Journal of Coastal Research	SI 64	790 - 794	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

Coastal morphology along the Central Algarve rocky coast: Driver mechanisms

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ABSTRACT

Moura, D., Gabriel, S. and Jacob, J., 2011. Coastal morphology along the Central Algarve rocky coast: Driver mechanisms. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 790 – 794. Szczecin, Poland, ISSN 0749-0208

The boundary between the mainland and the sea – the littoral fringe - crosses several sub-environments, among them, the rocky coasts whose evolution depends on marine and sub-aerial processes as well as on the rocks' mass properties. The study area - in central Algarve (South Portugal) - is framed in a rocky coast exposing carbonate rocks. This work identifies the main drivers to the coastal morphology in that region. Several morphological features such as beaches, cliffs, and shore platforms were surveyed, mapped, and correlated with the most common wave conditions in the area. Shore platforms show a strong correlation with the most vigorous wave climate conditions. In opposition, zeta bays occur in the more sheltered sector to the dominant waves and in a relatively straight coastline. Symmetrical small bays are mainly related with the sedimentary influx from rivers reaching the coast. The cliff heights and profiles are lithologically and structurally controlled.

ADDITIONAL INDEX WORDS: *Coastal cliff, Shore platform, Wave Climate,*

INTRODUCTION

The morphology of rocky coasts depends on the intensity of the weathering mechanisms and the time during which they operate and on the rocks' mass properties, structure and fracturation (Trenhaile *et al*., 1998; Andriani *et al*., 2005; Thornton and Stephenson, 2006; Llopis, 2006; Naylor and Stephenson, 2010; Naylor *et al*., 2010). Additionally, morphological inheritance also may play an important role on the modern coastal morphology (Storlazzi and Field, 2000; Gomez-Pujol *et al*., 2006; Stephenson, 2008; Trenhaile, 2010).

Cliffs, shore platforms, pocket beaches and other less conspicuous features like stacks, arcs, caves and notches compose the coastal landscapes. The knowledge about shore platforms genesis and evolution is of extreme importance once they are frequently used as a morphological proxy on past sea level reconstructions (Thornton and Stephenson, 2006).

Marine geomorphic processes include mechanical weathering such as abrasion, hammer effect, hydrostatic pressure, salt weathering and wetting and drying as well as biochemical weathering such as dissolution by inorganic or biological activity (McGreevy, 1982; Trenhaile, 2000; Colantoni *et al*., 2004; Duperret *et al*., 2005; Trenhaile, 2006).

The main goal of this work is to correlate morphological features with geomorphic processes operating at the central Algarve rocky coast (Figure 1).

STUDY AREA

By the end of the Miocene (Tortonian- Messinian) the Lagos-Portimão Carbonate Formation (LPCF) was exposed to sub aerial weathering, leading to the intense karstification of the carbonate rocks that are very vulnerable to the chemical attack. As a consequence, an erosive surface intercepts the Miocene carbonate rocks drawing deep valleys later filled by Pliocene and Pleistocene fluvial and marine sands. Therefore, cliffs expose carbonate rocks and sandy sediments in their lower and upper portions respectively or carbonate rocks contact laterally with sandy sediments filling the paleo valleys, some of them related with major fractures. The LPCF shows a noteworthy lateral continuity but a highly variable vertical facies ranging from fossiliferous limestone and calcarenite to siltstone weakly cemented.

The Algarve coast where the study area inserts experiences a mesotidal regime with a mean tidal range of 2.8 m during spring tides and 1.3 m during neap tides with a maximum tidal range of 3.5 m (Instituto Hidrográfico, 1990).

Offshore wave climate is dominated by waves from the WSW sector (in 71% of the year) followed by the SE sector (in 23% of the year). The annual average significant wave height and peak period offshore are 1.0 m and 8.2 s respectively (Costa *et al*., 2001). The wave height ranges from 0.3 to 1.8 m, although exceptional heights of more than 3.7 m may occur associated with storms from the SW (Pires and Pessanha, 1979; Pires, 1989).

METHODS

The following morphological attributes were accurately surveyed by using a differential Global Positioning System (dGPS) and parameterized: karstic morphology, cliff height and profile, beach occurrence and dimensions (either in bays and pocket beaches), intertidal shore platform occurrence and dimensions, raised platform occurrence, stacks, block chaos and rivers draining to the coast. The nearshore wave field modifications due to shoaling, refraction,

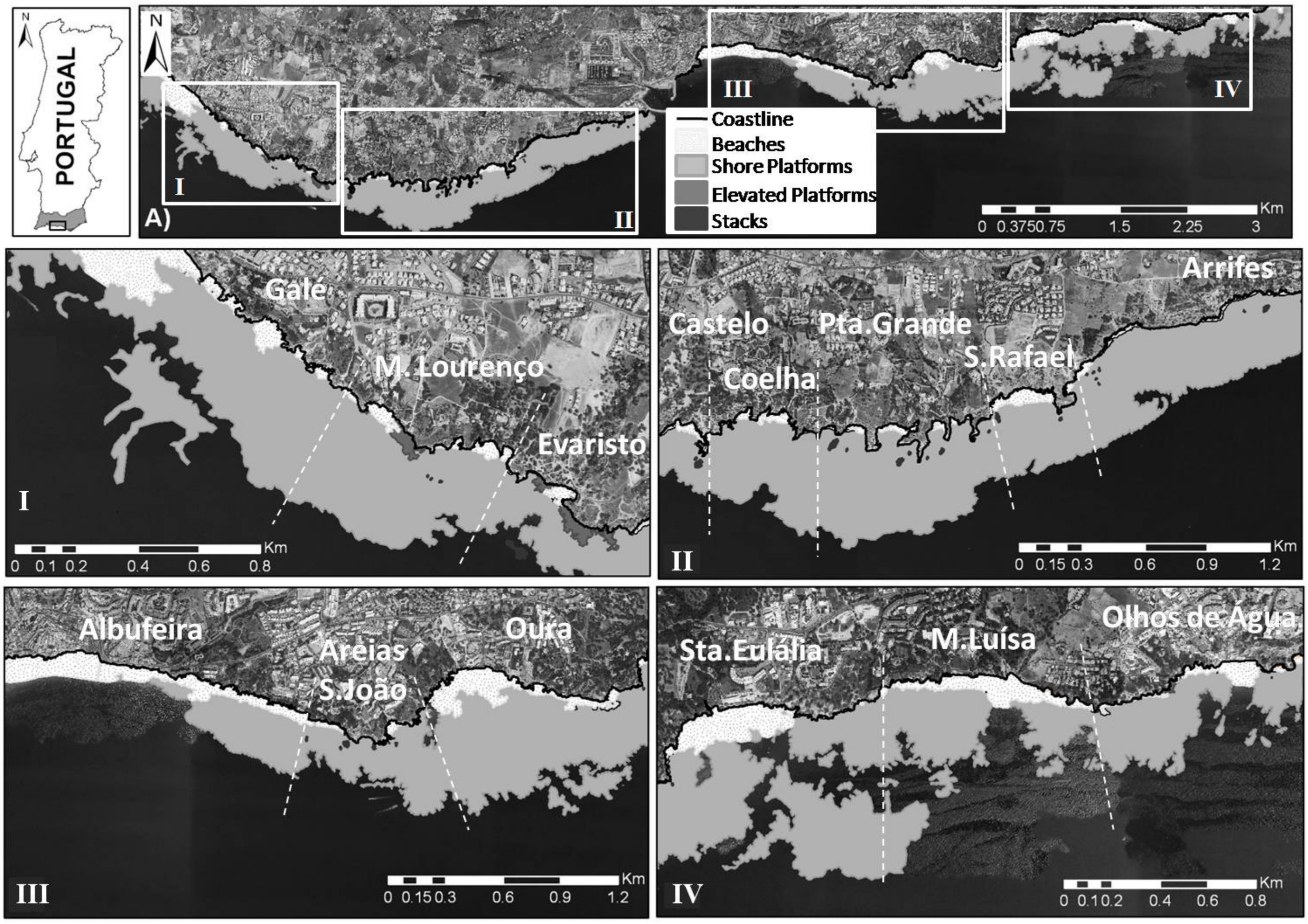

Figure 1. A)- General view of the study area; I, II, III and IV- details of each sub-sector reported in A). The main morphological features are discussed in the text.

diffraction and breaking were simulated using the third-generation spectral wave model SWAN (Booij et al., 1999; SWAN TEAM, 2008). The correlation index between the surveyed morphological features and climate wave was quantified through the R statistical program. Those features were parameterized using four values, the higher one meaning that the considered feature shows the highest degree of occurrence or the maximum dimensions inside the study area (Figure 3).

RESULTS AND DISCUSSION

Coastal Cliffs

The cliff profiles can traduce the relative role of marine and subaerial processes and were parametrized according to Emery and Kuhn (1982). However, there are no relationship between the cliff profiles and the simulated wave conditions at the study area. In fact, in sedimentary sequences with alternations of rocks with different resistance the profile depends mainly on the position where the weakest layers occur (Trenhaile, 1987). A silty layer (mean porosity of 7.04%) inside the carbonate sequence is responsible for the height at which the intense karstification occurs between Galé and Castelo (Figures 1I, II and 2). Due to the SW layers inclination (up to the 10º), the karstic forms sculpted into the calcarenite (mean porosity of 13%) overlying the silty layer are close to the upper inter tidal zone at Galé where cliffs are ca. 5 m high (Figure 2). The cliffs height increases eastward from Galé up to 14 m at Castelo, exposing very resistant fossiliferous limestone in its lower section. The dense fracture system (spaced ca. 1 m) led to the development of caves along the SW-NE fracture plains. The pocket beaches occurring inside the largest karstic depressions anchored between headlands provide the extreme crenulated tracing of this coastal sector.

On the contrary, cliffs exposing vertical layers of marl and claystone (Cretaceous) and inclined layers of limestone up to 30º (Jurassic) at the Arrifes sector (Figure 1II) are located in a quite straight coastline probably related with the occurring faults. Caves are carved into the softer claystone vertical layers at this sector.

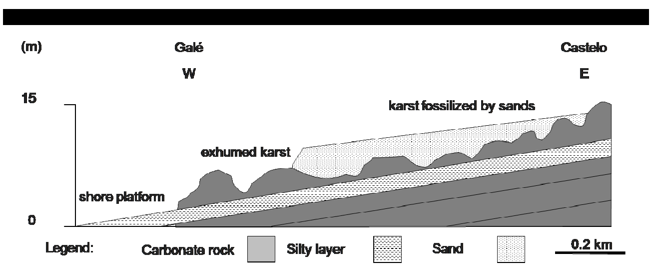

Figure 2. Layers structure and lithology (Galé – Castelo) influencing the cliff heigths and the height at which karst occurs.

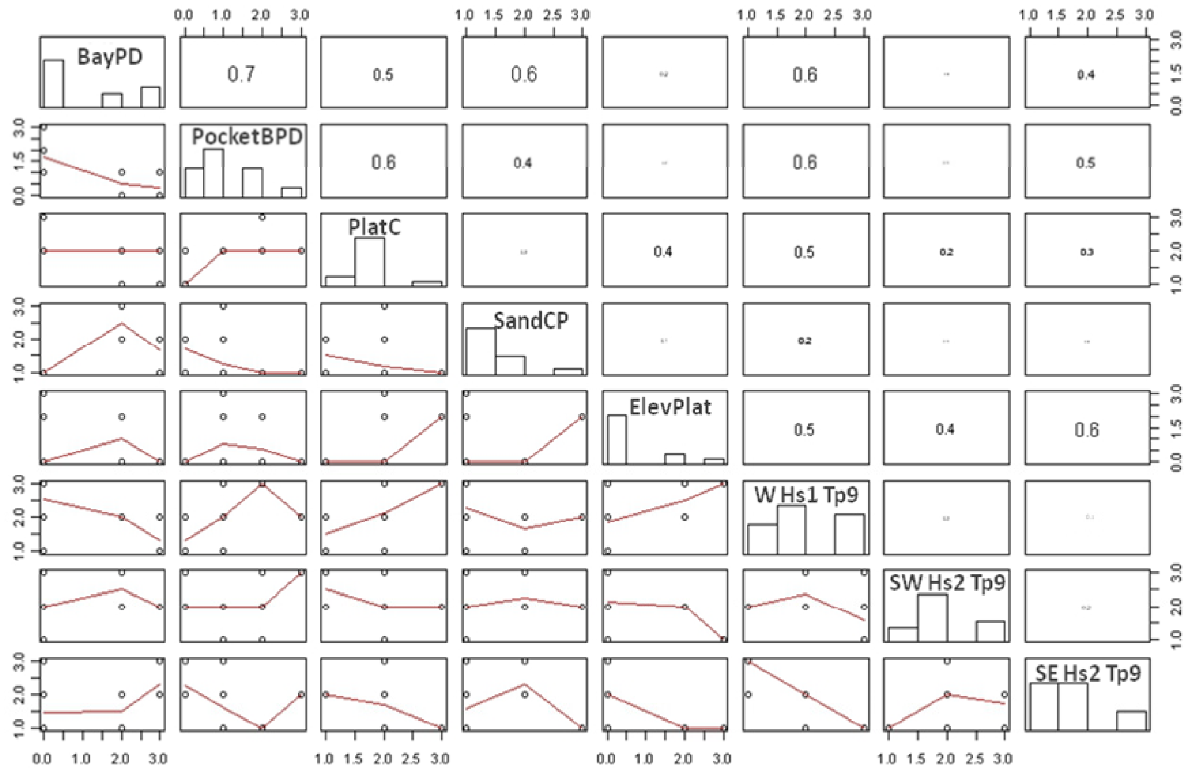

Figure 3. Correlation index between the climate wave and the discussed morphological parameterized features at the study area (Figure 1), obtained by the statistical software R. BayPD- shore parallel dimension; PocketBPD- shore parallel dimension; PlatC- Platform dimension; SandCP-sandy accumulation in the cliff- platform junction; ElevPlat- raised platforms; W, SW and SE - wave conditions discussed in the text. Axis values (dimentionless) correspond to the parameterization of the morphological features (see methods).

Eastward from Albufeira (Figure 1III, IV) cliffs expose more detritical rocks (calcarenite weakly cemented) than in the previous sectors and layers are sub-horizontal. The karstic forms filled by reddish sands (Plio-Pleistocene) affect large portions of the cliffs down to the beach or shore platform at the cliff foot. As a consequence of the karst cavities collapse, mass movements show the highest occurrence inside the study area (Nunes *et al*., 2009).

Similar to coastal cliff attributes, the occurrence of stacks, marine caves and block chaos did not reveal any kind of relationships with the simulated wave field scenarios. The cave occurrence in cliffs exposing inclined layers depends on the geometric relationship between the layers and the coastal section orientation. Once layers incline mainly to SW, caves develop when the coastal sector is NE-SW (normal to the dip), which coincide with sheltered sectors to the WSW waves approaching the coast (Figure 1A)

Shore Platforms

Shore platforms are conspicuous morphological features at the study area, showing different dimensions and preservation degrees. The most extensive intertidal platforms occurs at the following coastal sectors: (i) between Galé and Manuel Lourenço (Figure 1B), connecting directly with the cliff foot; (ii) at Arrifes (Figure 1C) where the extensive intertidal shore platform cuts the vertical layers and its junction with the cliff foot is covered by block chaos; (iii) between S. Eulália and Maria Luísa (Figure 1E), where either connect directly with the cliff foot or are covered by sand at the cliff platform junction. However, only the Galé-Manuel Lourenço sector shows significant positive correlation (0.5) with the dominant waves from W, which represent 52,3 % of the year (Figures 3 and 4). When simulating several wave field conditions, waves with peak periods (Tp) of 9 s produce two well-differentiated sectors, one to the west and the other east of Castelo, the latter being the less energetic, whereas lower Tp values (5 s) induce an almost uniform wave field for the entire area. A more uniform wave field was also obtained for SW incoming waves with Tp= 5 s and maintaining the wave height constant (Hs=1 m). Considering more energetic conditions (Hs=2 m and Tp=9 s) for both SW and SE incoming wave directions, which represent 41.5% of the year, a ribbon pattern oblique to the coast was obtained (Figure 4B and C). For those conditions, the largest concentration of energy occurs in the same sectors with exception of the Galé area in a sheltered position relatively to the incoming waves from ESE. That ribbon pattern correlates very well with the more extensive shore platforms (Figures 1 and 4). In addition, shore platforms may occur up to 5 m above the intertidal zone at the sectors between Manuel Lourenço and Oura, particularly at Evaristo (Figure 1I). In these cases, the present intertidal platform develops at the foot of the raised platform edge.

The genesis of that raised platforms is not completely understood, being some of them probably from structural origin. However, several among them may be preserved testimonies of past sea levels (Moura *et al*., 2006). Nevertheless, they correlate positively with waves approching the coast from W (correlation index=0.5) and in a higher degree with waves from SE (correlation index 0.6) with significant height of 2.0 m and peak period of 9 s (Figures 3 and 4).

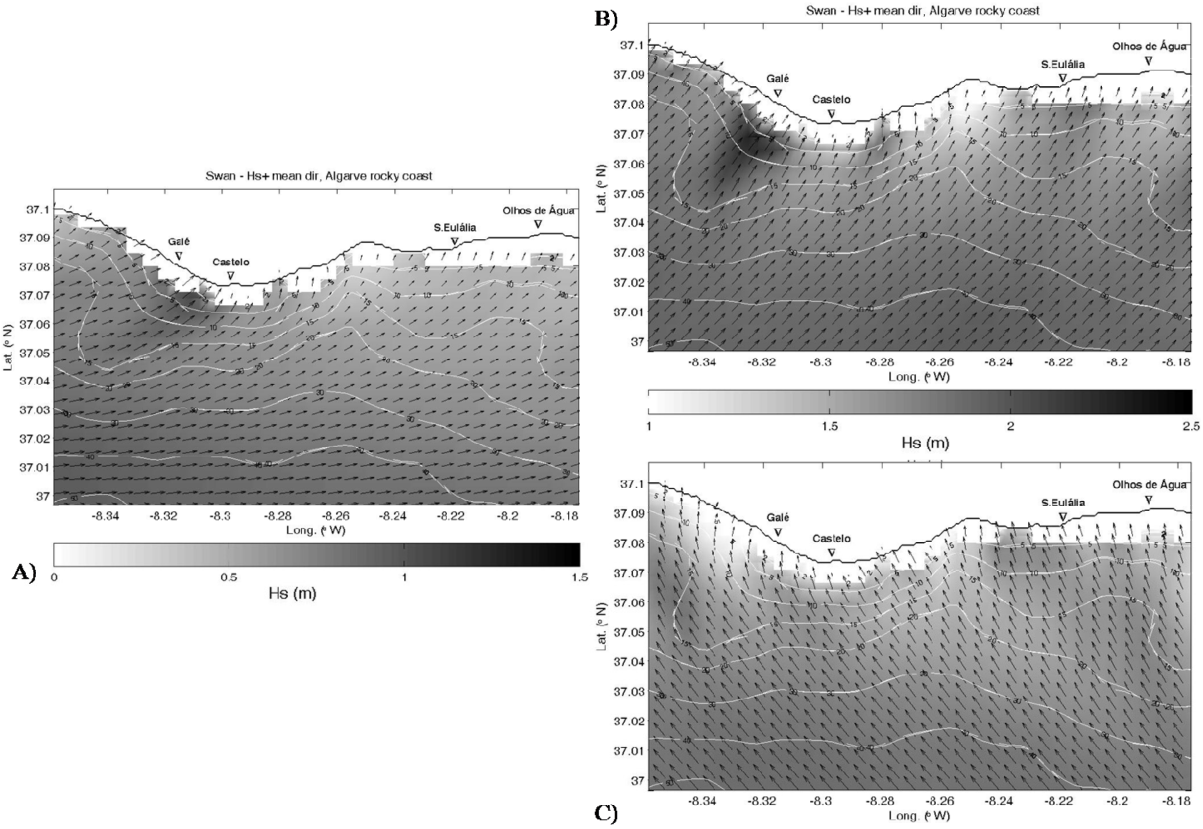

Figure 4. Simulations of wave conditions. A) wave direction W, Hs= 1 m, Tp= 9 s; B) wave direction SW, Hs= 2 m, Tp= 9 s; C) wave direction SE, Hs= 2 m, Tp= 9 s.

Pocket beaches and bays

Sandy accumulations occur as: (i) Pocket beaches between Galé and S. Rafael (Figure 1I); (ii) Zeta bays between Albufeira and Oura (Figure 1III), with the longest arm developed eastward; (iii) symmetric small bays between Oura and Maria Luisa (Figure 1IV).

The most exposed sector to the dominant waves incoming from W shows the highest number and dimensions (shore-normal) of pocket beaches (positive correlation index=0.6, Figure 3), revealing the major contribute of the cross-shore currents because they are anchored between headlands with shore platforms that reduce the longshore drift. However, as above referred, the pocket beaches occurrence is primarily related to karst morphology in this sector. The large dolines close to the sea were exhumed and partially eroded leading to the sand accumulation inside them (Figure 2).

Contrary to pocket beaches, zeta form bays are located in more sheltered areas oblique to the dominant waves and in straight sectors. This reveals a larger contribution of the longshore drift (from W to E) due to this distance between headlands. The third type of sand accumulation in small symmetric bays relates with fluvial input from rivers draining to the coast or with sandy cliffs backing the beaches (Figure 1IV). The available sediment, either from fluvial input and sandy cliffs erosion, offsetting the transport by shore currents and waves. This fact led to the quasi equilibrium state of the bays. Accordingly, the form of the bays in the studied crenulated coastline depends on the angle of the waves approaching the coast, the distance from headlands and the available sediment as also reported in previous works (Finkelstein, 1982; Phillips, 1985; Silvester, 1985).

CONCLUSIONS

The layer's structure, vertical lithological facies variation and fractures are the main drivers on the coastal cliff height, the degree of the coastline crenulation, the intensity of the karst affecting the face of the cliff and its profile at the carbonate coast in the centre Algarve.

Similarlly to the cliff properties, marine cave genesis is mainly related with the layers struture. Caves develop either in horizontal or vertical layers, due to the sucessive fall of layers and to erosion of softer layers respectivelly. In coastal sectors exposing inclined layers, caves form when the coastline is perpendicular to the layers dip.

The current intertidal shore platform and raised platform occurrence and dimensions correlate positivelly with the more energetic conditions, independently of the layers structure and lithology. Therefore, waves erosion seems to be an important driver mechanism on shore platform's genesis and evolution.

Pocket beaches and zeta form bays depend on the longshore drift importance as determined by the headlands occurrence and exposure to the dominant waves. Zeta form bays occur in coastal sectors oblique to the dominant waves, whereas pocket beaches occurs mainly in well exposed sectors. Symetrical bays are mainly related with the balance between the sedimentary fluvial input and marine erosion and transport.

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ACKNOWLEDGEMENT

The authors thank the reviewer Norbert P. the significant contribution to improving the paper. This work is supported by the Portuguese Foundation for Science and Technology (FCT), through the PTDC/CTE-GEX/71357/2006 and PTDC/CTE-GEX/70448/2006 Research Projects.