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Letter

Downwearing rates on shore platforms of different calcareous lithotypes

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ABSTRACT

Vertical lowering (downwearing) of shore platform surfaces is a very important mechanism in their morphological evolution albeit much remains incompletely understood. The efficacy of mechanical and chemical weathering acting on a given substrate, together with erosional processes, influences downwearing rates. In order to determine the relationship between lithotypes and downwearing rates, data collected from a Transverse Micro-erosion Meter were obtained for shore platforms of three different calcareous lithotypes (biocalcarenite, calcarenite and carbonated siltstone) along the central Algarve coast (Southern Portugal). Downwearing rates ranged between 0.096 mm year^{-1} and 1.676 mm year^{-1} in biocalcarenite and weakly cemented calcarenite, respectively. In addition, physical properties of the rocks comprising the platforms were measured, including uniaxial compressive strength (as determined by the Point Load Test), porosity, and calcium carbonate content. The results show that downwearing depends primarily on the intrinsic properties of the substrate. Porosity, in particular, acts in two ways: (i) it tends to weaken the substrate; and, (ii) it controls the downward extent of the water percolation and therefore the depth of the weathering mantle subject to erosion by waves and currents.

1. Introduction

Active shore platforms occur within the intertidal zone in rock and cohesive substrates. Shore platforms width, slope and morphology depend on the substrate attributes including lithology, rock mass properties and structure, fractures direction and density as well as on the amount of time that weathering and erosional processes exceed the threshold determined by the balance between energy and rocks resistance (Robinson, 1977a, b; Trenhaile, 2000; Sunamura, 2005; Hall, 2011). Shore platforms evolution involves the combination of two vectors: horizontal (backwearing) and vertical (downwearing). Downwearing on shore platforms is the surface vertical lowering promoted by several weathering processes, which contribute to reduce the rock strength (Sunamura, 1996) leading to the formation of a weathering mantle at the platform surface easily eroded by waves and currents. The depth of the weathering mantle depends on the depth which weathering processes operate and therefore discontinuities in the rock such as fractures and voids.

Both the micro-erosion meter (MEM), and its variant the transverse micro erosion meter (TMEM), have frequently been used to estimate downwearing rates on shore platforms (e.g., Robinson, 1976; Gill and Lang, 1983; Stephenson and Kirk, 1996; Stephenson and Thornton, 2005; Trenhaile and Porter, 2007; Stephenson et al., 2010). As Stephenson and Finlayson (2009) concluded in their review on the use of micro-erosion meters, MEMs provide data that contribute to better knowledge about erosion rates over short time and small spatial scales. Aiming to combine the accuracy of downwearing measurements with the survey of larger spatial scales than the ones provided by MEM and TMEM, the terrestrial laser scanner technique underwent significant advances concerning the micro-scale analysis of erosion rates (e.g., Gómez-Pujol et al., 2006; Swantesson et al., 2006a, b).

This study aims to compare downwearing rates based on TMEM data on shore platforms cut into calcareous rocks (biocalcarenite, carbonated siltstone and differently cemented calcarenites) of different physical properties such as porosity, mechanical strength and durability.

2. Study area

The coastal sector at the Algarve southern coast, which comprises the study area (Fig. 1), intercepts a Miocene sequence composed of metre-scale layers of micritic limestone, biocalcarenite, sandstone, and siltstone. Shore platforms in the intertidal zone vary along the study area with respect to constituent lithology, roughness, topography, and slope.

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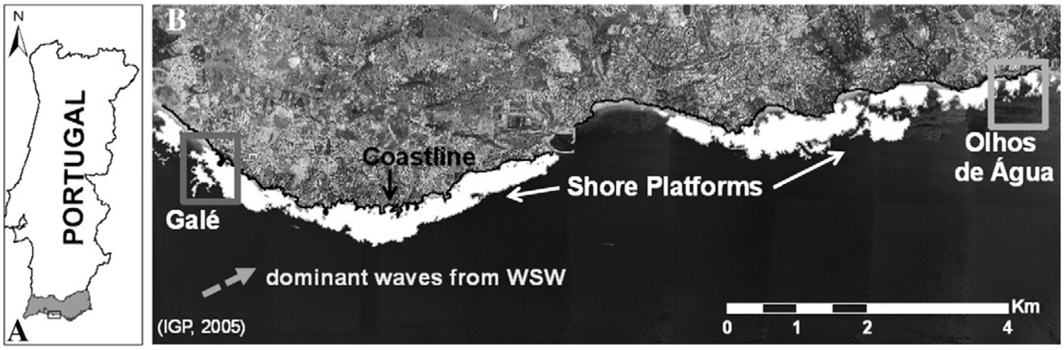

Fig. 1. (A) Location of the study area and (B) Transverse Micro Erosion Meter (TMEM) stations.

The studied coastline 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). The annual mean temperature of coastal waters ranges between 15 and 20 °C and salinity is 35. Offshore wave climate is dominated by WSW waves (71%) and SE waves during 23% of the year. Average annual significant offshore wave height is 1.0 m and average peak period is 8.2 s (Costa et al., 2001).

3. Methods

3.1. Rock mechanical strength, durability, and porosity

In order to quantify the relationship between the mechanical strength of the rocks upon which shore platforms are sculpted and downwearing rates, in situ measurements of rock hardness index were made using an 'L' type Schmidt hammer. The Schmidt hammer is commonly used to determine rock mechanical strength in the field and has often been used on coastal morphology research (e.g., Stephenson and Kirk, 2000; Trenhaile and Porter, 2007; Naylor and Stephenson, 2010). However, even if the surface rocks' hardness can reasonably be estimated based on the rebound hardness as determined by the Schmidt Hammer, the rocks' microstructure, such as grain size and porosity, is very important on the rock hardness (Kahraman, 2001; Shalabi et al., 2007, Demirdag et al., 2010). Thereby, rock blocks were collected for laboratory testing adjacent to the stations where erosion rates were measured (see Section 3.3). Point load strength index tests (ISRM, 1985) were performed rather than uniaxial compressive tests. The advantage of this test stems from using relatively unprepared specimens for a rock strength test. These measurements provide an index of tensile strength that can be empirically related to uniaxial compressive strength (UCS).

Slake durability tests (ISRM, 1977) were performed to assess the resistance offered by rock samples to weakening and disintegration when subjected to standard cycles of drying and wetting. Other physical properties, including saturated unit weight, dry unit weight, porosity, and water absorption were also measured. At least ten specimens from each representative sample of rock material were machined to conform closely to the geometry of a prism with the minimum mass of 50 g (ISRM, 1977).

3.2. Calcium carbonate content

A positive correlation has previously been observed between the total carbonate content and mechanical strength of the rocks exposed along the Algarve coastal cliffs (Marques, 1997). In physical terms, this is because carbonate cement or matrix reduces the porosity relative to detrital rocks and, as a consequence, mechanical strength increases (Demirdag et al., 2010). Sub-samples from the rock blocks taken for point load tests, slake durability tests, and porosity tests (as described above) were used to determine the total amount of $CaCO_3$ by measuring weight loss before and after digestion in 30% HCl.

3.3. Downwearing measurements

Four triangular sections designated here as 'stations,' were chosen to quantify the rate of downwearing of surface shore platforms by using a TMEM which allows monitoring of 255 points following the methodology developed by Neves et al. (2001). Two TMEM stations were positioned at Olhos de Água (OA1A and OA1B) and two at Galé (G1A and G1B). The TMEM frame is an equilateral triangle with 33.0 cm side constructed in stainless steel resistant to marine environments. The frame legs are 9.0 mm thick to guaranty high resistance against deformation. The digital comparator is a SYLVAC with 0.001 mm of resolution. Screws corresponding to the vertices of the triangular TMEM sections were fixed into the rock at each station. The initial set of micro-topography measurements (255 points inside each TMEM triangular section) was performed monthly between September and December 2008 and, after this initial set, measurements were performed bimonthly until September 2009. The monthly and bimonthly measurements were performed in order to observe if seasonal differences occurred due to environmental variables such as temperature as observed by Spate et al. (1985) in laboratory experience. As opposed to the findings of Stephenson and Kirk (1998), no seasonal differences were observed, probably because temperature range between measurements was not high enough and this parameter does not significantly affect the surface lowering rate in some rocky shore platforms (Spate et al., 1985). The supporting screws directly and permanently bolted into the rock during the1 year of measurements, as well as the careful handling of the comparator, avoided surface damage by successive measurements. Total downwearing rates were quantified by calculating the difference between the mean value of the 255 points obtained during the first measurements and those taken 12 months later.

4. Results

4.1. Mass properties

The shore platform at the study area exposes calcareous rocks with highly variable values of calcium carbonate content and porosity (Table 1). A negative correlation ($R^2 = 0.53$) between porosity and $CaCO_3$ content was found for the analyzed samples.

The mean values of the Schmidt hammer rebound (r) measured *in situ* ranges between 23 and 48, which roughly corresponds to a Uniaxial Compressive Strength (UCS) range from 27 to 100 MPa (Table 1). Rock blocks saturated in sea water for 48 hours showed mean values of resistance index ($I_{s(50)}$) of between 1692 and 1752 kPa, which corresponds to UCS values between 37 and 39 MPa. Slake durability tests revealed that the standard value I_{d2}(%) ranged between 90.3% and 97.4% of the original dried weight after different

Table 1
Data from TMEM stations, rocks physical properties and downwearing rates. Heights are reported to the national hydrographical zero (−2 m b.m.s.l.). UCS, Id2 and porosity are mean values.

TMEM stations	TMEM height (m)	Lithotype	$CaCO_3$ (%)	Schmidt index (r)	UCS (MPa)	I_{d2} (%)	Porosity (%)	Downwearing rate (mm $year^{-1}$)
G1A	1.671	Biocalcarenite	92.55	48	100	97.4	10.1	0.096
G1B	2.110	Siltstone	21.79	23	28	90.3	19.7	0.640
OA1A	1.170	Calcarenite	66.47	32	45	96.9	14.7	0.361
OA1B	2.021	Calcarenite	63.33	23	27	93.7	21.4	1.676

numbers of slaking cycles (Table 1). According to the durability classification system proposed by Franklin and Chandra (1972), the studied rocks range from extremely high (G1A, OA1A) to very high (G1B, OA1B) durability.

The Schmidt hammer rebound (r), UCS and durability correlate inversely with porosity, the more porous rocks being less resistant (Fig. 2A, B). Pores in the fabric of a rock decrease its strength, and a small volume of pores can produce an appreciable mechanical effect (ISRM, 1977). In contrast, a positive correlation between $CaCO_3$ content and r ($R^2 = 0.65$), UCS ($R^2 = 0.61$) and durability ($R^2 = 0.85$) was found for the analyzed samples. Accordingly, the $CaCO_3$ play a dual role in that it: (i) reduces the volume of voids by precipitating as a chemical cement between the grains and, (ii) the large aragonite and calcite shells that occur in G1A lithotype contribute to increase the rock's mechanical strength and durability (Litvin et al., 1997; Achal et al., 2011). In contrast, the rocks showing high carbonate content are expected to be more vulnerable to chemical weathering.

4.2. Rates of downwearing

Downwearing rates ranged between a minimum value of 0.096 mm $year^{-1}$ and a maximum value of 1.676 mm $year^{-1}$ (Table 1). When comparing downwearing rates between G1A (biocalcarenite) and G1B (siltstone), the latter is more than six times higher (Table 1). Additionally, despite being located in a more sheltered sector (Fig. 1) TMEM stations OA1A and OA1B showed respectively downwearing rates of more than three and seventeen times higher than TMEM station G1A, indicating the importance of the rocks' mass properties on vertical erosion. Downwearing rates are positively correlated with porosity and inversely correlated with UCS (Fig. 2C, D) and durability, the latter being only weakly correlated ($R^2 = 0.20$).

5. Discussion

The quantification of surface lowering rates in natural environments is very important to understanding landform evolution and to solve questions related to the origin and possible inheritance of shore platforms from previous highstands, and is of extreme significance in investigating processes in a wide range of lithologies (Stephenson and Finlayson, 2009).

Carbonate sediments have great textural diversity and undergo various diagenetic processes that change their physical properties, among them porosity (Friedman, 1975; Gamage et al., 2011).

Downwearing rates in the study area appear to be strongly related to mass properties of the rocks. The calculated downwearing rates (Table 1) were higher for the more detrital and porous rocks, comprising siltstone (G1B) and calcarenite weakly cemented (OA1A and OA1B), than for the more carbonated and less porous rocks (G1A). The highest downwearing values correspond in both well exposed and sheltered coastal sectors to the higher elevations (Table 1), which

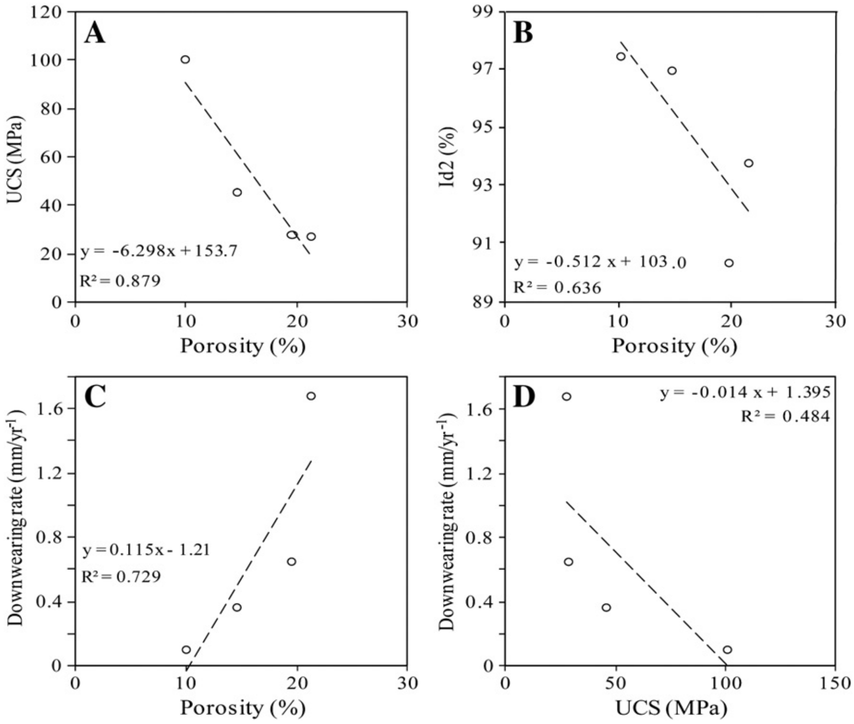

Fig. 2. Relationships between rocks physical properties and downwearing rates.

are rarely reached by breaking waves. These results suggest a substrate control on downwearing rates rather than wave abrasion.

In our study, downwearing rates correlate positively with porosity (Fig. 2C). Water is important either for chemical or physical weathering. Solution, hydrolysis, oxidation and reduction, carbonation and cation exchange are mechanisms of chemical weathering involving water. Therefore, the larger the number of voids, the higher the contact surface between the water and the rock which enhances the chemical reactions that also depend, among other factors, on the temperature and the rocks composition. Moreover, the above-referred chemical actions do not exhaust the role of water as a weathering agent. For instance, wetting and drying, salt weathering and frost weathering involving volumetric changes within the rocks' pores, fissures and other discontinuities have been reported as important mechanisms in the shore platforms evolution (e.g., Robinson and Jerwood, 1987; Stephenson et al., 2004; Trenhaile, 2004; Naylor and Stephenson, 2010). In addition to increasing the contact area between rock and water, porosity also contributes to weaken the substrate (ISRM, 1977).

The value for biocalcarenite downwearing measured in our work is similar to that observed by several other authors for limestone in shore platforms between 0.034 and 0.400 mm year^{-1} (Neves et al., 2001, Cucchi et al., 2006, Swantesson et al., 2006a, Furlani et al., 2010) whereas lowering rates in calcarenite and siltstone fall within values reported by other works for detrital rocks: (i) siltstone: 1.8 mm/year^{-1} (Gill and Lang, 1983), (ii) sandstone: 1.254 mm/year^{-1} (Porter et al., 2010), and (iii) greywacke: 0.300–0.405 mm/year^{-1} (Gill and Lang, 1983). That difference between carbonate and more detrital rocks is likely to be related to mass properties like fabric and porosity. Faster vertical erosion rates in carbonate rocks (0.009 mm/year^{-1}) relative to crystalline ones (0.004 mm/year^{-1}) were observed by Swantesson et al. (2006a) and were attributed to greater bio-erosive activity in carbonate rocks. Furthermore, Porter et al. (2010) stated that they did not observe any relationship between rock hardness and downwearing rates, even though in their study they obtained 1.254 mm/year^{-1} for the softer sandstone, and 0.722 mm/year^{-1} for basalt.

To further investigate the importance of porosity, we parameterized data from our study and from other published data (Gill and Lang, 1983; Spencer, 1985; Stephenson and Kirk, 1998; Neves et al., 2001; Andrade et al., 2002; Swantesson et al., 2006a; Blanco-Chao et al., 2007; Stephenson et al., 2010) concerning rock texture, instead of grouping them in the conventional way by lithological composition. Our parameter attribution was based on general concepts such as: (i) crystalline rocks are less porous than sedimentary rocks; (ii) fine-grained rocks are less permeable than coarse-grained sedimentary rocks; and (iii) the texture of rocks with large fossils is more heterogeneous (i.e., more porous) than those containing microfossils. When comparing texture with downwearing rates based on the above referenced authors, an overall positive relationship is established ($R^2 = 0.4$); that is, the more porous the rock, the greater the rate of downwearing. However, this is not true for all the considered examples.

As demonstrated in this work, porosity decreases the rock mechanical strength but porosity also controls permeability (Gamage et al., 2011), that is, the ratio between runoff and water infiltration. Thus, in the more impermeable substrates like mudstone, runoff can be responsible for high downwearing rate. Additionally, physical breakdown of crystalline rocks such as the granite, composed by minerals showing different thermal expansion and contraction may be an efficient mechanism in regions experiencing large temperature fluctuations.

Therefore, the rock's porosity and fabric influences the downward extent of water penetration and, consequently, the downward extent of chemical and physical weathering whereas lithology may also influence other weathering mechanisms depending on environmental variables. Waves and currents then remove the resultant weathering mantle and the weakened substrate exposing new fresh portions of the shore platform surface to weathering (Davidson-Arnott and Ollerhead, 1995; Davidson-Arnott and Langham, 2000).

6. Conclusion

The relationship between physical lithological properties and downwearing rates on shore platforms of three different lithotypes was investigated. This study showed that rock porosity and mechanical strength are important factors that control downwearing rates. Mechanical strength of the carbonate rocks correlates positively with calcium carbonate content. Downwearing rates are inversely related to both mechanical strength and calcium carbonate content while porosity is positively correlated with downwearing rates.

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