SEDIMENTOLOGICAL CONSEQUENCES OF POSIDONIA OCEANICA BANQUETTE REMOVAL: SAKARUN BEACH CASE STUDY (DUGI OTOK, CROATIA)

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Abstract – Removal of *Posidonia oceanica* banquettes from Sakarun beach (Dugi otok Island, Croatia) was a common practice to increase recreational use during the summer tourist season. The sandy part of the beach showed gradual erosion and has partially disappeared. Geological and geomorphological investigations (including bedrock characterization, analysis of sediment grain size and carbonate content, beach profiling, and digital surface modelling) were conducted over nine-month period to investigate the relationship between the banquette removal and sediment loss. The results indicate that the continuous removal of sediment-laden posidonia banquette may cause a deficit in the beach sediment budget, the effects of which may not become apparent until several-year delay.

Introduction

Seagrass meadows are ubiquitous habitats in the coastal areas of the Mediterranean. One of them, *Posidonia oceanica* (hereinafter posidonia), a legally protected species in most Mediterranean countries [1], is one of the most important taxa of this group. It is the basis of primary production in the sea [2], increases the oxygen concentration in the water column [3] and provides a habitat for numerous marine organisms. In addition to their biological importance, posidonia meadows influence water currents, sedimentological and geomorphological characteristics of the seafloor [4], and the coasts where its detritus is deposited [5]. Seabed sediment is more stable in the dense network of plant rhizomes, and the meadows reduce sediment resuspension and promote sedimentation [3,4,6]. Deposits of plant detritus, called banquette, usually form on the beaches off which posidonia meadows grow [7,8]. Banquettes are massive and more or less firm structures that make the beach more resistant to the action of waves: by covering the beach sediment, they protect it from erosion, while the banquettes themselves may contain considerable amounts of sediment. Although posidonia banquettes are known to have an effect on reducing beach erosion [2], there is far too little published research detailing this effect.

The occurrence of posidonia banquettes on the Croatian coast is known in several places, but according to the available literature, they are more common in other Mediterranean countries (e.g., Italy, France, Spain). To date, there are few data and research results on posidonia banquettes on the Croatian coast. Considering the orientation of the Croatian coast (NW-SE) and the prevailing wind waves that last long enough to form banquettes (south-east waves), posidonia detritus it expected to accumulate on coastal sections and beaches that are most exposed to south-eastern waves. One of tthese is Sakarun

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beach on the of Dugi otok Island (Figure 1). This beach can be characterized as a pocket beach, although it exceeds the average dimensions of this type of beach on the Croatian coast: they are usually smaller, located within bays, composed of loose gravel and different from the rocky headlands by which they are they are bordered. Pocket beaches are a popular geomorphological coastal form on the Croatian coast [9]. They have an attractive landscape and are therefore a valuable resource for the Croatian tourist industry. A deeply indented spacious Sakarun Bay with a sandy bottom and a long pebbly-sandy Sakarun beach deviates from the above description and attracts numerous beach goers and boaters.

Deposits of posidonia detritus, which settle on the Sakarun beach every year, were regularly removed in order to achieve a more representative and attractive appearance of the beach, which would increase its popularity and thus strengthen the overall tourist activity on the Dugi otok Island. Due to the observed increased erosion on the beach, i.e. in particular the decrease in the amount of sandy sediment, the complete removal of posidonia banquettes was stopped in 2020.

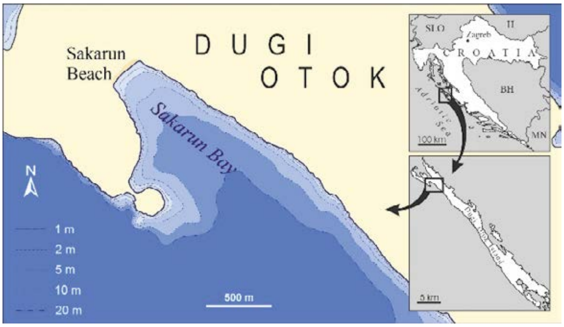

Figure 1 – Up: Location map of the Island of Dugi otok. Right: Sakarun beach within the Sakarun Bay containing posidonia detritus in the shallow sea.

Study site

Sakarun Beach is 300 meters long and up to 36 meters wide. The beach is known as a popular tourist destination. It is accessible from two sides by road, but it is also a destination for many sailors who use the buoy field in the wide bay. The bay is cut about 800 meters deep, while its average width is about 500 meters. The sea depth in the bay does not exceed 20 meters. Along its edge and in the open sea in front of it there are posidonia meadows. The biogenic detritus accumulates and settles in the bay (Figure 1), while up to 2 m thick banquettes are formed on the beach itself. Preliminary field investigation revealed that the beach sediment is primarily gravel, combined with a thin strip of sandy sediment in the intertidal. The beach is surrounded by the carbonate bedrock and oriented toward southeast (Figure 1), directly to Sirocco wind waves of shore-normal incidence. Previous results of beach morphodynamics are lacking, as well as description of beach sediment characteristics. Monitoring period of the beach banquettes began in the fall of 2020 through the summer of 2021 and lasted a total of 9 months. During the monitoring period 4 Sirocco episodes occurred (one in October, two in December, one in February) with wind speed in 8-10.7 m/s range.

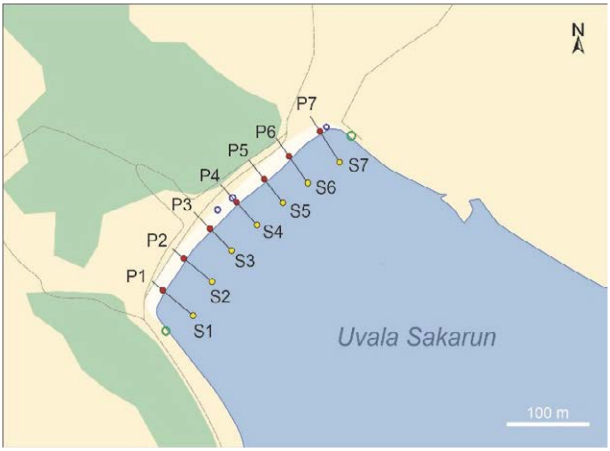

Figure 2 – Sakarun Beach with sediment sampling locations. Sampling locations P1-P7 refer to upper intertidal beach sediment, while sampling location S1-S2 refer to shallow subtidal sediment.

Materials and methods

Gravel beach sediment and bedrock were collected once for thin sections preparations to determine the origin, composition, and age of the underlying bedrock and the origin of the gravel material.

Sandy sediment samples were collected once along the sandy strip of sediment cover, in the intertidal (P1-P7) and in the shallow subtidal zone (S1-S7) along 7 profiles. A total of 14 sediment samples were collected. All sandy samples were subjected to grain size analysis by wet sieving and sediment classification was done according to [10]. Carbonate content was calculated from volumetric measurement of CO_2 produced after treatment with 1:1 dilute HCl acid in the Scheibler apparatus. All sediment fractions of each sediment sample were examined with a stereomicroscope to identify the origin of the sediment grains.

The mineral composition of the sandy sediment was determined by powder X-ray diffraction (XRPD technique) using a Philips PW 3040/60 X'Pert Pro diffractometer.

During the 9-month monitoring period, samples of posidonia banquettes were collected 9 times. Sediment was extracted from each banquette sample by rinsing in freshwater and subjected to the sediment analyses described above. The weight of each banquette sediment sample was determined as weight per 1 m^3 of posidonia banquette. Average sediment weight was calculated as a mean of all obtained weights.

Surveys of Sakarun beach were conducted each month along the 7 profiles (Figure 2) using a high-precision DGPS (Trimble R8 GNSS receiver) and the real-time kinematic positioning service CROPOS VPPS (virtual reference station). Aerial photographs were taken by drone each month during the monitoring period and then used to create DEM using Agisoft Photoscan (Metashape). DEMS of the differences were created using Golden Software Surfer.

Results

Both, the beach bedrock and the gravel beach sediment are highly erodible and thin-bedded bioclastic pelagic packstones and bioclastic floutstones of Cretaceous age, generally characterized as carbonate flysch.

The main characteristics of the sandy sediments are listed in Table 1. Intertidal beach sediment is mostly very well sorted slightly gravelly sand or sand with the mean size of ~0.2. mm. Subtidal sediment is mostly characterized as sand with a similar mean size. Both sand sample groups are highly carbonaceous and usually contain over 94% of carbonates. The sediment extracted from the posidonia banquettes had very similar characteristics to the intertidal and subtidal sands. The weight of sediment extracted from the posidonia banquette varied from 0.5 to 220 kg of sediment in 1 m^3 of banquette, with a mean (average) of 64 kg/1 m^3. Microscopic examination revealed that almost all grains in all sediment samples were skeletal grains, composed of marine skeletal material, including molluscs, foraminifera, bryozoans, serpulids, echinoids etc. (Figure 3). Most of skeletal grains exhibit a high degree of fracturing.

The mineral composition of selected sand samples showed that calcite, aragonite and Mg-calcite are the dominant mineral phases in all sand sample groups studied (Table 1).

The analysis of all beach profiles and the detected processes were explained using representative profile P1-S1. The beach profiles showed that the maximum changes occurred along profile 1 during the monitoring period (Figure 4). The maximum dynamics of posidonia banquette destruction and build-up occurred during and after Sirocco episodes, respectively, while the maximum elevation changes of posidonia banquettes occurred in the intertidal and the lowermost supratidal. Profiles along the entire beach indicated the presence of sandbar that moved along the shallow subtidal during the observation period.

3D models of the beach confirmed the beach profiling results and showed the maximum changes between two sucessive fieldworks up to 1 m in the intertidal and the lowermost supratidal (Figure 5).

Table 1 – Intertidal and subtidal sandy sediment characteristics. Description: (g)S – slightly gravelly sand, S – sand.

Sample:	Mean (mm):	Median (mm):	Sorting ():	Sediment type (after Folk, 1954):	Carbonate content (%):	Dominant minerals:
Intertidal beach sediment						
P1	0.208	0.196	0.564	(g)S	94	calcite, Mg-calcite, aragonite
P2	0.211	0.198	0.566	(g)S	99	/
P3	0.258	0,252	0.763	(g)S	99	/
P4	0.235	0.225	0.628	S	94	calcite, Mg-calcite, aragonite
P5	0.218	0.205	0.596	(g)S	98	/
P6	0.192	0.189	0.486	S	96	/
P7	0.241	0.235	0.625	S	94	Mg-calcite, calcite, aragonite
Subtidal beach sediment						
S1	0.187	0.186	0.475	S	94	Mg-calcite, calcite, aragonite
S2	0.183	0.183	0.460	S	93	/
S3	0.199	0.191	0.556	S	94	/
S4	0.183	0.183	0.455	S	94	Mg-calcite, calcite, aragonite
S5	0.187	0.187	0.466	S	95	/
S6	0.209	0.197	0.579	(g)S	95	/
S7	0.176	0.176	0.524	S	94	calcite, Mg-calcite, aragonite

Table 2 – Posidonia banquette sediment characteristics. Description: (g)S – slightly gravelly sand, S – sand.

Sample:	Mean (mm):	Median (mm):	Sorting ():	Sediment type (after Folk, 1954):	Carbonate content (%):	Dominant minerals:
Posidonia banquette sediment						
POS1	0.221	0.207	0.598	(g)S	99	Mg-calcite, calcite, aragonite
POS2	0.214	0.199	0.669	(g)S	95	Mg-calcite, calcite, aragonite
POS3	0.211	0.197	0.629	(g)S	95	Mg-calcite, calcite, aragonite
POS4	0.233	0.223	0.704	(g)S	99	Mg-calcite, calcite, aragonite
POS5	48	/	/	limestone gravel*	96-98*	/
POS6	0.217	0.201	0.650	(g)S	97	/
POS7	0.207	0.193	0.722	(g)S	98	/
POS8	0.228	0.211	0.771	(g)S	96	/
POS9	0.221	0.206	0.682	(g)S	95	/

*according to carbonate content of basement rock after [13]

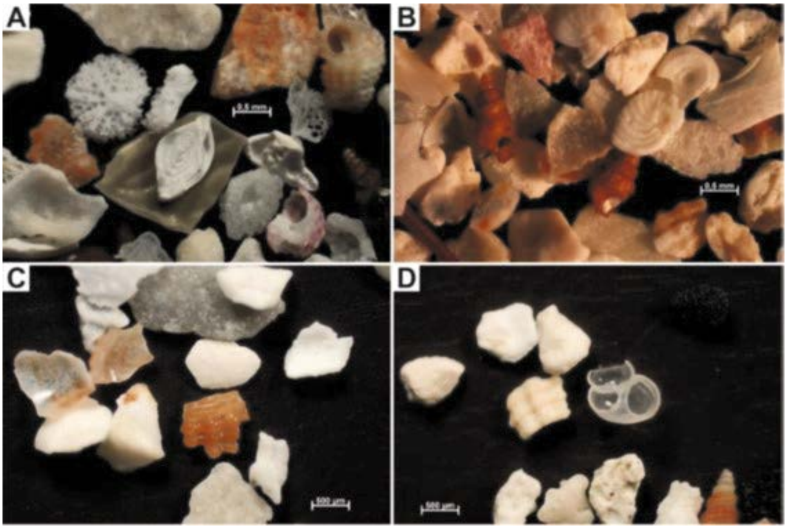

Figure 3 – Biogenous skeletal grains in fraction 0.5-1 mm of various samples. A) Sample P1 – foraminifera test with mollusc and bryozoan fragments. B) Sample P4 – mollusc and foraminifera tests with echinoid spine and mollusc fragments. C) Sample S4 – mollusc fragments. D) Sample S7 – mollusc fragments.

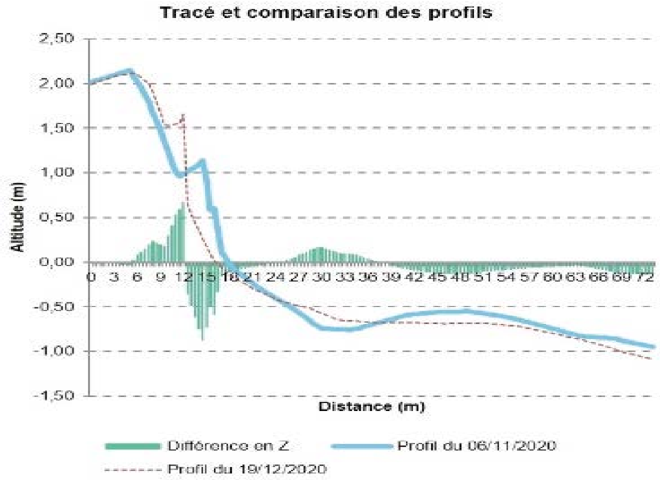

Figure 4 – Difference of profile 1 between November (blue line) and December (dotted line) 2020.

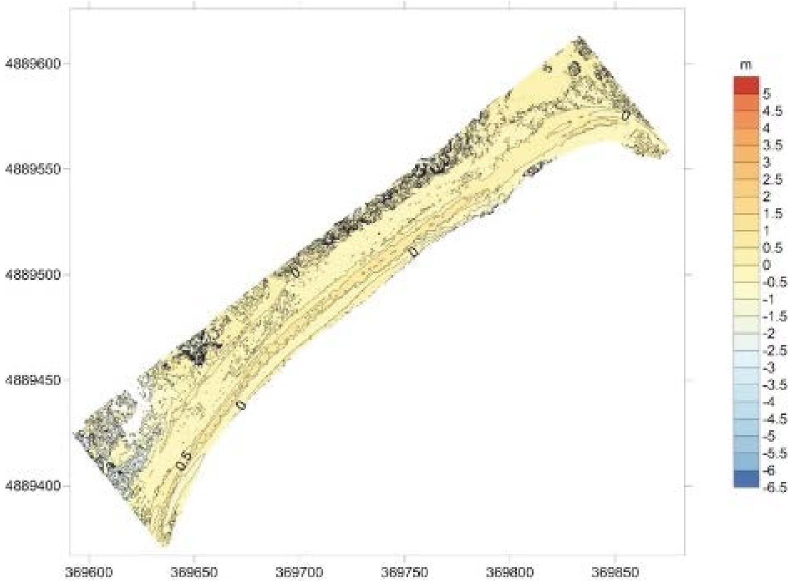

Figure 5 – DEM of difference for the November/December 2020 with postition of the profile 1.

Discussion

The Sakarun beach and the Sakarun Bay are the result of the erosion of erodible carbonate bedrock by the action of the prevailing Sirocco waves to which is the Bay oriented. The erodible nature of the bedrock resulted in the accumulation and rounding of carbonate gravel, which makes up most of the beach. The presence of posidonia meadows in the coastal area of the Dugi otok island leads to a massive accumulation of posidonia detritus and the formation of banquette (Figure 6). This accumulation is largely favoured by the prevailing Sirocco waves of SE incidence. Banquette are composed of posidonia leaves, rhizomes and aegagropilae. Banquettes are generally formed in the intertidal zone and cover sand deposited in the lower (intertidal and subtidal) part of the beach. All banquettes contain sediment, mostly sand, and to a lesser extent gravel. Because of the sediment they contain, banquettes are considered biogeomorphological structures. All sand samples collected from the beach and extracted from banquettes are pure marine biogenic sands and slightly gravelly sands, composed of carbonaceous skeletal remains. Such sediments are ubiquitous along the eastern Adriatic coast [11,12]. A high high degree of fracturing, indicating that original biogenic material was brought to the coast and further crushed by wave action.

Figure 6 – Banquette formed on the Sakarun beach.

Banquette dimensions usually change during and after Sirocco storms. During the storm, all the banquettes and the sand can be removed from the beach, as noted by the locals between the two fieldworks. When the storm subsides, both sand and banquettes are re-accumulated on the beach, indicating that sand and posidonia leaves have accumulated for a short time in shallow Sakarun Bay, awaiting re-accumulation on the beach. During the monitoring period the largest variations in banquette height were observed on the SW section of the beach (profile 1; Figure 4), while the largest changes occurred in the intertidal area. DEMs of differences between fieldwork during the monitoring period supported the results obtained from the beach profiles. In addition, all beach profiles showed that the sandbar exists in the shallow subtidal area of the Bay. It is hypothesised that its movement pattern may be explained by wave climate, which should be investigated during further monitoring.

Based on the average amount of sediment (mainly sand) in the banquettes of 64 kg/1 m^3 and the estimated volume of 1560 m^3 of banquettes on the beach during the monitoring period, it is calculated that the complete removal of banquettes from the beach removes 37 m^3 of sediment. According to [14,15], the accumulation rate of biogenic carbonate sediment in the temperate region is usually 1-2 cm in 1000 years. Assuming that all the sand on Sakarun beach is made in the Sakarun Bay, a rough estimation indicates that the total annual sediment production is 14 m^3. The result of the amount of sediment removed and produced clearly showes that erosion occurs at the Sakarun beach. The erosion results became visible after several years of banquette removal, indicating that further erosionall impacts on the beach can be expected in the coming years.

Conclusions

Sediment and posidonia banquettes form biogeomorphological structures on Sakarun beach. Removal of the banquettes for the tourist purposes leads to erosion of the sand, the most valuable part of the beach for tourism. The processes observed on Sakarun beach indicate the need for a development plan for posidonia management, in which permanent removal of the banquettes should be avoided.

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