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EVALUATION OF SEA-LEVEL RISE IMPACT ON CEMENTED AND UNCEMENTED BEACH. CASE STUDY FROM THASSOS ISLAND, GREECE

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Abstract: A semi-buried underwater beachrock exposure, in the west coast of Thassos Island (N. Greece), has been investigated due to coastal erosion phenomena. The partial removal of the beachrock's outcrop by locals incurred rapid regression of the beach, while the protected by the formation coast, remained stable during the same time interval. The use of the Bruun Rule as a contributor in the quantification of the marine transgression in the study area showed a participation of the sea level rise to the beach erosion equal to 7% of the total erosion at minimum. Several other factors which are related to the unique dynamic conditions at the eroded coastline, might have contributed to augmented erosion values.

Keywords: beachrock, coastline, sea-level, Thassos, Greece.

1. Introduction

Beachrocks are rocky sedimentary formations consisting of carbonate-cemented coastal material (clastic, skeletic, anthropogenic), consolidated in the intertidal or supratidal zone (Chivas et al., 1986; Gischler, 1994; Milliman, 1974). The main sources of the carbonate precipitations are interstitial sea water and meteoric water (e.g. Ginsburg, 1953; Kelletat, 2006; Milliman, 1974; Schmalz, 1971; Hanor, 1978) as well as biological activity (Neumeier, 1999), following several different physicochemical processes. Several impacts on coastal evolution result from the presence of beachrocks. These include the reduction of littoral sediment volume, the change in coastal morphology and the change in preservation potential of shoreline facies (Cooper, 1991). On retreating coasts, outcrops of beachrock may be evident offshore where they may act as a barrier against coastal erosion. Beachrock presence can also induce sediment deficiency in a beach and out-synch its wave regime (Cooper, 1991; Rey et al., 2004). A further important issue which is related to the formation of beachrocks has to do with the coastal management and the outcrops' impact on tourist industry (Vousdoukas et al., 2009a). Although beachrock can prevent extended beach erosion and recession, its exposure causes several socioeconomic impacts, as a result of the alteration of a beach from sandy to rocky. The recorded sea-level rise of recent years may cause further exposure of buried beachrock outcrops in tectonic stable regions like the study area (Cooper, 1991; Kindler and Bain, 1993; Chowdhury et al., 1997; Alexandrakis et al., 2006), which in turn could lead to a decline of many coastal areas.

The global rise of sea level during the Holocene (Pirazolli, 1991) and during the historical period have prompted studies of the short-term response of shorelines to changes in sea water level (Hands, 1979, 1980, 1983; Brambati et al., 1998; Ciavola and Corbau, 2002), geomorphological analysis of shoreline behaviour during transgression (Rosen, 1978; Carter and Orford, 1993; List et al., 1994, 1997) and investigations of transgressive coastal stratigraphic sequences (Kraft, 1978; Thom, 1983; Cowell et al., 1995; Cattaneo and Steel, 2003). Recent studies in the Mediterranean area show a varied mean annual sea level change, whose spatial distribution is not uniform. From 1990 and afterwards, most gauging stations in Mediterranean sea have showed an extremely high sea-level rise of 5 to 10 times the average 20th century rise, and notably higher than the global average measured by Topex/Poseidon for the same years (Klein and Lichter, 2009).

Recent studies have introduced that beachrock-occupied beaches are characterized by particular and distinctive morphodynamics (e.g. Vousdoukas et al., 2009b). This study aims to examine the behaviour of the coastline at a particular beach, where the abrupt change of its character after the beachrock removal incurred a rapid response of the littoral equilibrium.

2. Setting of the area

The case study presented in this work was conducted in Thassos Island (N. Greece), which is located in Northern Aegean Sea. The study area is located at the west coast of the island, between Skala Sotira and Skala Kallirachis villages (Fig. 1). The beach is 375 m long and reaches width of 25 m (Psomiadis et al., 2009a). Coastal sediments are fine to medium well graded sand with some gravels on the south side where a stream is discharging.

The prevalent rocks in the area are gneiss and marbles. The basins that end up to the study area include Holocene sediments, Miocene marbles, marbles and gneiss alternations and Maries gneiss (Mountrakis, 1985). Two local ephemeral streams end up to the study beach, with a total length of 26.48 km, which cross carbonate rocks and transfer similar sediments to the coast.

The area of Thassos is characterized by coastal – marine climatic type, transitional to continental climate (high summer temperature, storms), due to the slight distance of the island from the coast of Macedonia at the north. The average annual temperature is 15.8^{o}C, the average annual precipitation is 770 mm and the prevalent wind direction is NW for the western part of the island (study area) (Weingartner, 1994). Fetch length to that direction reaches up to 26 km (F_1), whereas the longest fetch is to the west, reaching 65 km (F_2).

The exposed beachrock is located in the swash zone and dips gently seawards (mean 5^{o}), following the arrangement of the beach. The main body of the formation has a total length of 305 m and

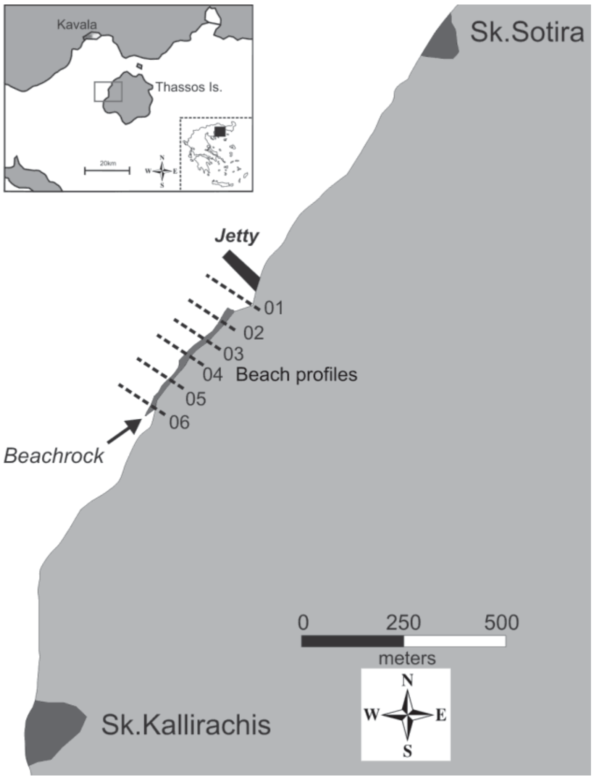

Fig. 1. Location of the study site, showing the studied beachrock as well as the position of the morphological beach profiles (dashed lines).

exposure width 2-10 m. The height of the beachrock at its underwater face (Fig. 2) reaches up to 70 cm. This face is quite steep and has been undercut in many places, resulting in cracking, collapsing, even in displacement of blocks of the formation. Core drilling across the formation and ultrasonic velocities recorded that deeper layers are less porous than surficial, indicating older age at the bottom (Psomiadis, 2005; Psomiadis et al., 2009b). At the NNE side of the beach, a part of the beachrock was broken and removed by local citizens in 1994. This act had an immediate impact on the coastal equilibrium. Beach sand in the specific part of the coast retreated rapidly, while the rest of the coast remained in equilibrium state, behind the protection of the beachrock body. At the north end, a jetty separates the study beach from the prolongation of the coastline at the north (Fig. 2).

3. Techniques and Methods

In order to quantify the expected shoreline retreat during the last 15 years, the 50-year-old Bruun Rule (so named by Schwartz, 1967) was used (Bruun, 1954; 1962; 1988). The Bruun Rule is extensively used as a tool for shoreline retreat estimation as response to rising sea level. However, it

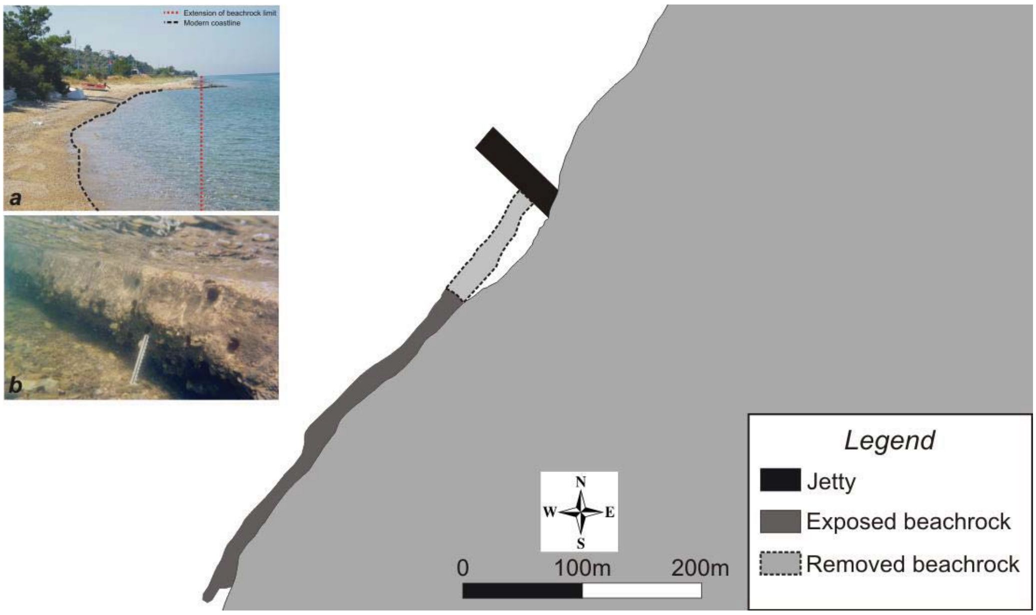

Fig. 2. Position of the removed beachrock in relation to the exposed formation and the jetty. a) coastal erosion due to beachrock removal, photograph taken stepping on the jetty, b) height of the beachrock. Scale equal to 30cm.

has been critically reviewed basically for three main groups of reasons: 1) the assumptions behind it are so restrictive that they probably do not exist in nature, 2) it omits many important variables and 3) it relies on outdated and erroneous relationships (Cooper and Pilkey, 2004). In this study, the Bruun Rule was used just as a contributor in the quantification of the transgression in the study area, without attempts for modeling or predictions. It also aided to estimate the effect that the sea level rise alone would have on the beach in the case that no erosional processes were active and enough time allowed for the beach to reach a new equilibrium. So, in a typical equilibrium nearshore profile, L is the length of the profile, B is the berm height and H is the depth at the base of the profile beyond which significant sediment exchange with the offshore does not occur (depth of closure). For a sea level rise of the amount of S, the profile will shift landward by the amount R according to the Bruun Rule equation (Bruun, 1988):

$$R = S \cdot [L/(B+H)] \quad (1)$$

The depth of closure is estimated by the equation (Coastal Engineering Manual 2002):

$$H = 6.75\ H_s \quad (2)$$

where H_s is the mean annual significant wave height, given by the relationship (Coastal Engineering Manual 2002):

$$H_s = 5.112 \cdot 10^{-4} \cdot W \cdot F^{0.5} \quad (3)$$

$$W = 0.71 \cdot U^{1.23} \quad (4)$$

$$U = U_z \cdot (10/z)^{1/7} \quad (5)$$

where W is the wind stress factor, U is the wind speed at 10 m above sea surface, F is the fetch length and U_z is the wind speed at height z above sea surface. Wind speeds and corresponding annual frequencies of occurrence of the winds as weights (recorded by the meteorological station of Limenas, Thassos Island, 15km NE from study area) were used to calculate the wave heights and mean annual wave heights for NW and W wind direction (in accordance to fetch directions, F_1 and F_2).

The sea bottom was surveyed to obtain the detailed bathymetry of the area, in the zone in front of the study beach. The survey covered a total area of 1300m x 300m, reaching maximum depth of 16 m, using a NAVMAN D22100 Sonar device attached via a NMA183 interface on a Garmin GPS plotter, with EGNOS corrections, where x,y,z data were stored. The survey was performed along transects perpendicular to the coastline by a small inflatable speedboat. The total x,y,z data reached 1704 measurements, covering in detail the surveyed area. Geographic Information System (GIS) software was used to reproduce 2D contouring and a 3D Digital Elevation Model (DEM), which in turn provided all necessary data (Fig. 3).

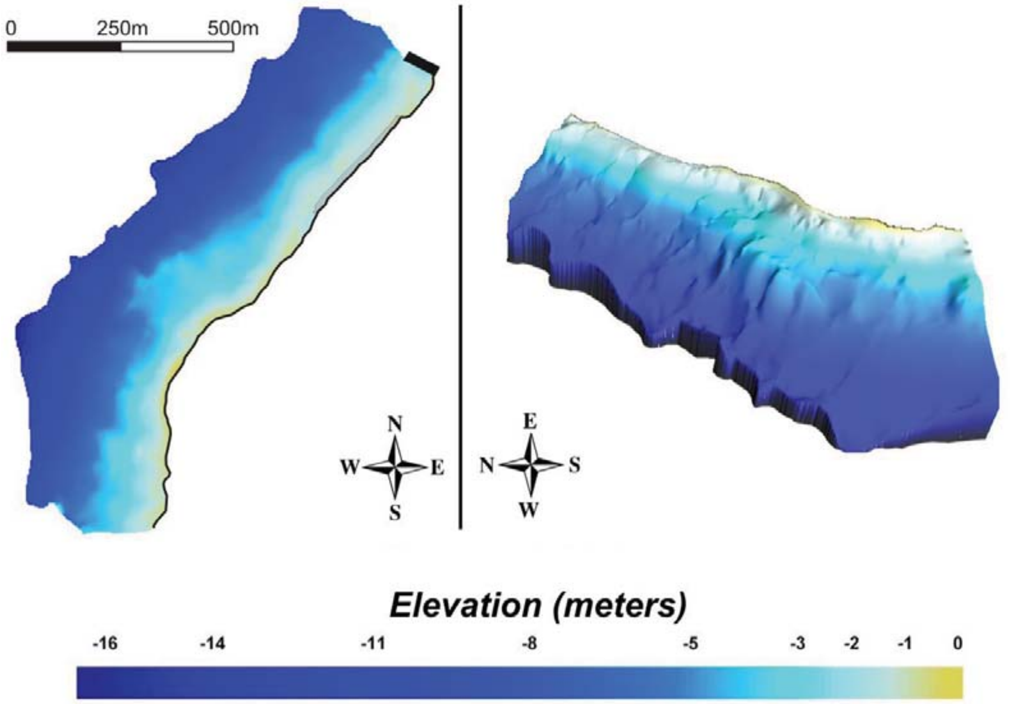

Fig. 3. 2D and 3D Digital Elevation Models (DEM) of the wider study area, used for the calculation of the profile lengths (L_1 and L_2, Tab. 1).

Coastal profiles were constructed in order to estimate the mean berm height along the beach (Fig. 4). The profiles were done according to the proposed method by Komar (1998).

Sea level data from recent statistical analyses (Klein and Lichter, 2009) for the last 15 years were used. The mean annual sea level rise for the N. Aegean Sea is calculated by the data from Klein and Lichter (2009) as the relative weighted mean annual sea level rise for the two reliable (regarding their standard deviation) stations (Thessaloniki and Alexandroupoli), equal to 6.8 mm/yr.

4. Results and Discussion

By the equations (3), (4) and (5), two values of mean annual significant wave height H_s were calculated, using the two different fetch lengths (F_1=26 km and F_2=65 km) (Tab. 1), while equation (2) provided the respective values of closure depth (H_1, H_2). Based on the DEM of the sea bottom (Fig. 3), the length L takes two values, respective of the estimated closure depths (Tab. 1). Berm height (B) was calculated as the mean berm height recorded on the beach profiles (Fig. 4), equal to 75 cm above mean sea level (amsl). The Bruun Rule equation (1) gives two estimations for the annual shoreline retreat, which do not differ much from each other (R_1 = 3.3 cm/yr and R_2 = 4.2 cm/yr, Tab. 1).

Beachrock initially enhanced erosion (sediment loss) but after its subaerial expose it has protected the study beach for several years, providing a natural breakwater along the shoreline. However, the removal of an outcrop's block, approximately 110 m long, had an immediate regressive impact on the shoreline. The total retreat during the 15-year wave erosional action on the beach was 9.3 m, estimated as the vertical distance from the beachrock face seawards to the modern shoreline at the "naked" part of the beach. The latter estimation stands for the speculation that the beach was limited at the beachrock front at the time the erosion started. This is confirmed by the fact that beachrock is formed in the intertidal zone of the beach (e.g. Al-

Table 1. Morphodynamic calculations based on data and equations 1-5

	F (m)	U_z (m)	U (m)	W (m)	H_s (m)	H (m)	L (m)	B (m)	S (m)	R (m)	R_t (t=15yr)
1 (NW)	26000	1,56	1,96	1,63	0,13	0,90	8,00	0,75	0,0068	0,033	0,495
2 (W)	65000	1,47	1,85	1,51	0,20	1,33	13,00	0,75	0,0068	0,042	0,630
									Actual retreat	0,62	9,30

exandersson, 1972; Hanor, 1978; Stoddart and Cann, 1965) and it stands there after its exposure. Just a few small blocks of the formation were cracked and collapsed on the sea bottom at the front, without altering the frontline of the formation (Psomiadis et al., 2009a). By a simple calculation, the mean annual retreat rate of the shoreline during the last 15 years of exposure to wave action is 62 cm/yr. This value is much higher than the estimation in this study [4.2 cm/yr maximum (R_2), Tab. 1]. Significant causes for this discordance may be the stress for dynamic equilibrium at the new conditions after the abrupt removal of the beachrock, the unique wave regime in such a small part of a sandy shoreline with rigid sides as well as the presence of the jetty at the north end of the beach. The above factors are closely associated to the sediment budget instability caused by natural (littoral zone characteristics) or man-made (constructions) parameters, which finally induced the shoreline retreat. It should also be taken into account the comparison of the natural processes relatively to the hypothetical case that no erosion affected the beach for a time period long enough to allow it reach a new equilibrium. Apart from all these factors which may change the dynamic equilibrium, other minor parameters that are not included in the Bruun Rule may also have affected the underestimated value of shoreline retreat in comparison to the actual one. However, sea level rise should be considered to have caused at least 7% of the total shoreline retreat at the study area. The protected by the beachrock part of the beach is also affected by sea level rise, as its previously sandy nature has been altered to rocky due to beachrock exposure after sediments swept away, whereas storm events will eventually have serious impact on sediments at the backshore.

Regarding the evolution of the coast, the first phase took place when sea level was lower than today (Fig. 5), the coast was at dynamic equilibrium and the conditions in the intertidal zone were suitable for carbonate precipitation and sediment consolidation (beachrock formation). As sea level was rising, budget equilibrium was disturbed and the shoreline began to retreat. Beachrock formation was not interrupted in the intertidal zone, probably in a slightly higher level. As coastal erosion con-

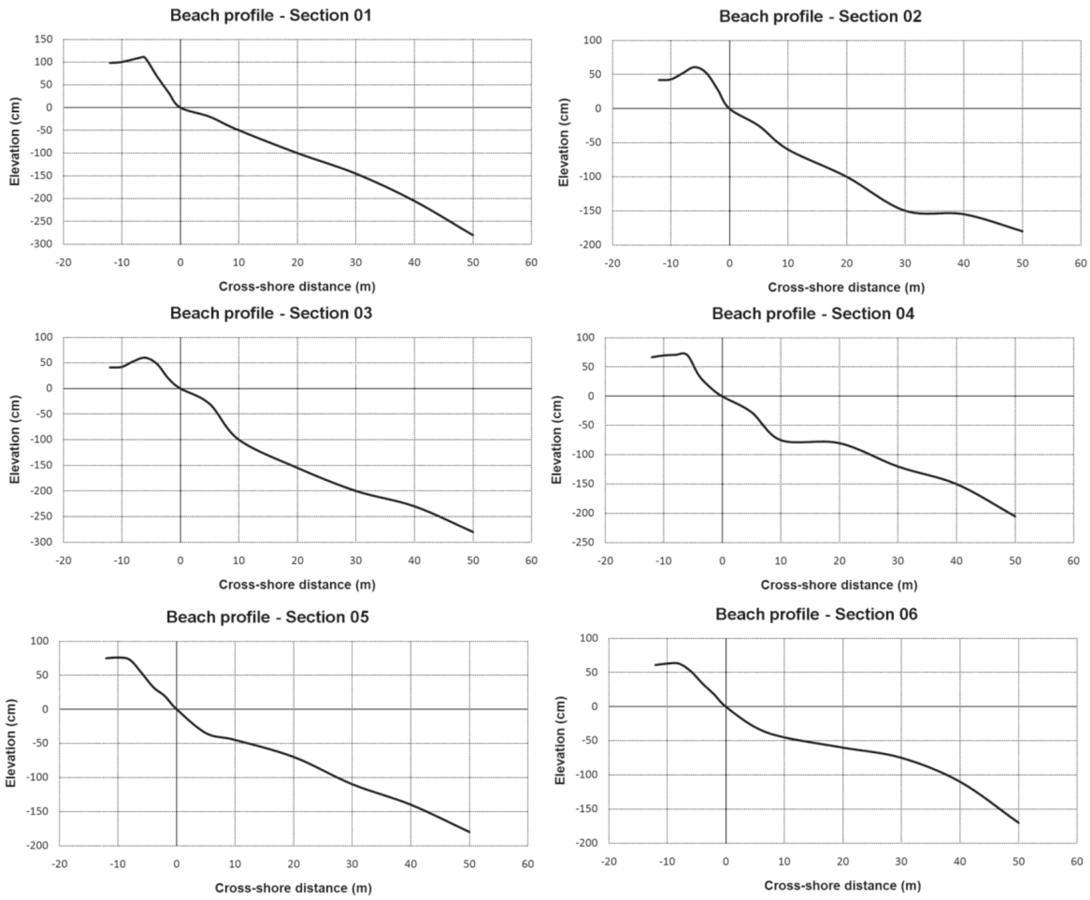

Fig. 4. Morphological beach profiles, as shown in figure 1. Elevation datum is the mean annual sea level.

tinued, the face of the beachrock towards the sea began to outcrop, whilst consolidation of beach sediments kept on at even higher level. Reaching modern situation, beachrock formation has been widely exposed across the coastline. The shoreline is now protected by the beachrock, although erosional trends are still active at the coast.

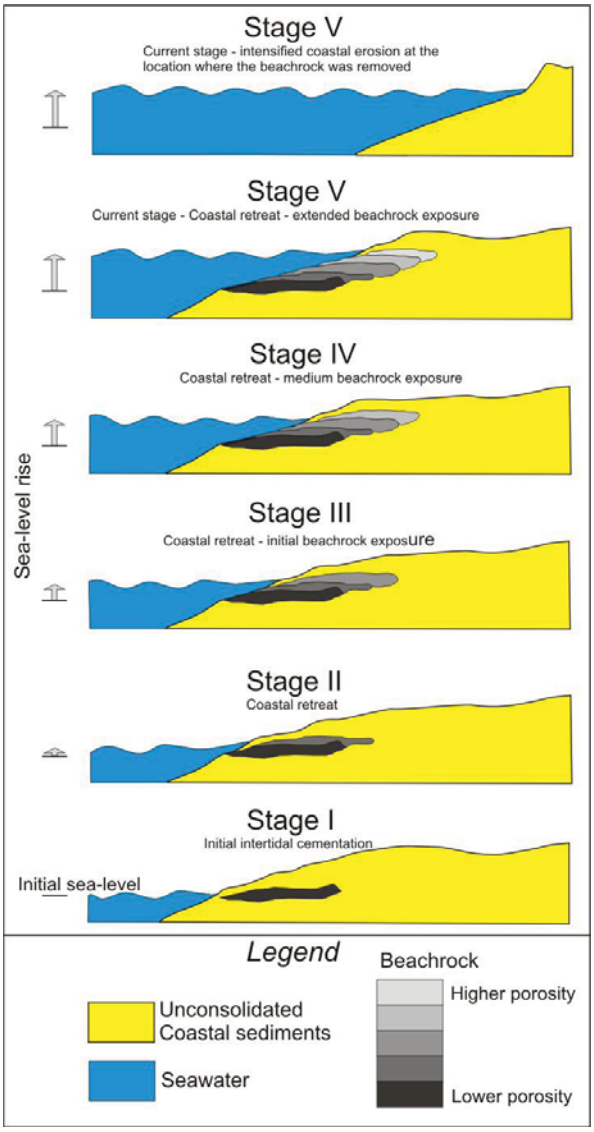

Fig. 5. Proposed evolution stages of the study coast,

5. Conclusions

The specific setting of the study beach provides a unique case for the evaluation of the morphodynamic impact of beachrock outcropping on the coastline. The comparison of the surveyed with the estimated transgression indicated that although beachrock was playing a protecting role for the coastline, the actual retreat was incurred also by several other factors apart from beachrock removal. In our case, these factors intensified the regression of the coastline relatively to the Bruun Rule estimation model. It is shown however, that sea level rise has caused at least 7% of the total shoreline retreat at the study area. An advanced modeling of the morphodynamic behaviour of a beachrock-occupied shoreline should include many parameters in order to model in precision the littoral responses, especially in cases of abrupt changes.

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