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ORIGINAL

Characterization of abrasion surfaces in rock shore environments of NW Spain

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Abstract Despite the recent upsurge in rock coast research, many aspects of abrasion and their relationships to other processes remain poorly understood. In this paper, mechanisms subsumed under the general term *abrasion* were investigated at the beaches of Oia and Sartaña along the Galician coast of NW Spain, in particular at the micro- to meso-scale (mm–cm). Relationships between abrasion and mechanical rock strength served to explore feedbacks between weathering and abrasion on rock coasts, based on measurements of rock surface strength by means of the Equotip (Proceq) method, and stereomicroscope analyses of rock surfaces undergoing varying degrees of abrasion. The results suggest that (1) abrasion along near-vertical rock surfaces leads to a decrease in rock strength with elevation above the top of the basal sediment layer, (2) abrasion processes encompass two different modes, namely, the wave-induced sweeping and dragging of sand and gravel, and the projection of clasts against rock surfaces, each mode depending predominantly on the grain size of the abrasive agent, and (3) the two abrasion modes produce different rock surfaces whose roughness is strongly influenced by the properties of diverse minerals, in particular fracture and cleavage.

Introduction

In the last two decades of geomorphological research on rock coast environments, an increasing number of studies have focused on investigating the role and nature of wetting and drying processes (e.g., Stephenson and Kirk 1996, 1998; Stephenson 2000; Kanyaya and Trenhaile 2005; Foote et al. 2006; Swantesson et al. 2006), whereas less attention has been given to erosion by processes associated with wave forces, such as abrasion and quarrying (see recent overviews by Naylor et al. 2010; Dasgupta 2011; Moses and Robinson 2011; Trenhaile 2012). Abrasion is certainly one of the major erosive forces operating in rock coast environments but overall it has been surprisingly neglected in research on the erosional origin of landforms such as shore platforms, probably because of the difficulty of measuring abrasion rates in situ, and because it operates at a rather restricted spatial scale. Nevertheless, the last 40 years has seen a considerable advance in quantitatively assessing downwearing/swelling-induced changes in surface elevation by means of, for example, the well-known traversing micro-erosion meter (TMEM; e.g., Robinson 1977; Williams et al. 2000; Blanco-Chao et al. 2007; Porter et al. 2010a, 2010b; Trenhaile and Lakhan 2011; Stephenson et al. 2012).

In coastal geomorphology, abrasion has been defined as the erosion of a rock surface by the movement of sediment particles through wave action (Trenhaile 1987 p. 25, 1997 p. 265; Sunamura 1992 p. 78). Although this movement can potentially occur from the breaker line to the level reached by wave run-up, its efficacy tends to decrease rapidly below the water line (Robinson 1977; Trenhaile 1997 p. 265, 2000). The term *abrasion* subsumes a variety of mechanisms ranging from friction by sand to the impact of clasts projected against the rock surface, although it commonly also includes the attrition of clasts. The occurrence and intensity of this range of abrasion processes depend on factors controlling the movement of sediment particles, such as grain size and wave energy, but also on the geometry of the rock surface and the thickness of sediment accumulation. In this context, the term *weathering* usually implies a general decrease in rock strength and often also an increase

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in the roughness of the surface (McCarroll and Nestje 1996), the latter being more accentuated in rocks of heterogeneous mineral composition. Abrasion, by contrast, results in an increase in the mechanical strength of the rock (e.g., Blanco-Chao et al. 2006a, 2007; Feal-Pérez et al. 2009) because it removes the weathered layer and thereby reduces roughness. Abrasion also impedes the biological colonization of the rock and, consequently, bio-erosion and bio-weathering processes that deteriorate rock surfaces at the micro-scale (mm; e.g., Naylor et al. 2012).

Surface rock strength can be assessed by means of the Equotip durometer. Working on the same principles as for the Schmidt hammer test, this hardness testing device was originally developed for metallic materials but has been used successfully to predict the unconfined strength of intact rocks (e.g., Verwaal and Mulder 1993; Hack et al. 1993; Meulenkamp and Grima 1999; Aoki and Matsukura 2008). To date, only a few geomorphological studies have applied the Equotip to assess the reduction in strength of weathered rocks (e.g., Wakasa et al. 2006; Aoki and Matsukura 2007; Mol and Viles 2010; 2012; Viles et al. 2010).

Within the wider context of abrasion outlined above, the aim of the present study was to investigate the reduction in rock strength expected to occur across near-vertical surfaces with elevation above the top of the sedimentary layer that acts as the abrasive agent. Other main targets were to identify the effects of different modes of abrasion in explaining the vertical variation in rock strength at micro- to meso-scales (mm–cm), and to characterize the role of the mineralogy on the mechanical properties of abraded rock surfaces.

Physical setting

Two study areas of contrasting geology but exposed to similar wave conditions were chosen for the fieldwork: the beaches of Oia and Sartaña along the Galician coast of NW Spain (Fig. 1). The embayment of Oia has been studied intensively in the past. Its morphodynamics is thus well known, and the area provides good examples of different abrasion mechanisms acting on the same rock type (Blanco-Chao et al. 2003, 2006b). The narrow embayment is lined by a coarse-grained beach in the upper zone of a wide shore platform eroded into granitic rocks. The grain size of the beach sediments decreases southward, characterized by boulders in the northern and central sections, and pebbles to cobbles in the southern section. The main rock types comprise two medium-grained granitic suites that, besides quartz and a variety of heavy minerals, are composed of 27% K-feldspar and 24% plagioclase. Pegmatitic dykes are also abundant in the area.

At Oia, three study sites were selected, site 1 being located at the rock flank near the southern limit of the beach where the beach sediment has the finest grain sizes, and where sediment thickness varies strongly due to elevation changes along the beach profile. The dominant mode of abrasion at the southern end of the beach is the sweeping and dragging of coarse sand and gravel, which explains the vertical displacement of the abrasion strip in the wake of changes in sand cover. The abraded rock surface has a very uniform and polished surface. Site 2 comprises an isolated boulder 1.5 m in diameter situated at the mean high-tide level close to site 1, and with the same type of sediment. Site 3 is a structural channel at the center of the embayment. The abrasives in the channel are boulders, cobbles and pebbles, with a smallest size of 5 cm. Because the channel is narrow (about 1.5 m wide), it induces a compression and acceleration of the incoming waves, leading to high turbulence that continuously projects clasts against the channel walls. This major abrasive mechanism causes detachments and plucking, resulting in an uneven microtopography.

The Sartaña study area comprises a medium- to coarse-grained sand beach located in a small embayment eroded along the lithological contact between metamorphic and igneous rocks at its western flank. The low cliffs at the back of the beach and the rocks outcropping at the mid-level of the beach consist entirely of a quartz-rich schist that is characterized by very narrow foliation planes dipping about 35° to the NE. The beach is fronted by a narrow shore platform that remains exposed at low tide. At the middle of the beach is a rock stack about 3 m high, its base showing a polished abrasion surface that is totally free of biological activity. Above the basal abrasion fringe is an area with recent erosion scars where rock fragments have recently been detached along the foliation planes of the schists, whereas other areas are colonized by barnacles. This is followed upward by a supratidal weathering area.

The tidal regime of the western coast of Galicia is mesotidal, with a mean spring range of 3.75 m. Along the Sartaña coastal sector, offshore waves with significant heights of 1–3 m and associated periods of >6 s are the most frequent (70%), approaching mostly from the NW and W (>70%). The coast of Oia is exposed to waves propagating from the NW, W and SW, with significant heights of 1–3 m and periods of 10–14 s representing 78% of the total wave spectrum.

Materials and methods

The Equotip was deployed along three vertical profiles at Oia and one profile at Sartaña, the intervals between sampling points being 10–15 cm. The elevation of the sampling points was measured taking the lowest point of each profile just above the top of the sediment as the zero level.

At the three Oia study sites, the profiles represent three vertical rock surfaces located at mean high-tide elevation. Profile 1 (S1) extends 180 cm above the base level at the

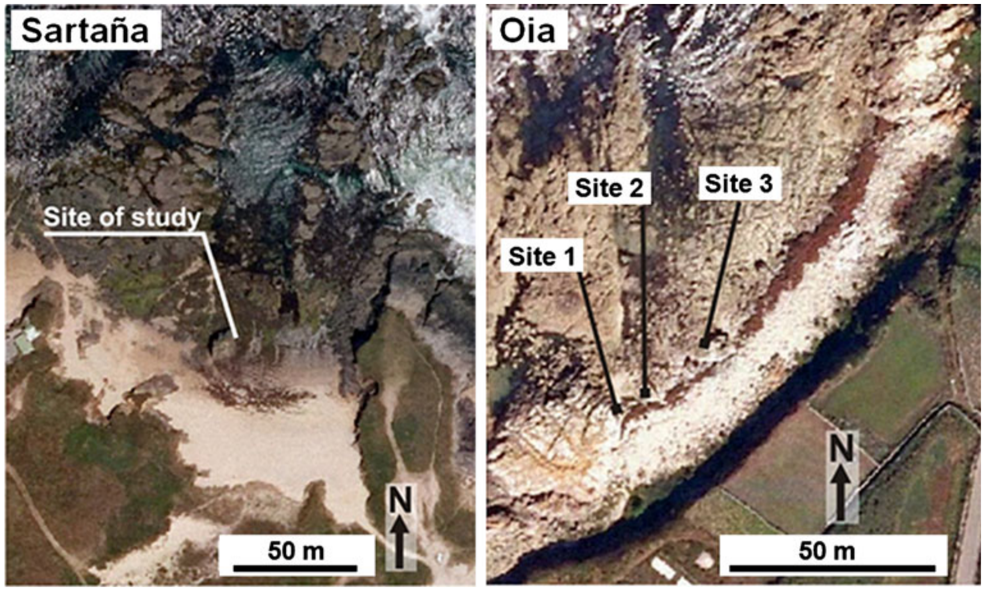


Fig. 1 The Sartaña (43°33′21″ N, 8°16′32″W) and Oia (41°59′ 52″N, 8°16′32″W) rock coast study areas in NW Spain

southern flank of the beach, profile 2 (S2) 125 cm up a rock boulder, and profile 3 (S3) 120 cm up the wall of the structural channel described above. At Sartaña beach, a single, 180-cm-long vertical profile was sampled at a stack located at the mid-point of the beach.

A total of ten readings were taken in each case. Equotip measurements are recorded as L values, which are interpreted as being equivalent to rock strength. For each profile, the Huber M estimator of the mean L values was calculated using SPSS v.15. This M estimator is a robust version of the classic mean, and avoids the effects of possible outliers.

In both study areas, several rock samples were collected (1) from the basal surfaces subjected to abrasion, and (2) from the upper surfaces that are only occasionally or never abraded, and in which weathering is the dominant process. The rock samples were analyzed under a stereomicroscope to identify differences in the resultant rock surfaces.

To characterize the abrasive agent, a sediment sample was taken at each site and analyzed in the laboratory. An exception was site S3 at Oia, where the abrasives consist of pebbles, cobbles and boulders (5–60 cm longest axis). In the laboratory the sediments were air-dried, sieved through a set of meshes from 0.05 to 6.3 mm, and the residue in each sieve weighed. These data were processed by means of Gradistat version 4 software (Blott and Pye 2001), and then statistically evaluated according to the method of Folk and Ward (1957). The biogenic sediment fraction was determined by acid leaching of $CaCO_3$ with 10% HCl.

Results

The grain-size analyses document the substantial textural differences between sediments from the two study areas (Table 1). In the channel at Oia (profile S3) the sediments are very coarse, comprising material ranging from well-rounded pebbles with a minimum longest axis of 5 cm, to boulders of up to 40 cm longest axis. In the southern sector of Oia (profiles S1 and S2), the sediment consists of moderately sorted sandy fine gravel. The most abundant component is quartz, followed by feldspar, although in the coarser fractions (>2 mm) there is abundant mica and fragments of granite and pegmatite. The grains are sub-angular to sub-rounded. With the exception of a few scattered shells, there is no bioclastic material in the sediments at Oia. By contrast, the sediment at Sartaña consists of moderately well-sorted coarse sand (Table 1). The most abundant component is sub-rounded to rounded quartz, with some rock fragments in the coarser fractions. The bioclastic fraction ranges from 13% to 31%.

The Equotip data show a common pattern at all the sites, with higher L values in the lower strips subjected to abrasion, decreasing upward as abrasion becomes less frequent or is absent (Fig. 2). There are statistically significant differences between the measurements from the abrasion zone and those from above it (Table 2). Rock strength and elevation show a significant negative correlation in all profiles (Table 3). At Oia, the best fits are achieved for the S1 and S2

Table 1 Sediment characteristics of the gravel and sand beaches in the two study areas (sediments of site S3 at Oia were not analyzed)

	Oia, sites S1 and S2		Sartaña beach	
	(mm)	(phi)	(mm)	(phi)
Mean	2.48	–1.31	0.61	0.70
Sorting	1.71	0.77	1.58	0.66

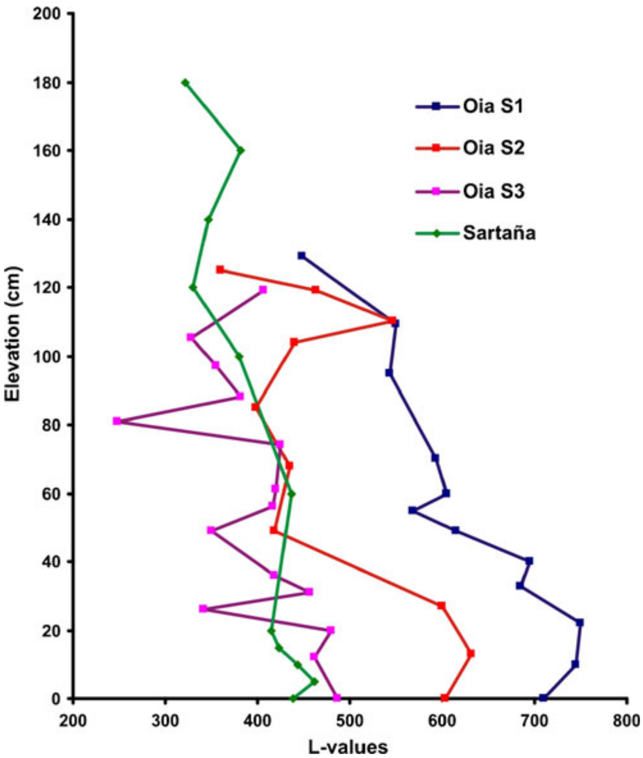


Fig. 2 Rock strength variation represented by Equotip rebound L values recorded at the four study sites

sites, corresponding to the southern flank and the boulder where the sweeping of gravel against the rock surface is the dominant mode of abrasion.

The standard deviation of the L values shows a weak negative correlation with rock strength for sites S1 and S3 at Oia and for the Sartaña site. There is a weak positive correlation with elevation for the Oia site S1 and for Sartaña, but none was found for the Oia site S3 (Table 3). The Oia S2 profile is the only showing moderate and statistically significant correlations between the standard deviation and both rock strength and elevation. Despite the relatively low correlation coefficients, these data suggest an increase in the dispersion of the values. This could be caused by (1) an increasing irregularity of the rock surface as the degree of weathering increases, and (2) a varying degree of weathering for the various rock-forming minerals.

Table 2 Statistical analyses of Equotip rebound values (L) determined at the three Oia (S1 to S3) and the Sartaña sampling sites, with Mann-Whitney U tests (*p* values) revealing significant differences between sample points undergoing frequent abrasion (*ab.*), and occasional or no abrasion (*no ab.*)

Site	Surface	Mean	Min.	Max.	*p* values
Oia S1	Ab.	722.2	684.3	750.3	0.013
	No ab.	522.5	257	694.2	
Oia S2	Ab.	611.6	600.7	631.3	0.019
	No ab.	429.7	359.7	546.0	
Oia S3	Ab.	475.5	461.1	486.0	0.015
	No ab.	379.24	248.5	457.2	
Sartaña	Ab.	431.1	263.0	515.0	0.013
	No ab.	350.3	170.0	456.0	

Table 3 Pearson correlation coefficients for relationships amongst rock strength, elevation (*elev.*), and the standard deviation (*std*) of L values at the Oia and Sartaña sites (statistically significant differences at the 95% confidence level are indicated in italics)

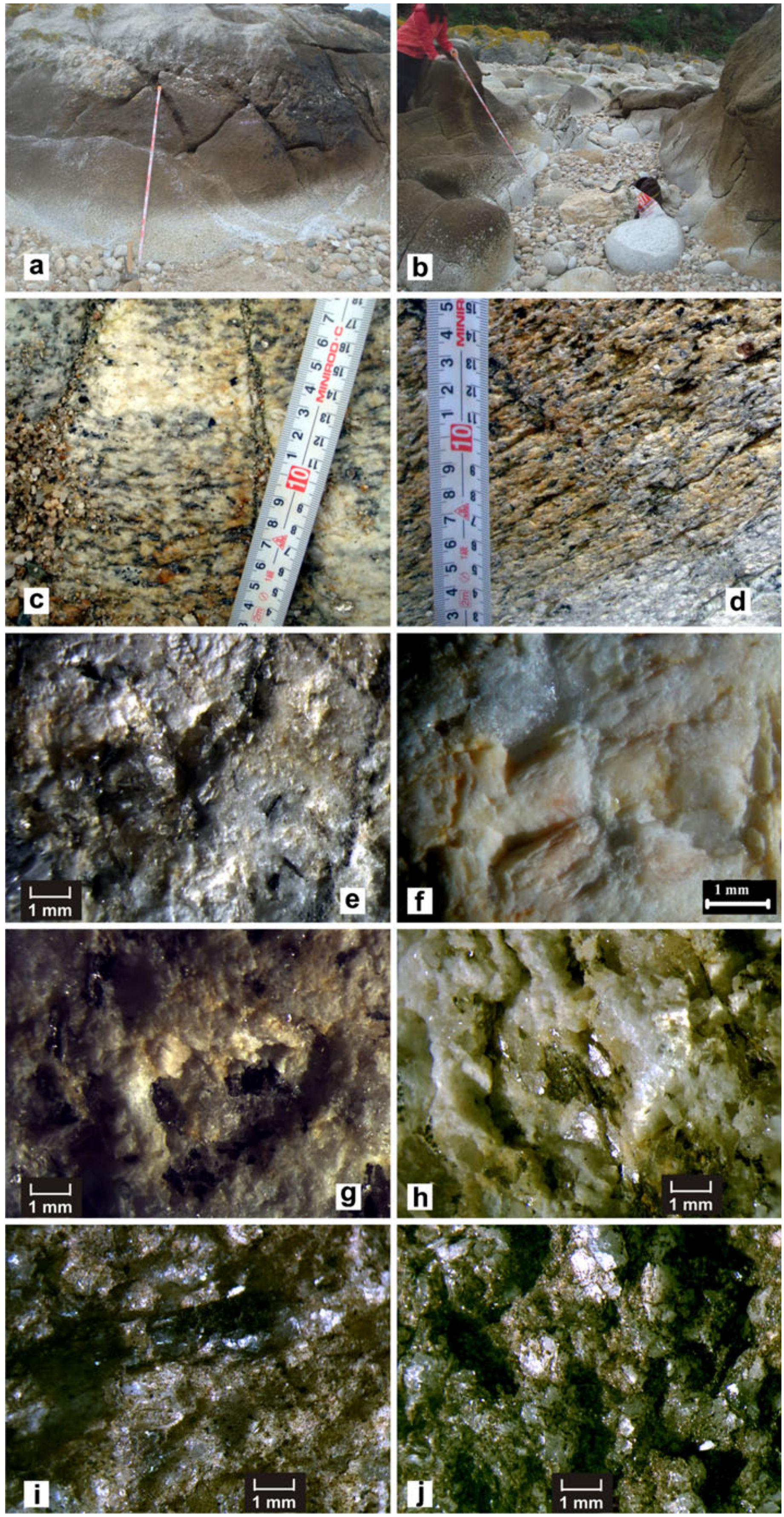
Site	Strength/elev.	Std/elev.	Std/strength
Oia S1	*–0.93*	0.30	–0.38
Oia S2	*–0.63*	*0.70*	*–0.63*
Oia S3	*–0.57*	0.03	–0.31
Sartaña	*–0.89*	0.37	–0.55

To the naked eye, the abraded rock surfaces appear smooth and polished (Fig. 3a, b), and lacking sharp edges along discontinuities such as joints or foliation planes of the schists. However, a more detailed analysis reveals that the resultant surfaces differ depending on the dominant process of abrasion. As the clast size increases, and impacts by clasts become dominant, the surface appears more irregular than that of the same rock abraded by the friction of gravels (Fig. 3c, d).

Under the stereomicroscope, the rock surfaces show features controlled by the properties of the minerals, mainly cleavage and fracture. Those minerals with a good cleavage and irregular fracture, such as feldspars, tend to give uneven surfaces that follow the foliation planes (Fig. 3e–h). In places where abrasion is caused mainly by friction, as in the case of sites S1 and S2 at Oia, edges tend to be smooth even though fractures follow the foliation planes of the minerals (Fig. 3e, g). However, when the sediments are coarser, as in the case of site S3 at Oia, the fractured minerals commonly show sharp edges (Fig. 3f, h). Minerals without cleavage, e.g., quartz, only show typical conchoidal fractures irrespective of the grain size of the abrasive sediment. Mica, by contrast, has a perfect foliation, is extremely flexible, and does not show any type of fracture. Here it was observed that, when the cleavage planes of the mica were orthogonal to the abraded rock surface, they were bent and folded but not eroded. However, when cleavage planes show low angles with the abraded rock surface, the mica was eroded by flaking (Fig. 4).

At the Oia sites S1 and S2, where the main abrasive mechanism is friction, there is a gradual transition in the profile. In areas not subjected to abrasion, the rock always shows a more irregular surface on which the contacts between minerals define the microtopography (Fig. 3i, j). At site S3 of Oia, scattered marks left by the impact of clasts can be found up to 1 m above the base of the profile.

Fig. 3 **a** Study site 1 and **b** study site 2 at Oia. **c**, **e**, **g** Examples of abrasion surfaces at site 1 and **d**, **f**, **h** at site 2. **i** Examples of surfaces not undergoing abrasion at site 1 and **j** at site 2



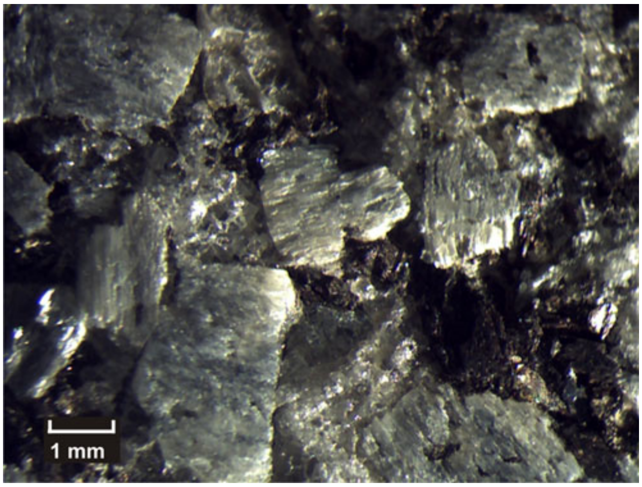


Fig. 4 Photograph of muscovite in an abrasion surface comprising pegmatite

In the quartz-rich schist at Sartaña, a fine-grained metamorphic rock, the surfaces under abrasion show a microtopography where, as expected, the quartz grains protrude above the surface, although some depressions were probably caused by the detachment of quartz grains (Fig. 5d, e). In those parts of the stack that are not subjected to frequent abrasion, the microtopography of the rock surface is completely controlled by the foliation planes of the schist (Fig. 5f). The upper fringe, which is too high for abrasion, shows a weathered and very irregular surface. Here, quartz veins with angular edges protrude above the lowered rock surface (Fig. 5g), and small pits (<2 mm) characterize the microtopography.

Discussion

A necessary condition for the effectiveness of abrasion is that the sediments must be moved in contact with the bedrock surface by bed load transport. Bed load is defined as sediment transport in which the particles move in an almost continuous contact with the bed by rolling, sliding or jumping (e.g., Aagaard and Masselink 1999). The movement of particles on coarse-grained beaches is controlled by the flow asymmetry between swash and backwash, an effect that becomes prominent in sediments coarser than 1.5 mm (Masselink and Li 2001). In the case of gravels, particle shape becomes important as it determines the buoyancy of clasts that can be thrown by the short-energy peak of the swash (Bluck 1967; Williams and Caldwell 1988). There must therefore be a minimum grain size and/or shape that, in the unsteady flow of a broken wave, defines the type of movement of the particles acting as abrasives. In cases where the abrasive sediment is coarse enough to be projected against the rock (cobbles and boulders), the dominant mechanism is characterized by repeated impacts, and abrasion is reduced to the biggest clasts pivoting and rolling against the rock surface. The finer the sediment gets (finer gravels and sands), the more dominant does the abrasion mechanism of particle sweeping become. However, as wave energy increases, an increasing number of particles will be transported in suspension, which reduces the contact with the rock surface and hence abrasion (Robinson 1977).

The upshore extent of abrading surfaces also varies with the topography, and orientation to the incoming waves. On rock surfaces with very low slopes, the upshore extent of the abrading zone is defined by the horizontal movement of the sediment layer occurring along the seaward fringe of coarse-clastic beaches. As the slope of the rock surface increases, a vertical zonation can be identified, comprising a basal strip in which abrasion is dominant, and which is progressively transformed upward into surfaces increasingly dominated by weathering. The width of the abrasion zone in this vertical succession depends on the dominant abrasion mechanism, and on variations in the thickness of the sediment layer. The rock surfaces swept by sands and gravel usually show a gentle gradient from a polished basal abrasion strip to an irregularly weathered surface at the top. However, rock surfaces in which the abrasives are pebbles can show impact marks at elevations high above the polished basal strip.

For a given energetic environment (wave climate) and sediment size, the effects of abrasion on rock surfaces change with the properties of different rocks (mineral composition, grain size, foliation planes, and previous weathering), the main factor being the structure and size of the minerals. When impacts are the dominant mechanism, the abraded rock surfaces show irregularities defined by mineral properties, especially cleavage and fracture. Minerals with crystalline structures characterized by good cleavage, such as feldspar, show angular detachments following the planes of foliation. In quartz, by contrast, the fracturing mainly displays a conchoidal form, although there can also be other types of fractures. Minerals with a micaceous cleavage and no fracture, such as muscovite and biotite, are very flexible against impacts and thus difficult to erode.

The differences in strength between abrading rock surfaces and those not subjected to abrasion have been assessed in earlier work using the Schmidt rock test hammer (e.g., Blanco-Chao et al. 2006b, 2007; Feal-Pérez et al. 2009). The results obtained in the present study confirm that the Equotip detects the same type of variations in rock strength resulting from the frequency and the dominant mechanism of abrasion. However, it is important to keep in mind that the Equotip is very sensitive to the roughness of a surface to which it is applied. This has had a marked influence on the lower values of rock strength recorded across the abrasion strip of profile S3 at Oia, even though the erosion rates of the rock by abrasion are more severe than those along

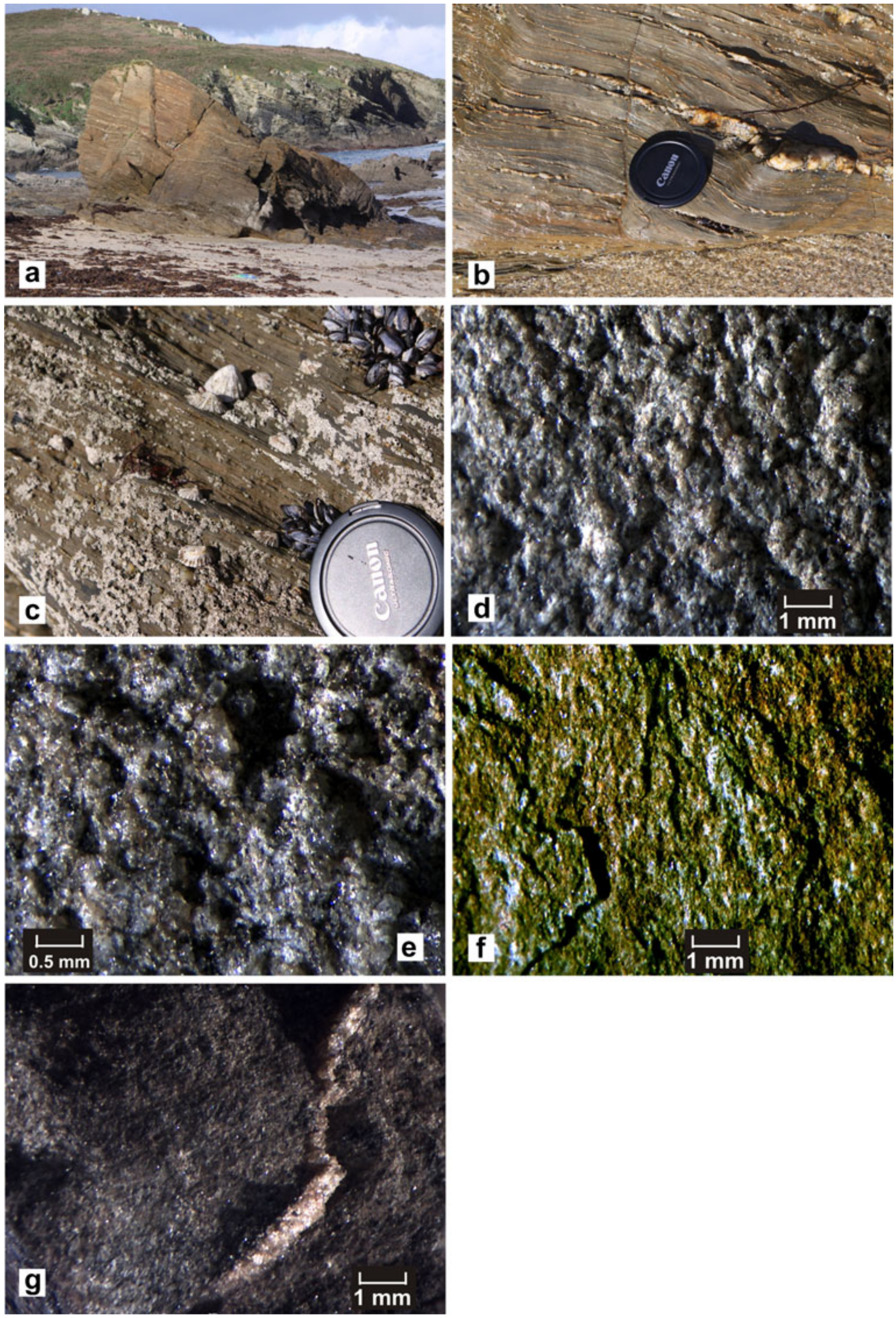


Fig. 5 **a** Rock stack at Sartaña beach. **b** Detail of the abrasion strip and **c** of the surface not undergoing abrasion. **d**, **e** Abrasion surface. **f** Rock surface above the abrasion strip. **g** Weathered, upper rock surface

profiles S1 and S2. Using a TMEM, Blanco-Chao et al. (2007) found an erosion rate of 0.35 mm year^{-1} at the base of profile S1, and a Schmidt hammer rebound value of 67.6; at the base of profile S3, the erosion rate was 1.88 mm year^{-1} and the Schmidt hammer rebound value 54.3. The L values obtained with the Equotip in the present study were also higher along profile S1 than along profile S3. The apparently contradictory results between the rates of erosion and rock strength can be explained by the different abrasion mechanisms active at the two sites. Compared to when abrasion by sweeping sands was the dominant mechanism, the roughness of the resultant microtopography was always higher when the abraded rock surface was shaped by impact.

The more uniform surface and the gradual change in rock strength detected along profiles S1 and S2 at Oia and along the Sartaña profile can be explained by the fact that abrasion by sweeping has an upper vertical limit. In the case of fine abrasives, an increase in wave energy will result in a larger number of particles being moved as suspended load, which results in a reduction of contact between the abrasives and the rock surface. There is thus an upper limit to abrasion above which suspended sediment particles rapidly decrease in number and hence become ineffective as an abrasive agent. This vertical limit was at about 30 cm above the top of the sediment layer at sites S1 and S2 at Oia, and about 50 cm at Sartaña. It is important to keep in mind, however, that this upper limit will vary in dependence of the thickness of the basal sediment layer, this being controlled not only by height variations in the beach profile, but also by other common processes such as scouring.

In contrast to sites S1 and S2 at Oia and the Sartaña site, the pattern of variation at site S3 at Oia is very irregular and the L values fall into a narrow range between 248 and 486, despite the finding of a progressive decrease in rock strength with elevation. The occurrence of impact marks at 1 m above the basal sediment layer proves that waves are able to project the local clasts to relatively high elevations. Although less frequent, repeated impacts at high elevations would be responsible for the more uniform microtopography along the entire profile, which is otherwise characterized by a rugged surface that will influence the behavior of the Equotip plunge.

Conclusions

Abrasion in rock coast environments contributes to an increase in bedrock strength and leads to a decrease in the roughness of the rock surface; at macro-scales, this results in the typical polished coastal rock surfaces. Along the near-vertical surfaces studied here, there is a good correlation between the decrease in rock strength measured with the Equotip and the relative elevation of the sampling points. However, the high sensitivity of the Equotip to surface roughness calls for caution in data interpretation in relation to the type of abrasion mechanism active at a particular site.

Two main abrasive mechanisms have been identified: sweeping, and repeated impacts. Sweeping is the dominant abrasion mechanism in the presence of sands and fine gravels, whereas repeated impacts dominate where coarse gravels and pebbles occur. Compared to the former mechanism, the abrasion strip can extend to higher elevations when impacts dominate.

The rock surfaces shaped by abrasion processes show differences in the roughness of the rock surface depending on the dominant mechanism (impact or sweeping). The foliation and fracture properties of the minerals are the main factors controlling the microrelief of the abraded surfaces.

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