Rivers, where, at their western banks the sediment is characterized as gravely, sand (gS) and at their eastern banks as sandy gravel (sG). This is because during the sampling period the longshore current orientated the torrents exits westwards, leaving the coarse-grained material in the eastern bank. To the beach face the material is characterized as slightly gravely sand ((g)S) and afterwards the forehead as sand (S). The seabed is characterised as slightly gravely sand ((g)S) in the first meters from shore and as sand (S) up to the depth of 5m.

Middle Section 2

The shoreline of the middle section presents an horizontal offset towards the land of about 40 m, with respect to the shoreline of section 1 (Fig. 5). Moreover, the reef starts to be present at distances of 40-50 m from the shoreline of section 2.

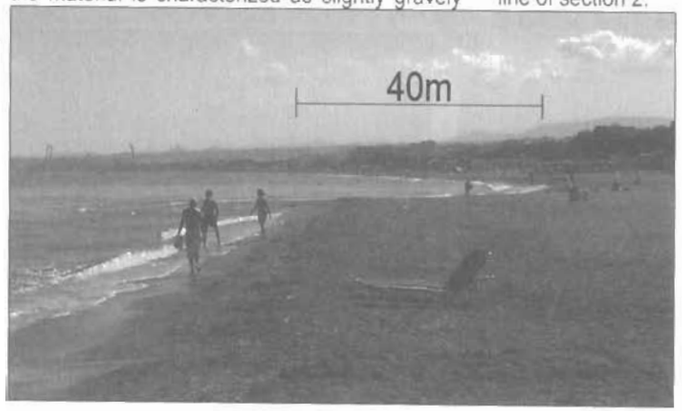

Figure 5. Photograph showing the shoreline offset (retreat) at the commencement of section 2.

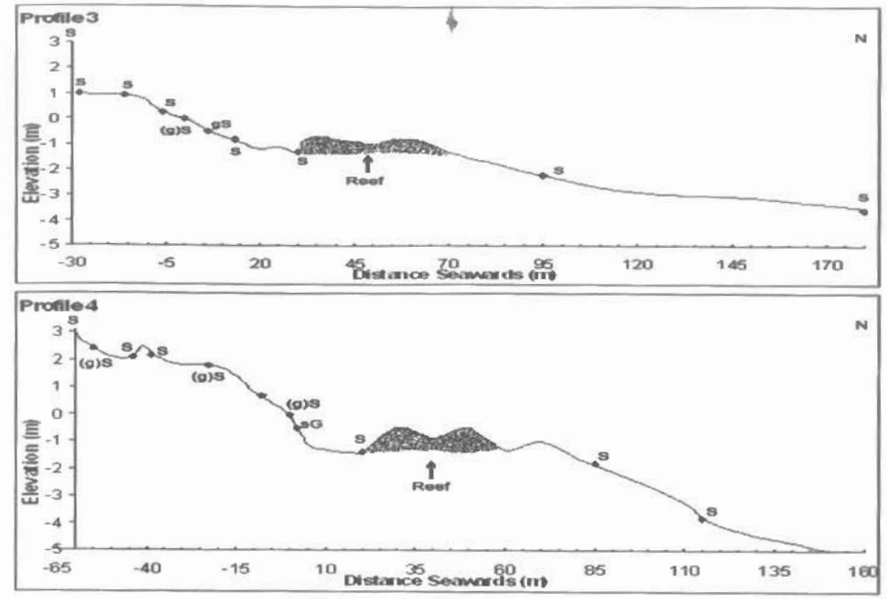

Figure 6 – Beach zone elevations along profiles 3 and 4 (for locations see Fig. 2) and sediment classification (Folk, 1974) taken across each profile. [(g)S = slightly gravely Sand; S = Sand; sG = sandy Gravel].

The subaerial part of the beach zone in section 2 has gradients close to 6°. The sand dunes are at an average distance of 50m from the coastline and have an average height of 2m. The beach face has gradients that vary from 2° (Profile 3) up to 8° (Profile 4) (Fig. 6).

The seafloor sediments are characterized as sand (S) and the beach face material as slightly gravely sand (g)S. Exception to this is the area at the river Xiropotamos mouth, where the beach face material is characterized as sandy cobble gravel (sG).

To the East of the Gazanos river mouth, the reef appears at an average distance of 30m from the coastline. It is parallel to the shore and disappears at the River Xiropotamos mouth area, where, for a distance of about 200m, it is replaced by pebbles and gravels with some small rocks (Fig. 7D), which are of the same material as the reef. The seaward limit of the reef creates a step 80cm high (Fig. 7B). Seawards of the reef, the seafloor presents a smooth relief. The surface of the reef is planar, dipping seawards by 3°-4° (Fig. 7B). Its width is from 15m up to 50m and it is located on average 0.7m below the sea surface (minimum depth 0.5m). Furthermore, its surface is characterised by a large number of runnels, potholes and grooves (Fig. 7C), whilst its lower part is cross-bedded (Fig. 7A), resembling the cross bedding of coastal aeolian formations. The grooves are similar to the ones formed in typical beachrock formations by the retrograde movement of water on them in the beach face.

Eastern section 3.

The subaerial part of the beach zone in section 3 has an average width of 40m (maximum width: 74m) and a topographic slope of 5°-6°. On the beach face the gradient increases to 6°-8°, and then remains constant (4°-5°) up to the reef (Fig. 8). The latter appears 100 m to the east of the mouth of the River Xiropotamos and continues up to the eastern end of the Ammoudara beach, at the artificial regulated mouth of the River Giofiros. The reef lies parallel to the shoreline at a distance of 35 m and at a water depth of 1.4 m. Its surface is almost level, being in places as little as 0.3m below the sea surface. At its east end the reef presents large cracks, whilst the bathymetry at its seaward side is characterised by a 1-1.5m step (Fig. 8); these

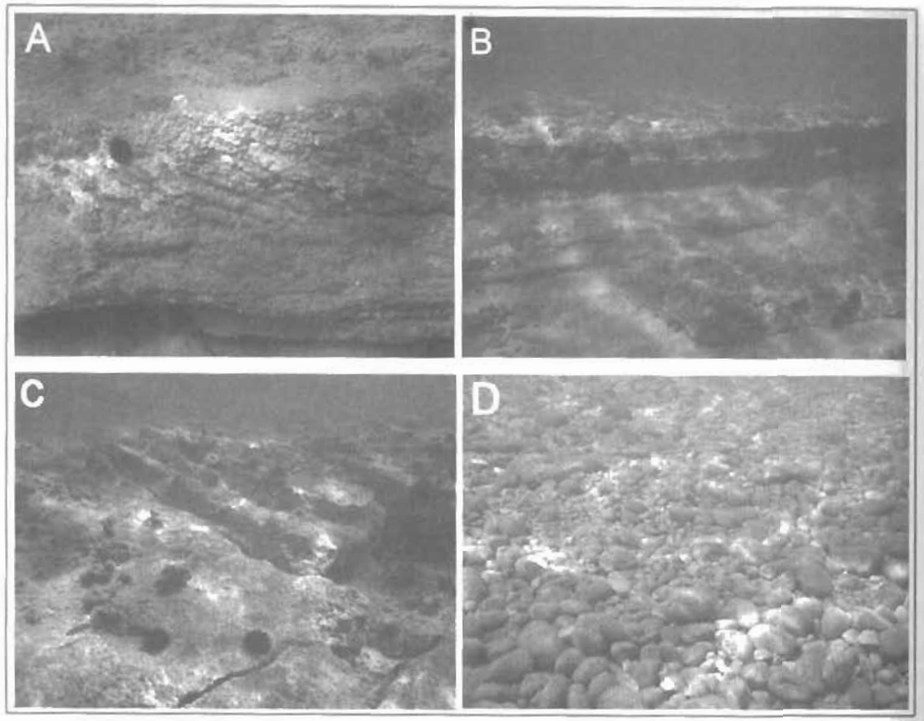

Figure 7.- Underwater photographs from section 2 (for location see fig. 2). (A): Cross bedding in the lower layer of the reef; (B): The upper and lower layers of the reef; (C): Runnels in the surface of the reef; and (D): Seabed at the River Xiropotamos mouth area, consisting of pebbles and cobbles.

may be attributed to the concentration of wave energy caused by the combined presence of the reef and the breakwater at the river's mouth, which increase the erosive potential of the on-offshore currents.

In this section, the beach zone is characterised by sandy (S) material at its subaerial part and between the fore zone and the reef, whilst the shore face consists of relatively coarser material ((g)S-sG-G). Seawards of the reef, the seabed is characterised also by coarser material, i.e. sandy cobble gravel (sG) and gravel (G); this is attributed to the strong offshore currents that are capable of removing most of the fine-grained material.

The overall morphological and sendimentological characteristics of the reef are very similar to those of the present beachrock formations in the western part of the Ammoudara beach. The evidences of the formation of the reef along a former shoreline as a beach rock are the following: (i) its position parallel to the present shoreline; (ii) its morphological characteristics such as its width, thickness, upper surface slope and morphology (e.g. runnels); (iii) its absence in front of the river mouth areas; (iv) the material of its upper layer, which is similar to the modern beach zone material (v) the cross-bedding of its lower part, which is analogous to aeolian coastal formations; (vi) the presence of freshwater inputs along the beach zone available for mixing with seawater (e.g. carstic source of Almiros); and (vii) its western prolongation which coincides with the modern beachrock formations found on the current beach face.

Conceptual model

On the basis of the above, it is rather likely that the reef which is presently submerged at the central and eastern part of the Ammoudara beach zone, lying parallel to the shoreline, is beachrock which was initially formed along a

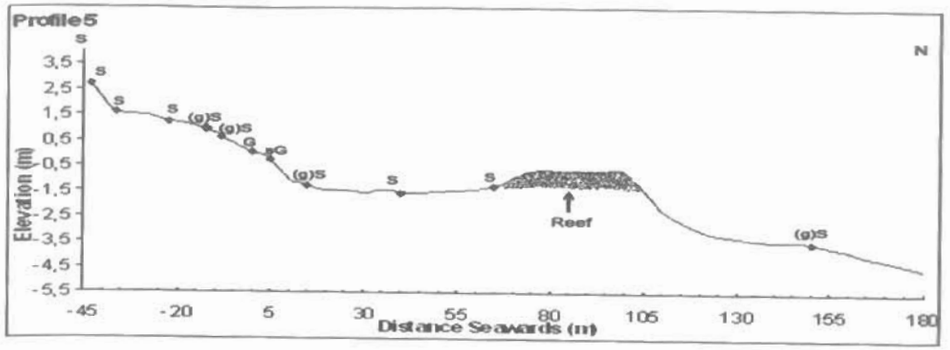

Figure 8 - Beach zone elevations along profile 5 (for location see Fig. 2) and sediment classification (Folk, 1974) taken across the profile.

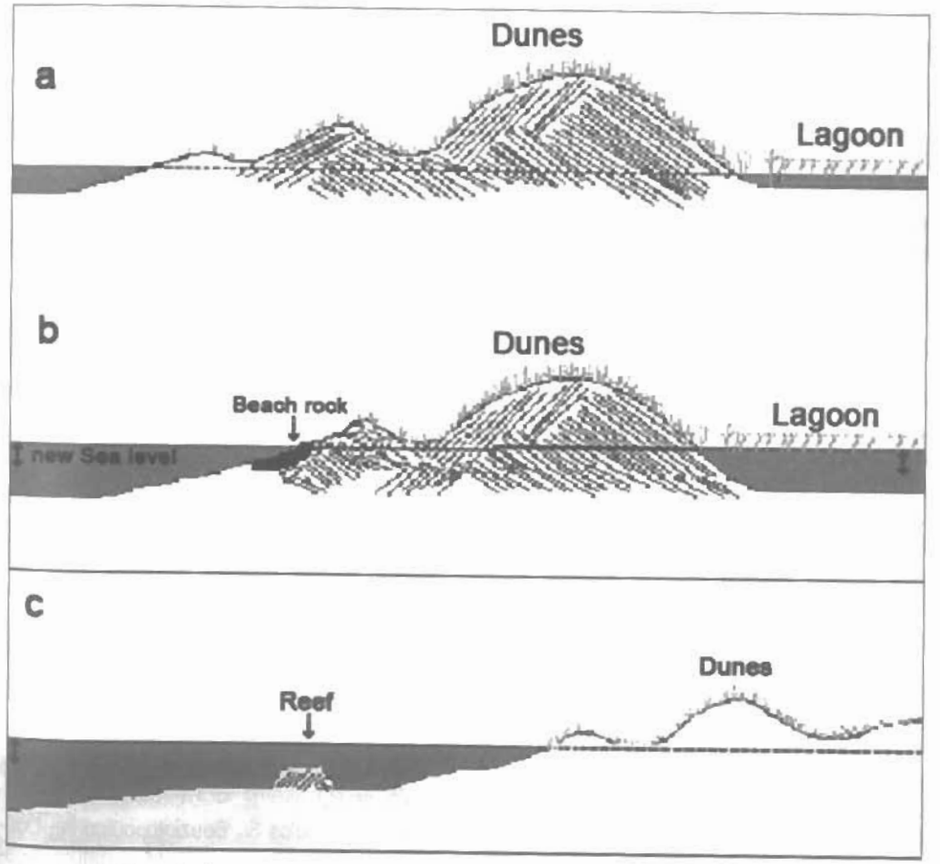

Figure 9 - Conceptual model for the formation of the submerged beachrock formation.

former beach face. Hence, it is an indicator, if not a proof, that the shoreline has retreated approximately 60m, that is observed today, is most probably associated with a relative sea level rise. A conceptual model for the formation of the submerged beach rock is presented schematically in figure 9.

According to Figure 9, initially there were more than one line of sand dunes, with the older ones being to be quite stable and hosting a lagoonal area behind them, formed by the mixing of freshwater inputs and seawater (Fig. 9a). As the sea level rose, either from tectonic activity or due to eustatism, the younger dunes were eroded and the previously formed aeolian and stable deposits were brought to the surface, where they were covered by the formation of beachrock due to the increased mixing of fresh and sea water (Fig. 9b). Subsequently, as the sea level reached its present stage (Fig. 9c), the wave activity reached higher levels on the beach, removed sediments from the beach face and eventually the beach rock was separated from the beach, submerged and formed the present-day reef. The increased wave setup, induced by the reef, gives rise to longshore currents and a longshore sediment transport that maintains the "trough" between the reef and the shoreline. At the western part of Ammoudara, which is protected from the strong winds and high waves of NW origin, the removal of sediment was less intense, the beach rock did not become detached from the beach and it continued to form at the present shoreline.

5. CONCLUSIONS

The shore-parallel reef in the Ammoudara nearshore zone is a submerged beachrock that was formed during the upper Holocene. Its current position, about 0.5m below sea level, indicates a relative sea level rise of more than 0.5 m; the latter has caused a coastline retreat of approximately 60m. At present, the beach zone of Ammoudara seems to be stable and in morphodynamic equilibrium with the nearshore hydrodynamic conditions. The reef acts as a natural submerged breakwater that protects the shore from erosion by reducing the incoming wave energy and inducing intense wave breaking farther from the shoreline.

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