Cliff Vulnerability Assessment on Rocky Coasts in southern Portugal

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ABSTRACT
Rocky cliffs are widely distributed around the world's coasts and are subject to natural and anthropogenic pressures. The coastal evolution and erosional processes of the southern Algarve coast in Portugal have been previously studied. However, a detailed analysis of the relationship between lithological characteristics and cliff vulnerability to erosion is lacking. Therefore, in this work we focused on lithological facies variation and structures of the cliffs from Olhos de Água to Albandeira. We combined a variety of data, including those derived from traditional field-based and laboratory analysis, remote sensing (UAV image analysis) and photogrammetry. We identified multiple key forcers concerning cliff vulnerability to erosion: high vertical facies variation, intense karstification, multiple notches and marine caves. Furthermore, our lab analysis revealed differences in CaCO3 content for each lithofacies, resulting in alternating rock strength and leading to the formation of multiple structural notches into the cliff face. A classification of cliff vulnerability was developed based on a combination of these lithological and geomorphological factors. The sector Arrifes - Galé was classified as most vulnerable; Sector Galé - Armação de Pêra Bay was classified as least vulnerable in the study area.

KEYWORDS
Cliff erosion, driver mechanisms, lithology, remote sensing, Portugal

INTRODUCTION
The research on evolution and processes of rocky coastal cliffs is of major importance as these environments experience great natural and anthropogenic pressures and are highly sensitive to climatic changes or extreme events (Inman & Nordstrom, 1971; Davis, 2013;). Several studies have been conducted concerning these matters and are precisely summarized by Naylor et al., (2010). However, thorough research on driver mechanisms with respect to the physical substrate is needed. This involves the examination of cliff features such as lithology, karstification, morphology and structures such as bedding, faults and joints (Trenhaile, 2002; Boye & Fiadonu, 2020).

Rocky cliffs can be observed throughout most of the world's coastlines. Compared to sandy shorelines, the evolution of rock coasts is rather slow, but a loss of material is irreversible. Erosional processes on rocky coasts depend on multiple factors, including lithological properties of the exposed rocks, physical (wave impact, mass movements), chemical (karstification), biological and anthropogenic (infrastructure, tourism) parameters (Kelletat, 1989; Summerfield, 1991; Bird, 2008; Prémaillon et al., 2018). Rocky sea cliffs can consist of different lithologies (lithofacies) with mechanically and chemically stronger (therefore more resistant to weathering) and weaker rock units. "Resistant" in this context means strength of the exposed rock or the resistance to physical, chemical and biological weathering (Moura et al., 2011; Sunamura, 2015; Bird, 2016). Due to these differences in resistance to erosional processes, some lithofacies may erode faster than others, which eventually leads to a partial recession of the cliff and to the formation of arches and sea stacks. These formations are further supported by the presence of discontinuities such as faults, joints and fractures, as they provide a greater surface for erosion to act on (Komar, 1976; Emery & Kuhn, 1982; Bird, 2016).

The objectives of this study are to characterize different lithological units and structures and to associate lithological properties (dimensions and features) with cliff vulnerability to erosion throughout the study area. Furthermore, we tested whether the used tools are suitable and constructive for research on cliff vulnerability to erosion in the southern
Algarve.

MATERIALS AND METHODS

The area under study is defined by the about 40 km long coastal stretch between Olhos de Água and Albandeira in the southern Algarve, Portugal and was divided into six sectors according to respective lithological characteristics (Figure 1). To investigate possible associations between certain parameters and cliff vulnerability to erosion and to obtain the necessary data, a multi-tool approach was implemented. This included fieldwork to explore lateral facies variation and geomorphological features, laboratory analysis of rock samples ($CaCO_3$ content), coupled with UAV (unmanned aerial vehicles) image analysis, and photogrammetry.

Figure 1: Study area in the southern Algarve, Portugal, identifying six sectors (STOCK 2020, ESA 2019).

The main purpose of the field survey was to observe the present cliff face, its geomorphological and lithological characteristics, structures and karst features. This included the identification and description of both lateral and vertical facies variation and their contact zones. Moreover, the extent of discontinuities, notches and marine caves in the cliff face, the presence or absence of shore platforms as well as rivulets reaching the shore were noted. In addition, rock samples were collected from each identified lithotype along the coast, whenever changes were detected.

The performed work in the laboratory focused on the quantification of $CaCO_3$ content of each collected sample. According to Hulsemann, (1966) and Lamas et al., (2005), an efficient method for this purpose is the determination of
released CO_2 after the reaction with hydrochloric acid (HCl). This was performed with a Bernard Calcimeter.

With the aim to quickly understand the lateral facies variation between coastal sectors, pictures were taken along the coast with both, a ground based digital camera (Panasonic Lumix GH4) and an UAV (DJI Spark). These images allow a better perception of the vertical and horizontal evolution of the cliffs' layered structure as well as the identification of cliff features.

For better visualization of the study area and to quantify geomorphological features (e.g., sinkholes), the captured UAV images were further processed in AgiSoft Metashape.

This software allows the three-dimensional reconstruction of the two-dimensional information contained in the images and the creation of orthomosaics and digital elevation
models (DEM).

RESULTS AND DISCUSSION

The results from field work showed vast differences in lithology, number of vertical facies, distribution of discontinuities as well as shore platform and beach width throughout the entire study area (Figure 2). For instance, Coelha and Albandeira displayed nine vertical lithofacies, whereas Alemães only showed three. A high abundance of faults and karst features could be detected in Alemães and Coelha. Multiple notches and marine caves were found in Maria Luísa. The widest beaches and shore platforms were observed in Armação de Pêra and Santa Eulália.

The highest average CaCO3 content values were detected at Albandeira (77,9%), followed by Santa Eulália (73%), Olhos de Água (59,7%) and Maria Luísa (56,6%), while the lowest average CaCO3 content could be found in the cliffs of Alemães (39,68%) (Figure 3). The CaCO3 content analysis provided valuable information as it is directly linked to rock strength and hence, resistance to erosion.

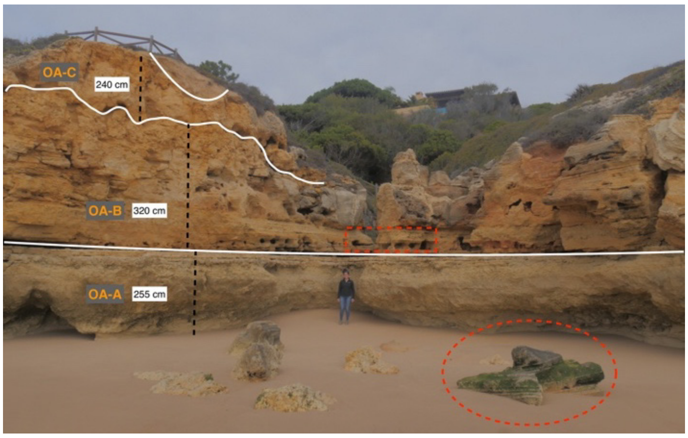

Figure 2. Cliff photograph of Olhos de Água showing lithofacies (OA-A, -B, -C), layer thicknesses, karst features (red squared) and elements of rockfall (red circled) (STOCK, 2019).

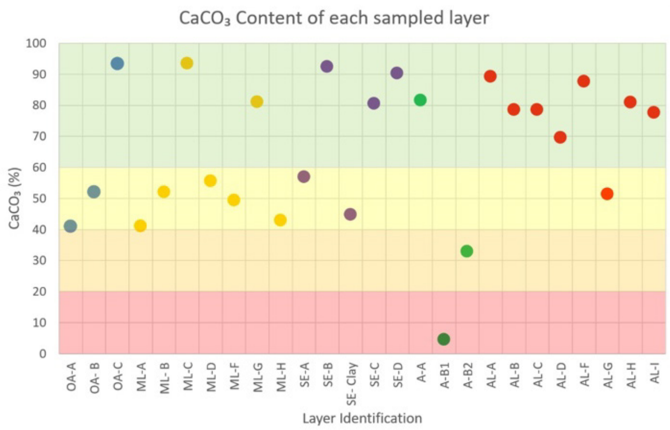

Figure 3. CaCO3 content of each sampled lithofacies organized from east to west with distinctly coloured dots according to the locations.

The outputs from AgiSoft Metashape established the possibility to observe cliff features from different and usually inaccessible angles. The created 3D model (Figure 4) helped to identify the overall morphology as well as minor scale features such as evidence of rock fall events, sinkholes and sediment fans, as well as to measure cliff heights.

Figure 4. 3D model of the cliffs near Maria Luísa displaying sinkholes and shore platforms (STOCK 2019).

After integrating the previous results, sector IV exhibited the highest vulnerability to erosion, mainly due to a high number of vertical facies and karstic features. Followed by the sectors I, II, III and VI. The lowest vulnerability was detected in sector V. The results are in accordance with previous research by Nunes et al. (2009) and Bezerra et al. (2011) who identified similar locations being exposed to drivers for erosional processes. Their research, however, was mainly based on parameters like wave energy and height and cliff exposition.

CONCLUSIONS

The parameters that primarily determine cliff vulnerability to erosion in the study area are lithological properties (vertical facies variation, CaCO3 content), discontinuities in the rock (faults, joints, karst features), notches, marine caves, wave exposure, as well as width of beaches and shore platforms. The approach using multiple tools and data sources showed potential for assessing cliff vulnerability to erosion. Particularly fieldwork with a thorough description of cliff properties and a lithological analysis and interpretation unveiled important results. Through this, the parameters of interest could be precisely analysed and combined for an overall assessment of vulnerability to erosion. However, an appropriate and detailed parametrization of the studied factors is needed to develop a profound vulnerability assessment of the southern Algarve cliffs. This is of high value as this coastal zone is subject to excessive touristic pressures.

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