Rock ledge and coastal cliff evolution during the winter of 2009-2010. An example from Praia Pequena, western coast of Portugal

Evolução da Arriba da Praia Pequena no decorrer do inverno de 2009-2010

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Abstract
Rocky coasts are complex geomorphological systems as their evolution depends on the interaction of different physical elements (geological structure, climate, wave and biological actions). It is common to find that in coastal cliffs that have a structure with alternating beds of different degrees of hardness (i.e. limestone, marls and clay) the response to weathering processes tends to be different in each bed, which leads to the formation of structurally controlled rock ledges. Under such structural and morphological conditions, coastal cliff retreat events are not limited to the cliff top but tend to occur along the slope if a rock ledge is present. This research work focus on the analysis of the processes responsible for coastal cliff erosion, with particular emphasis on the evolution of individual rock ledges along the cliff of Praia Pequena (Sintra, Portugal). The main goal is to examine the rock properties of individual rock ledges and the weathering processes responsible for triggering or increasing their instability. Thus, the main objectives are to: (1) evaluate the role of rock properties in mediating rock ledge erosion; (2) identify the processes involved in rock ledge erosion; (3) appraise the contribution of small scale ledge failures to bigger rockfall/slides; and (4) discuss possible rock ledge and coastal cliff evolution models for the study area.

Keywords
Rocky coast, slope movements, structural control, Praia Pequena (Portuguese west coast)

Resumo
Os litorais rochosos constituem sistemas geomorfológicos complexos dado que a sua evolução depende da interacção de múltiplos elementos físicos (estrutura geológica, clima, agitação marítima e acção biológica). Nas arribas talhadas numa alternância de bancadas resistentes e brandas (i.e. calcários, margas e argilas), a resposta aos vários processos de meteorização tende a reflectir estas diferenças, dando origem a um perfil transversal claramente controlado pela estrutura, onde se destacam as bancadas mais resistentes. Nestas condições estruturais e morfológicas, os episódios de recuo da arriba não afectam exclusivamente o topo, podendo ocorrer em qualquer sector da face da arriba em que aflorem as bancadas resistentes. Neste estudo, foram analisados os processos responsáveis pela erosão da arriba com particular destaque para aqueles que afectaram as bancadas salientes na Praia Pequena. Para além disso, foram também determinadas as propriedades físicas das rochas que constituem as bancadas resistentes e os processos de meteorização responsáveis pelo incrementar ou desencadear de instabilidade na vertente. Em suma, este trabalho teve então 4 objectivos: analisar a relação entre as propriedades das rochas e a erosão das bancadas resistentes; analisar os processos envolvidos na erosão das bancadas resistentes; analisar a contribuição de descontinuidades de pequena dimensão para o desencadear de eventos significativos de desabamento e/ou deslizamento; elaborar, para a área de estudo, modelos de evolução das bancadas resistentes e da arriba, em geral.

Palavras-Chave
Litoral rochoso, movimentos de vertente, condicionalismo estrutural, Praia Pequena (litoral oeste Portugal)

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1. Introduction

A large percentage of the coastal systems of the world is rocky, either plunging over sea or having their base level on shore platforms or on sandy and cobble beaches. (Emery & Kuhn, 1982; Griggs & Trenhaile, 1994). Rocky coasts are complex geomorphological systems as their evolution depends on the interaction of different physical elements (geological structure, climate, wave and biological actions), where rock resistance determines the amount of energy necessary for erosion to take place through the action of exogenic forces. As the geological and climatic context varies from site to site, the geomorphic response (i.e. processes, landforms and erosion rates) is equally distinctive. This observation led to the classification of rocky coasts as threshold-dominated, non-linear dynamical systems (Phillips, 2006).

The importance of *Rock Control* in coastal cliff evolution has been long recognized in the literature, and has been described as the influence of rock properties (geological and material properties) in landform evolution (Yatsu, 1966). Thus, the acquisition of precise measures of rock properties and the analysis of its connections to geomorphic response are highly important as coastal systems suffer from human pressure and sea-level rise (Griggs & Trenhaile, 1994; Thom, 2004; Stephenson & Thornton, 2005; Nicholls et al. 2007; Dickson et al. 2007).

In rocky coasts where alternating beds composed by harder and softer materials prevail (for example, limestone and marls), the response to weathering processes tends to be different in each bed. This process of differential erosion acts upon softer beds, leaving harder beds exposed and often overhanging along the cliff's face forming isolated, structurally controlled, rock ledges. These features, located at the base or placed several meters above present sea level, have been the focus of attention of several researches over the years, who question whether they constitute geomorphic markers to former, higher, sea level position, or the result of differential erosion between more and less resistant strata (Trenhaile, 1971).

According to Scheidegger (2004), rock ledges expose three sets of discontinuities: one runs horizontal to stratification and is normally related to lithological transitions, whilst the other two are sub-vertical to stratification and are normally related to past tectonic stress. Discontinuities such as joints or fractures play an important role in the way rock ledges respond to the action of external forces as they tend to facilitate the penetrative action of weathering processes (i.e. salt spray, sub-surface flow, weathering along fractures). Furthermore, the geometrical relation between discontinuities together with joint properties such as density, continuity and spacing help to determine rock fall block size, magnitude and frequency.

Therefore, exposed rock ledges tend to present a break-out niche morphology where the fracture plains are coincident with rockfall failure planes. In such structural and morphological conditions, cliff retreat events are not limited to the cliff top, tending to occur along the slope if a rock ledge is present. The partial collapse of a rock ledge creates new conditions for failure as it forces tension on neighboring fractures, creates accommodating space for slope instability along the upper sections of the cliff and compromises the stability of a complete section of the cliff due to post failure readjustments.

In this work we identified the processes responsible for cliff erosion focusing our attention on the evolution of individual rock ledges along the cliff of Praia Pequena. Our objective is to analyze the rock properties of individual rock ledges and the weathering processes responsible for triggering or increasing rock ledge instability. We use field and laboratory techniques to study the processes involved in cliff erosion over a period of 41 years. Geomorphological field mapping together with photo-interpretation of aerial photographs from the years 1967 (scale 1:25000), 1987 (scale 1:17000) and 2008 (scale 15000) enabled the identification of the surface processes involving cliff retreat events over that period of time. High quality digitalization of aerial photograph (2600dpi) allowed the identification of the cliff top and of the individual rock ledges along the cliff slope. For each rock ledge, the intact rock resistance was assessed through the use of the Q value of a Schmidt Hammer and the properties of

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discontinuities such as orientation (strike and dip), density, spacing, weathering and sedimentary fill were evaluated.

The high amounts of rainfall that took place in the winter of 2009-2010 allowed us to follow closely the response of the cliff to climatic forcing. The inexistence of a meteorological station at Praia Pequena and the unattainable data of the nearest station (Cabo da Roca), forced us to use data from the INAG stations of Malveira da Serra and Sobral da Abelheira, located 8km south and 20km NE of the study area, respectively. For those two stations, we analyzed daily rainfall data between 1/09/2009 and 1/09/2010. This allowed the cross analysis between rainfall events, the amount of rainfall (total and accumulated) and the events of cliff erosion identified in the field.
By comparing the results from the two time frames – 1967-2008 and 1/10/2009-1/09/2010 – and by focusing on the study of rock ledges, we achieved four main objectives: (1) evaluate the role of rock properties in mediating rock ledge erosion; (2) identify the processes involved in rock ledge erosion; (3) appraise the contribution of small scale ledge failures to bigger rockfall/slides; and (4) discuss possible rock ledge and cliff evolution models for the study area.

2. The study area

The study area is located on the western coast of Portugal approximately 30Km to WNW of Lisbon. Data from a 30 year climatic period (1931 – 1960) from the Cabo da Roca station (located 5Km southwest of the study area) shows that rainfall in the study area is concentrated from November to April, reaching an average a peak value of 76.5mm during November and dropping to its minimum values during the summer months (July and August). Average annual rainfall is 441.7mm and is distributed over 108 rainy days. Nevertheless, only 14 days have values over 10mm and are concentrated in the winter months. The temperature regime is characterized by high values during July and August with an average temperature of 18°C, reaching exceptional peaks of 36°C. Minimum values of average temperature are reached between December and February (approximately 11°C), occasionally dropping down to 0°C.
The prevailing winds come from N, NW, NE and SE, with wind from north and northwest being the most frequent from March to November and the most intense from July to August.
According to Lautensach (1987) and Henriques (1996) prevailing wave motion reaches the continental coast of Portugal from northwest (approximately 70% of the observations). Southwest storms, although less common, are more energetic and are normally concentrated at the beginning of the winter. The average wave amplitude calculated for the coastline of Cabo da Roca is 2.1m, reaching a maximum value of 9.9m (Pontes *et al.*, 1996 & 2000). Estimated average wave energy values range from 40 to 45kWm^{-1}y^{-1} (Andrade & Barata, 2002, in Andrade *et al*., 2002). The tidal variation along the Portuguese coastline is characterized by a semidiurnal regime with an average and maximum range of two and four meters, respectively (Neves, 2004).
The coastal cliff height at Praia Pequena varies between 20 and 35 meters and is cut in gently south dipping upper Cretaceous to Oligocene formations. The contact between the Oligocene and the Cretaceous is established by a vertical fault oriented towards N40 located in the northern sector of the beach. South of this fault outcrops a complete sedimentary sequence from middle Albian to middle Cenomanian. The upper Cretaceous (middle Albian to middle Cenomanian) is characterized by strong thickness variations. Middle to upper Albian is composed by an intercalation of nodular limestone, marls, clays and marly limestone, varying from 0.2 to 1 meter in thickness and by compact coral and sandy limestone attaining 2 meters in thickness. Lower to middle Cenomanian is represented by thin beds (0.3 to 1 meters) of marls, clays and sandstone and by thick (2 to 3 meters) compact dolomitic and wackstone limestone. The Oligocene sedimentation is limited to the northern sector of the study area and is characterized by a conglomeratic structure composed by marls and clays containing limestone and flint clasts.

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Ten rock ledges where chosen along the face of the cliff in Praia Pequena. Each ledge was numbered from the bottom to the top of the cliff from one to ten. The values of uniaxial compressive strength obtained during field work show an increment in rock strength from north to south and bottom-up, ranging on average from 40 – 55Mpa to 70 – 75Mpa. This trend is due to the presence of thick dolomitic and wackstone limestone beds that outcrop along the top of the cliff.

Measurements (bed thickness; Q value) 1 to 6 were made in the northern sector of the Praia Pequena in a sequence of marl-limestone (0.4m; 42.2), marly silt (0.3m; 54.5), sandy limestone (0.8m; 49.2), coral and sandy limestone (1.30m; 51.6), marly limestone (0.5m; 46.7) and dolomitic limestone (1.40m; 66.3). As stratification is dipping south, the base of the cliff along the central sector of the study area shares the same dolomitic limestone bed which outcrops at the top of the northern sector. Above this bed, Schmidt hammer measurements were made on marl (0.4m; 51.5) and marly limestone beds (0.8m; 54.5), as well as from the uppermost sections of the cliff where the dolomitic (1.5m; 64) and wackstone (1.6m; 70.9) limestone beds can be found. In the intermediate sections between the analyzed beds it was impossible to use the Schmidt hammer due to the presence of either thin and highly fractured beds (Schmidt hammer values would be too low) or a thick slope deposit that covers the outcrops.

The fracture orientation data reveals that, besides the discontinuities related to the contact between beds, three sets clearly stand out from the sampled set collected in the field: N40, 80E; N140, 90E and N170, 90E. The first set is present through the ten rock ledges and is particularly important because it corresponds to a sea-dipping fracture set parallel to cliff orientation. The other sets play an important role in individualizing blocks prone to future failure and are visible along the cliff controlling break-out niche morphology along every rock ledge.

Fracture properties, such as density and spacing, reveal that thicker beds (> 1m) with high uniaxial compressive strength value (> 50) present low fracture density (1 fracture per m^2) and a spacing between fractures of over 1.5 meters. This feature is particularly evident along the central and southern sectors of the study area in association with the dolomitic and wackstone beds (rock ledges 9 and 10). Rock ledges 1,4,5,7 and 8 have high fracture densities (10 to 20 fractures per m^2) and an average spacing of 0.1 to 0.3 meters.

Fracture weathering can be seen along each and every one of the studied rock ledges. However, weathering is particularly active in the northern sector, where exurgences can be seen along the bases of the coral and sandy limestone (rock ledge 5) and of the dolomitic and wackstone limestones, where calcium carbonate concretions fill the base of fracture planes. Clay-sand filling of fractures is limited to the limestone beds reaching a maximum value of 4cm in thickness.

The average cliff profile is highly influenced by the position along the slope, strength and thickness of the limestone beds in relation to the marl and clay beds. Vertical sectors are normally associated with thick dolomitic and wackstone beds, particularly along the central and southern sectors of the beach, where it outcrops along the top of the cliff. Rectilinear and concave sectors occur either in between thick limestone sections (i.e. central sector of the beach) or above, in association with marl, marly limestone and clay beds (i.e. in the northern sector of the beach). The rectilinear and concave sectors are normally covered by a 0.1m - 1m thick slope deposit.

The cliff retreat events can be classified in five distinct groups: (1) individual rockfalls from exposed rock ledges; (2) large rockfall/slides affecting several beds or complete sections of the cliff; (3) earth flow; (4) rotational superficial slides affecting the slope deposits along the concave sector of the cliff; and (5) one deep rotational slide affecting the Oligocene formation in the northern sector of the study area.

The southern sector of the beach has sand throughout the entire year and is covered by large dolomitic and wackstone blocks (4 to 10m^3) which protect the base of the cliff from wave erosion. The northern sector is partially covered by compact coral and sandy limestone blocks (1 to 3m^3) which lay on top of a cobble accumulation. During winter months, clearly associated to south and southwest storms, this

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sector is covered by sand all the way to the cliff toe, partially overlapping the base of the fallen blocks (+- 30cm).
These fallen blocks along the base of the cliff tend to protect it against the action of breaking waves. Nevertheless, some sectors along the northern and southern edges of the beach show evidence of being affected by minor wave quarrying.

3. Processes and models of rock ledge evolution during the winter of 2009-2010
The winter of 2009-2010 was characterized by heavy and prolonged periods of rain over a period of almost 6 months. Between the 1st of October and the 9th of March (160 days) the meteorological stations at Malveira da Serra and Sobral da Abelheira registered a total of 623.3 mm and 722.9mm of rainfall, respectively, distributed over 132 rainy days. Four rainfall events coincide with the dates when cliff erosion was observed: 28th and 29th of December 2009; 11th, 12th and 13th of January 2010; 21st of February 2010; and 6th of March 2010.
During the three months that preceded the first event, the water content along, and in between beds, along fractures and within slope deposits, increased, as the marl and clay composition of both bedrock and fracture fill sediment tends to reduce the cliffs draining capacity, retaining water in between precipitation events. Processes that are precursors of failure can be subdivided into several different groups: a) soil and bed saturation along the top of the cliff, saturating and adding weight to the dolomite and wackstone rock ledges; b) clay expansion and increase of water pressure along fractures; c) subsurface flow; d) fracture weathering; and e) expansion of clay beds and marl beds. Strong rainfall events push variables close to the threshold values and cause failure if there is no water draining capacity.
By the 27th of December, the accumulated rainfall in Malveira da Serra and Sobral da Abelheira since 17/11/2009 and 7/12/2009 (total of 40 and 20 days before the erosion event) had reached 155.8 – 187.9mm and 71.7 – 83.8mm, respectively. The events of the 28th and 29th of December added 50mm of rain, which is over the 100mm of rain threshold (for a period of 20 days), a value referenced in northern Lisbon for triggering slope failure (Zêzere & Rodrigues, 2002). For a period of 40 days the accumulated rainfall (249.2mm at Sobral da Abelheira) is below the threshold defined by the same authors. Over these two days, the northern and central sectors were affected by earth flows and several individual rockfalls along fracture planes, which blocked the access to the beach, and by the opening of tension fractures on slope deposits. In the northern sector, a rockfall along the coral and sandy limestone bed (rock ledge 5) mobilized approximately 30m^3 of debris and forced the reactivation of a superficial rotational slide on the upper section of the cliff. The failure plane was established along a N40, 80W oriented fracture and deformation was interrupted by a fracture oriented towards N140,90W. The next two events in January and February are responsible for continuing slope deformation along slope deposits and for triggering another earth flow in the central sector. During this period, wave action along the base of the cliff partially eroded the toe of a slope deposit, causing tension fracture opening and sliding.
On the 5th of March of 2010, around 14:28, an earthquake with a magnitude of 2.0 (ML – Local magnitude), struck the western coast of Portugal 10km southwest of the study area, at a depth of 2Km. During the night, 31mm and 40.9mm of rainfall where registered in Malveira da Serra and Sobral da Abelheira. A rock fall/slide mobilizing over 70m^3 of debris occurred on the southern sector of the study area affecting a complete section of the cliff. The landslide also evolved along a fracture oriented towards N40, 80W and deformation was limited by a N170, 90W fracture. Over the following days, erosion began to act upon the upper section of the cliff causing small superficial slides.

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4. Conclusions

The main problem in this research work is about data representativeness, i.e. whether the rainfall data measured at the meteorological stations are representative of the conditions on the beach. The issue arises due to the geographical position of the study area: on the northwestern flank of Serra de Sintra, the orographic effect on precipitation forces local showers that may not extend to the meteorological stations sites. Thus, it is likely that rainfall may actually be underestimated.

Nonetheless, it is interesting to observe that the time the cliff took to respond to climatic forcing coincided with the 100mm of rainfall threshold for a period of 20 days. During the 28th and 29th of December, the majority of unstable sectors along the cliff responded to 50mm of rainfall in two days by failing. Over the following days, rock ledge failure was practically inexistent and deformation was limited to the slope deposits where water content was higher. It is also important to point out the possibility that the earthquake which took place on the 5th of March contributed to the rock fall/slide that occurred shortly after that date. Nevertheless, the occurrence of 30 to 40mm of rainfall on that same day makes it difficult to separate both effects.

The N40 fracture set has proven to play an important role in the definition of rock fall failure plains. Perpendicular fracture sets tend to limit propagation of deformation sideways, which inevitably controls size and magnitude of rock falls.

Depending on rock ledge position along the slope and on rock fall location, the geomorphic response to future events related to climatic forcing will be different. Processes such as subsurface flow, rock and fracture weathering, fracture sediment expansion, and bed expansion and retraction from winter to summer tend to progressively reduce rock stability. Ledge failure momentarily renews stability along the ledge but destabilizes further the sections located above. This is particularly clear where slope deposits or marl beds are placed immediately above the ledge, because it triggers retrogressional superficial sliding.

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