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Shore platform abrasion in a para-periglacial environment, Galicia, northwestern Spain

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Abstract

The Schmidt Rock Test Hammer was used to study the effect of abrasion on shore platforms in Galicia, northwestern Spain. On platforms where tidally-induced weathering (salt, wetting and drying, etc.) is dominant, rock strength is significantly lower than in areas where abrasion is, or has been active in the recent past. This suggests that abrasion removes weathered surface material, exposing the stronger, less weathered rock below. Abrasion downwearing, measured with a transverse micro-erosion meter, ranged between 0.13 and 1.8 mm yr^{-1} over the last year. Most active abrasion occurs in the upper part of the intertidal zone, but weathering is slowly destroying formerly abraded surfaces at lower elevations. These abandoned surfaces were abraded by materials supplied by erosion of fluvio-nival and periglacial slope deposits that covered, or partially covered, parts of the Galician coast during the middle and late Weichselian. During the Holocene, rising sea level and erosion of the slope deposits caused the abrasion zone to gradually migrate up to its present position near the high tidal level. The spatial and temporal role of abrasion on this coast is, therefore, closely associated with the exhumation and inheritance of ancient platform surfaces from beneath Weichselian deposits.

Keywords: Shore platform; Abrasion; Periglacial; Weathering; Schmidt rock test hammer; Micro-erosion meter

1. Introduction

Recent research on the processes that operate on intertidal shore platforms has been concerned with the relative and absolute importance of mechanical wave erosion and weathering (Stephenson and Kirk, 1998, 2000a,b; Trenhaile, 2004a; Trenhaile and Kanyaya, 2004; Trenhaile, 2005; Kanyaya and Trenhaile, 2005; Trenhaile, in press). Wave quarrying is usually the most important wave erosional process on sloping shore platforms where there are upstanding rock scarps or steeply inclined beds, particularly in well-jointed rocks (Trenhaile and Kanyaya, 2006). The role of wave abrasion is less clear, however, although the genetic

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term “abrasion platform” has been used to refer to shore platforms in the past (Johnson, 1919; Wooldridge and Morgan, 1959).

The surfaces of shore platforms are abraded by the to-and-fro movement of beach material by breaking waves and the swash of broken waves. The occurrence of smooth, polished surfaces and undercut scarps suggests that abrasion is important sometimes at the foot of cliffs and high rock scarps, in clefts and grooves running along joints oriented at high angles to the shore, and in other places where local platform topography directs and contains the movement of abrasive material. Abrasion is often limited by the lack of suitable loose material. As Trenhaile (2004b) noted, many rocky coasts, particularly on exposed headlands, provide inhospitable environments for the accumulation of abrasive material. Frequently, rock coasts are composed of fine-grained rocks that break down into clays that are carried offshore, or resistant rocks that break down too slowly to provide much material. Platform surfaces therefore often consist of exposures of bare rock with abrasive material restricted to thin strips of sand or pebble at the cliff foot, or to small pockets trapped against scarps or at the bottom of topographic depressions. Even where there is beach material on a platform, abrasion is limited to a fairly narrow zone extending from a short distance in front of the seaward edge of the deposit to a short distance behind and under the edge, where the deposit is still thin enough to be moved over the underlying bedrock by waves.

This paper uses surface rock hardness variations to identify present and past abrasional activity on shore platforms in northwestern Spain, and to show how spatial and temporal variations in abrasion efficacy have resulted from the exhumation and inheritance of ancient platform surfaces from beneath Weichselian deposits. Following the definition of paraglacial coasts by Forbes and Syvitski (1994), the term para-periglacial is used in this paper to describe Holocene conditions on this coast, and the former and continuing influence of periglacial and fluvio-nival deposits on coastal evolution and dynamics. The term “beach” is used to refer to deposits of loose material on shore platforms, irrespective of their size or potential mobility.

2. Study areas

The research was undertaken on two study areas on the Atlantic coast of Galicia in the northwestern Iberian Peninsula, one between the Ria de Vigo and the mouth of the Miño River, and another at the seaward end of the peninsula that separates the Ria de Muros and the Ria de Arousa (Fig. 1). These areas were selected, in part, because of differences in their evolution during the middle and late Weichselian and in the Holocene. Ice did not reach the coast of western Galicia during the Weichselian, but the coast did experience several well-defined cold periods beginning about 38 000 years ago. The coast was covered in places by fluvio-nival and periglacial slope deposits (Blanco Chao et al., 2002, 2003), which were then eroded and cut back during the Holocene transgression, exposing the underlying Eemian shore platforms.

Two types of deposit can be distinguished according to the distance of the mountains from the coast, and the gradient and degree of channel dissection of the intervening area (Pérez Alberti et al., 1998a):

a) Those infilling valleys located close to the mountains. The central portions are filled with coarse debris, intercalated by organic-rich sediments. Radiocarbon dates indicate that the sediments were deposited between 35 000 and 2000 years ago (Costa-Casais et al., 1996; Pérez Alberti et al., 1998b; Blanco Chao et al., 2002, 2003).
b) Where the mountains are farther from the coast, the intervening surfaces are usually not dissected by valleys, and the coastal sediments are dominantly fine-grained and less than 2 m in thickness.

The Atlantic coast of Galicia has a high wave energy environment with marked seasonal behaviour. The highest waves usually occur in autumn and winter with a mean significant wave height ($H_{1/3}$) of 2.34 m, a maximum of 8.95 m, and periods between 7 and 8 s, with 9% of the waves having periods of more than 10 s. During the summer the mean $H_{1/3}$ is 1.3 m with a maximum of 6.62 m, and there is a mean period of 6 s, with less than 1% of the waves exceeding 10 s (Puertos del Estado, Silleiro REMRO buoy, data from 1991–2003). Spring tidal range often exceeds 4 m under storm surge conditions on this coast (Puertos del Estado, Vigo Tidal Station).

2.1. The Oia–Miadelo sector

This sector lies between the mouth of the Miño River and the Ria de Vigo, on one of the few straight sectors along a Galician coast that is otherwise characterized by its crenulated, ria planform (Fig. 1). The lithology is homogeneous, composed of two mica granites with a large number of quartz, pegmatitic and aplitic dykes. The joint pattern is very dense, with mean inter-joint spaces of 30–40 cm. Joints strike NE–SW and NW–SE, and they dip between 20 and 90°. The coastal sector is

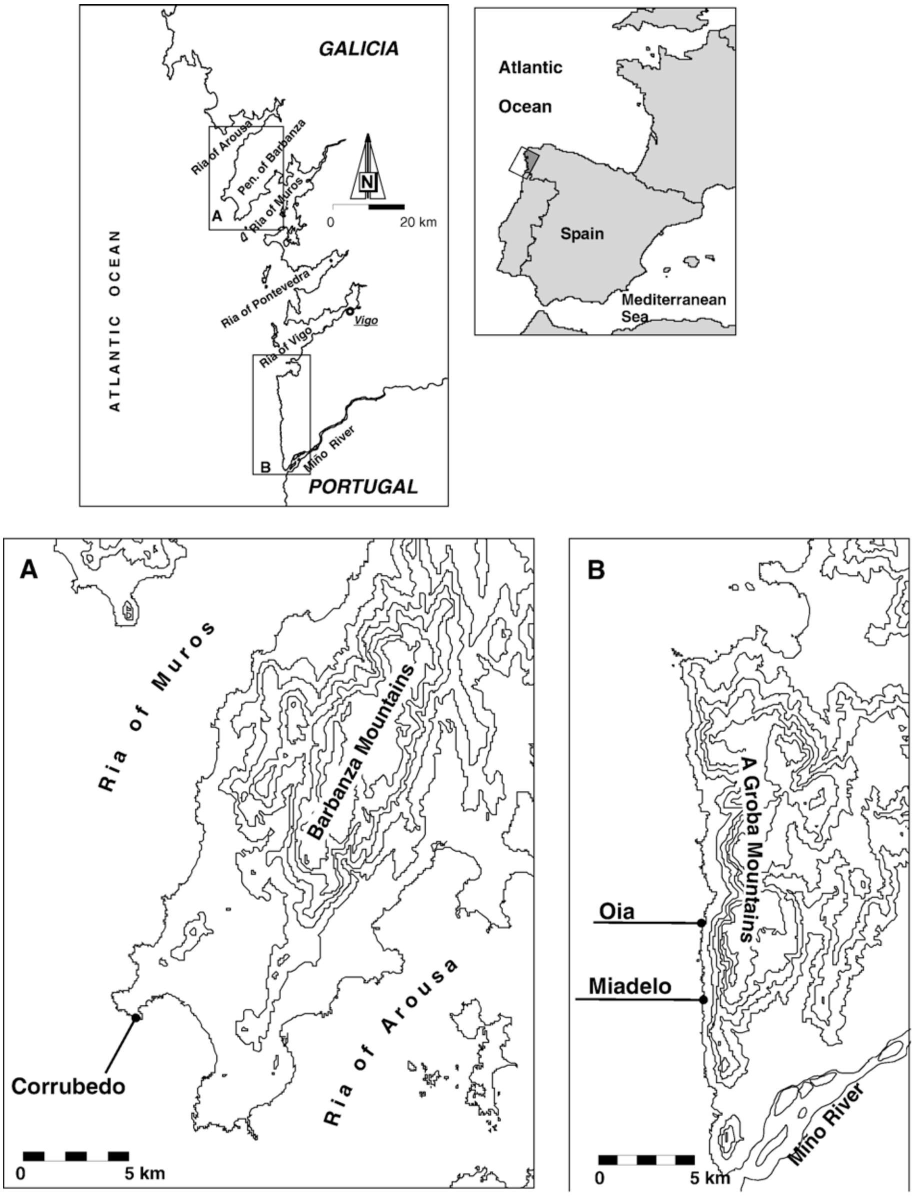

Fig. 1. The study areas in western Galicia. Contour interval is 100 m.

characterized by the presence of coastal mountains attaining elevations of up to 600 m, which are dissected on their seaward slopes by fracture-controlled valleys running E to W and NE to SW: these valleys usually terminate in small embayments at the coast. The mountains functioned as orographic barriers that provided suitable conditions for fluvio-nival and periglacial slope processes when sea level was lower than today in the middle and late Weichselian. The Weichselian deposits of the Oia–Miadelo sector were subsequently covered by Holocene sediments and cut into sea cliffs during the postglacial transgression.

The study at Oia was conducted on shore platforms in two small embayments that run along NW–SE fractures (Fig. 2). The platform in the northern embayment (Oia North) is backed by an 8 m high cliff composed of heterometric, coarse periglacial and fluvio-nival sediments. Erosion of these thick sediments by rising sea level during the Holocene provided material for a gravel to boulder beach that covers the upper portion of the platform. Clast size decreases from boulders (>60 cm on the *b*-axis) in the northern portion of the northern embayment to pebbles (mean size 7.5 cm on the *b*-axis) in the south. The beach has a gentler beachface and is

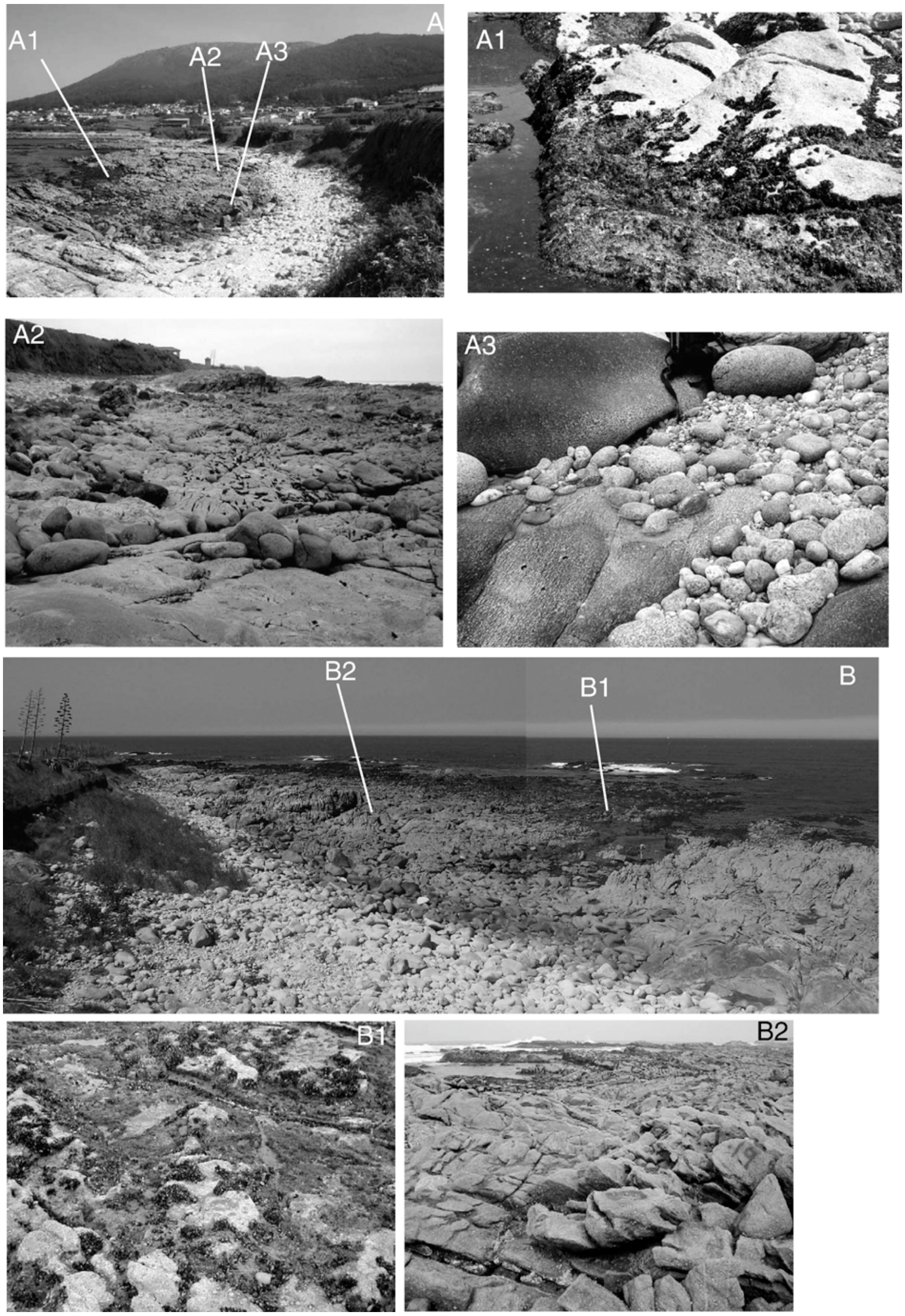

Fig. 2. A: Oia North. A1: the rugged surface with dense biological coverage near low tide; A2: the present abrasion strip near the high tidal level, backed by the boulder beach and fronted by the abandoned zone of abrasion; A3: smooth, abrasion strip surface. B: Oia South. B1: rugged surface with biological coverage near low tide; B2: irregular topography and rugged surfaces in the upper intertidal zone.

wider in the southern part of the bay. The beach is morphodynamically active today and abrasion occurs along its seaward edge and flanks. The southern embayment (Oia South) is at the mouth of a small river. The platform is slightly wider than in the northern embayment and the sediment cliff is lower (about 2 m) and composed mainly of fine sediments corresponding to more distal facies. These sediments were deposited by streams, in contrast to the coarser fluvio-nival or periglacial facies to the north. Erosion of these deposits during the Holocene transgression produced fewer abrasive clasts than in the northern embayment. The beach in the southern embayment is composed of boulders, and there is no obvious change in clast size from north to south. The boulders have weathered surfaces and they are covered by lichens, indicating that they are practically immobile.

The platforms in the northern and southern embayments of Oia have a mean gradient of 2.5–3° (Blanco Chao et al., 2003). The surface of the platform in the northern embayment, between the neap high and spring low tidal levels, is controlled by the joint pattern and it is irregular. The surface is more regular at higher elevations where there is a zone of smooth, polished rock, roughly 5 to 7 m in width, extending from the foot of the beach to the neap high tidal level, the degree of polishing decreasing seawards with distance from the beach. The entire platform surface in the southern embayment is irregular, from the low to the high tidal level, and there is little surface polishing.

The shore platform at Miadelo has a width of about 70–80 m and a mean slope of 2° (Fig. 3). At the back of the platform there is an immobile accumulation of large blocks, with long axes of 40 to 100 cm; these blocks are more angular than those at Oia and were probably derived from platform erosion. The crest of the accumulated blocks extends well above the high tidal level and may be of Eemian age. The mountains are several hundred meters from the coast and the intervening area is not dissected by valleys. Consequently, there were either no continental deposits in this area, or they were very thin, fine distal sediments that were subsequently washed away. This limited the supply of sediments and inhibited the development of active coarse-grained beaches. As a consequence, abrasion is restricted today to small pockets of clasts located between the neap and spring high tidal levels, in structurally controlled settings where small clasts can be moved by waves.

2.2. Corrubedo

The mountains of Barbanza (about 600 m high) run down the length of the peninsula between the Ria de Muros and the Ria de Arousa (Fig. 1). The northern tip of this peninsula, near the village of Corrubedo, is low and rocky. A gently sloping surface, up to 2 km in width, extends from the foot of the mountains to the coast and consequently, in contrast to the Oia–Miadelo sector in southwestern Galicia, there was no local sediment source in the Corrubedo area. Therefore, the platform at Corrubedo, which is in the same two mica granites as at Oia–Midelo, was not covered by sediments during the last marine regression. The shore platform in this area is between 60 and 90 m in width, and its gradient is about 2° (Fig. 4). The platform is backed by a large boulder beach which extends above the high tidal level and is assumed to be of Eemian age (Blanco Chao et al., 2002, 2003). There are also large blocks of material eroded from the platform possibly, as at Miadelo, as a result of frost action on platform surfaces that were not

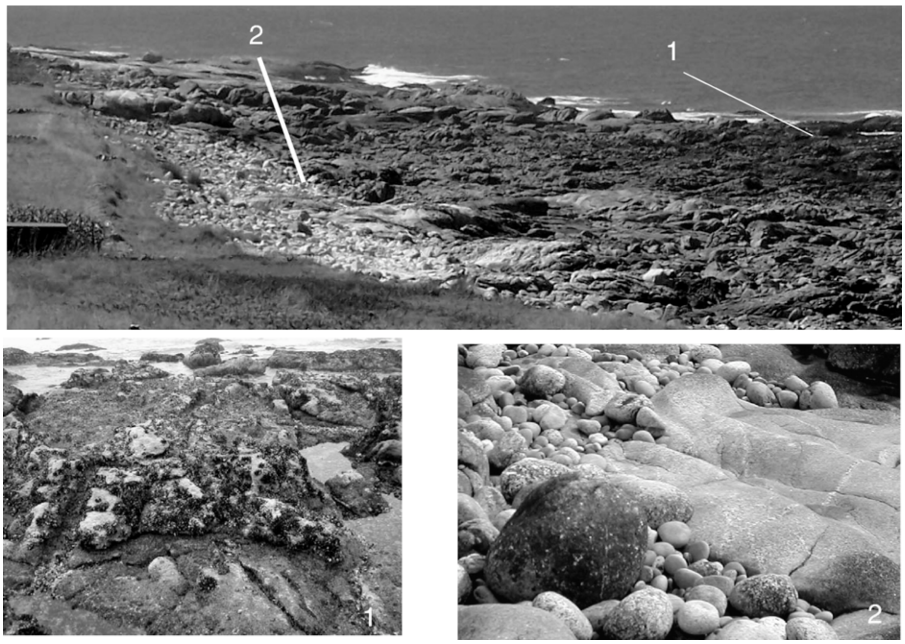

Fig. 3. Miadelo sector. 1: rugged surfaces and dense biological coverage at the low tide level. 2: polished abrasion surface near the high tidal level.

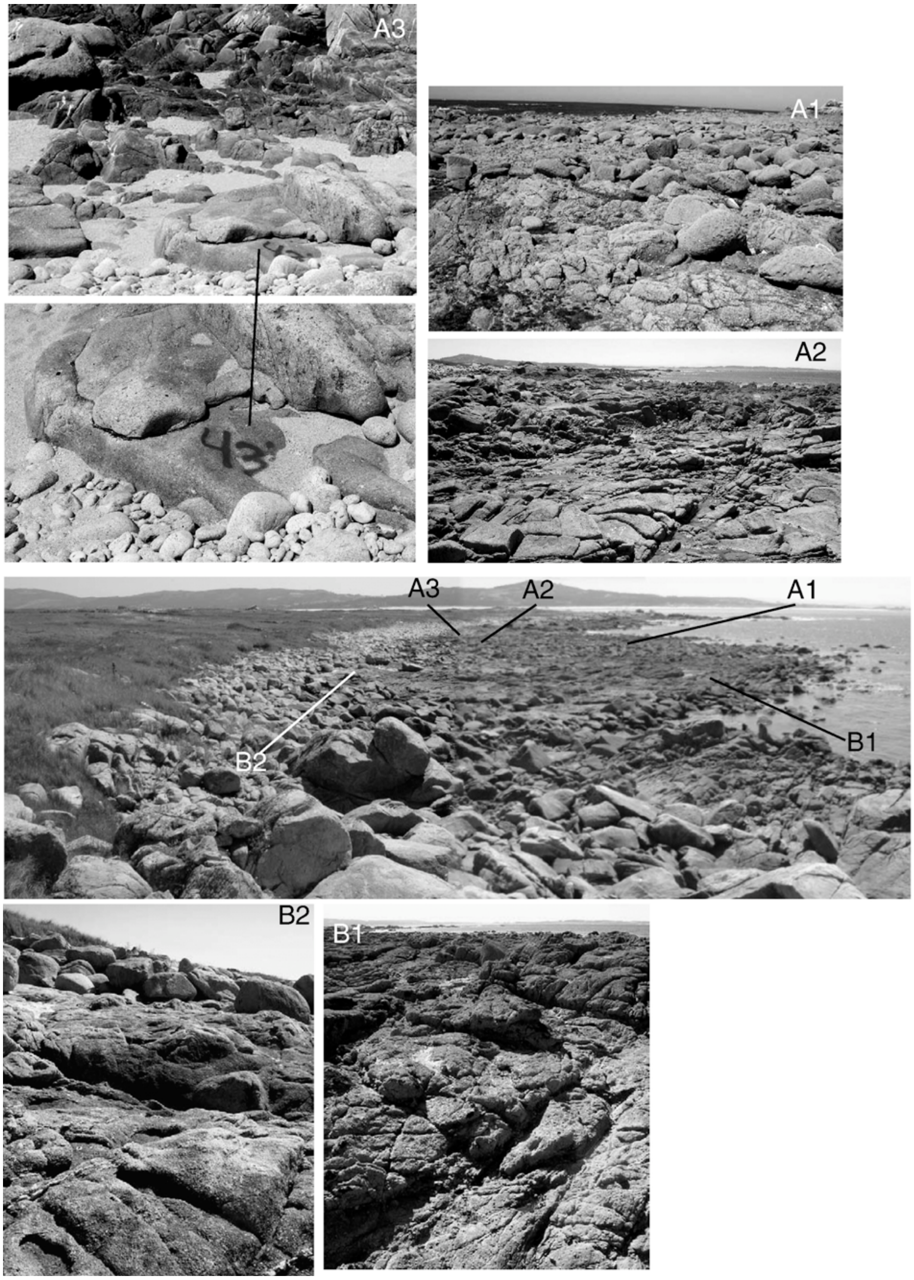

Fig. 4. Corrubedo. A: Corrubedo East. A1: rugged surfaces at the low tide level; A2: rugged surfaces near the high tide level; A3: the zone of abrasion. B: Corrubedo West. B1: rugged surfaces at the low tide level; B2: rugged surfaces, even at the edge of blocks and boulders, at the high tidal level.

protected under thick terrestrial deposits during the latter part of the Weichselian. Because of wave at tenuation over the platform and the large size of the material (0.4 to 0.8 m on average), the boulders and large blocks are immobile (Corrubedo West), but abrasion does occur on the eastern part of the platform (Corrubedo East), where there are small pockets of sand and cobble.

3. Methods

Several workers have used the Schmidt Rock Test Hammer to measure rock strength in coastal environments (Haslett and Curr, 1998; Trenhaile et al., 1998, 1999; Stephenson and Kirk, 2000a,b; Andrade et al., 2002; Dickson et al., 2004; Trenhaile and Kanyaya, 2004; Kennedy and Beban, 2005). An N-type Hammer was used at 109 stations, 35 along two profiles at Oia, 32 along one profile at Miadelo and 42 along two profiles at Corrubedo; all profiles were perpendicular to the shore. Standard corrections were applied to the data when the Hammer was used in a non-horizontal position (Day and Goudie, 1977). The platforms were surveyed and the position and elevation of each Hammer station were recorded (Fig. 5). Twenty-five measurements were made at each station and Chauvenet's Criterion was applied to the data. For *N* number of values, the criterion rejects observations if they have a deviation from the mean greater than that corresponding to a 1/2 *N* probability (Göktan and Ayday, 1993; Dickson et al., 2004). Only 0.6% of the readings were eliminated, however, and these were very low values probably derived from rock fragmentation: the mean of the remaining rebound values was then used to represent the strength of the rock at each station.

The selection of suitable stations for Rock Hammer measurement was constrained by such factors as the degree of surface roughness, the proximity to joint planes, and the presence of beaches. The lowest part of the intertidal zone has a dense cover of barnacles, mussels, algae, and gastropods, and there were only a few suitably bare surfaces between joint channels. Sites selected in areas that are experiencing abrasion were restricted to places where the clasts could be moved in order to make the measurements, and where large boulders dominated, measurements could only be made in a few places where the presence of scouring marks provided evidence of mobility.

All the Hammer stations were located in the intertidal zone, ranging from the mean low tidal level to positions very close to the spring high tidal level. Twenty-nine of the stations were in areas of the platforms where abrasion seemed to be active, based on morphological evidence including polished surfaces and rock clasts, fresh scouring marks, visual checking of clast movement over time, and the general absence of biological coverage (barnacles, mussels, algae, or hard, coralline algae of the Lithophyllum family). Nevertheless, because of their mobility there were often some *Patella* sp. gastropods in abraded areas, and green algae of the *Enteromorphia* type, which can quickly colonize abrasion zones in summer when clast movement is reduced. In contrast, weathered surfaces are very irregular and often have a micro-pseudo-karst morphology, consisting of small pits and grooves, taffoni-type cavities, and small quartz

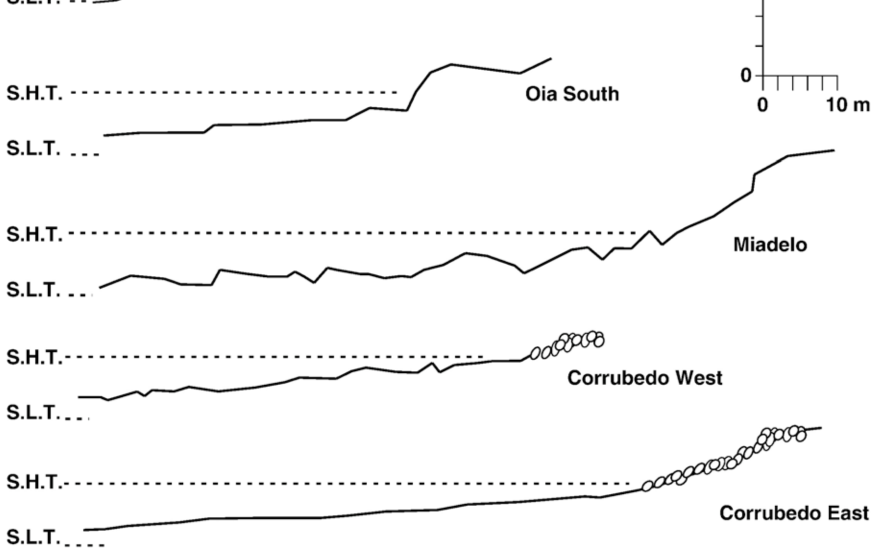

Fig. 5. Surveyed platform profiles in the five areas. S.H.T. = Spring High Tidal level; S.L.T. = Spring Low Tidal level.

veins and indurated joint planes protruding above the surface. Surface microtopography also varies at the granular scale across feldspar and quartz grains, and the rock surfaces are also darker (sometimes brownish or reddish) than abrasional surfaces.

This paper is concerned with temporally and spatially variable patterns of abrasive activity on shore platforms related to the occurrence and retreat of periglacial slope deposits. As the coastal mountains, which were the source area for the deposits, consist of the same granitic rocks as in the platforms, the abrasives consist of the same material as the abraded surfaces. Although this paper is not primarily concerned with modern rates of abrasion downwearing, some preliminary data have been collected from twelve traversing micro-erosion meter (TMEM) stations which were installed on surfaces experiencing abrasion in the northern embayment at Oia; measurements were not made in non-abrading areas because of the dense biological coverage. As the stations were only installed on September 2004, the records are neither long enough at present to make reliable comparisons between abrasion rates at each station, or to assess the role of abrasion in comparison with that of other wave and weathering processes. Abrasion data are, therefore, briefly reported in this paper only to provide some indication of the variable, site-dependent efficacy of this process. Some of the TMEM stations are on roughly horizontal surfaces whereas others are on the steeply sloping sides of rock scarps and joint-controlled grooves. Two people were required to make accurate measurements on steeply sloping surfaces, one to hold the instrument firmly against the rock and the other to make the measurements. To ensure that measurements on sloping surfaces were accurate, each measurement was immediately repeated one or more times, although differences were never found to be more than ±0.03 mm. Nevertheless, in recognition of the fact that measurements on sloping surfaces may be less accurate than on horizontal surfaces, abrasion was only considered to have occurred if the surface between measurement intervals (over several months) had been lowered by more than 0.05 mm. Three measurements were made at different points at each station, and these values were then averaged to provide a mean downwearing rate at each site.

4. Results

The highest hammer rebound values were generally recorded at stations that are experiencing abrasion,

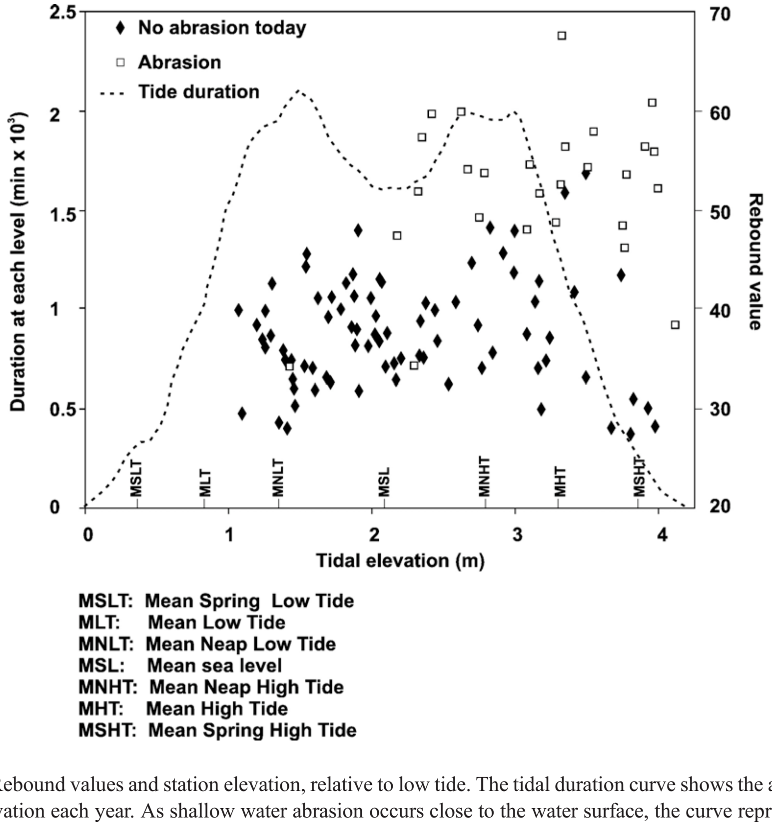

Fig. 6. Rock Test Hammer Rebound values and station elevation, relative to low tide. The tidal duration curve shows the amount of time that sea level occupies each intertidal elevation each year. As shallow water abrasion occurs close to the water surface, the curve represents the frequency not the intensity of abrasion. The duration curve was calculated from tidal data recorded every 5 min at Vigo.

Table 1
Rock hardness values and correlation between rock hardness and elevation at abrading and non-abrading sites

	Max	Min	Mean	S.D.	SE	*r*
Oia North						
No Ab	53.79	28.57	38.47	6.85	4.25	0.8 [a]
Ab	67.6	34.0	53.06	8.54	7.62	0.52
Oia South						
No Ab	42.8	28.0	37.62	4.74	3.69	0.69 [a]
Ab	–	–	–	–	–	–
Miadelo						
No Ab	45.7	32.1	38.9	3.90	3.26	0.58 [a]
Ab	59.7	48.1	54.6	3.47	7.08	0.38
Corrubedo West						
No Ab	44.3	27.5	34.19	4.21	3.37	0.62 [a]
Ab	–	–	–	–	–	–
Corrubedo East						
No Ab	51.7	35.1	43.05	4.90	4.84	0.33
Ab	55.9	38.4	47.80	6.23	7.00	0.23

Max and min are the maximum and minumum rock hardness values, respectively, S.D. is the standard deviation, SE is the standard error, *r* is the coefficient of correlation, No Ab represents sites with no present abrasion, and Ab represents sites with present abrasion.
[a] Indicates significance at the $p=0.05$ level.

which are generally between the neap and spring high tidal levels (Fig. 6) (Tables 1 and 2). This concentration corresponds to the shoreward margins of the beach deposits at Oia North and Corrubedo East, where clast mobilization is most frequent and where potential abrasives are in contact with the rock surface. Even where there is no active beach, as at Miadelo, there are some mobile clasts between the neap and spring high tidal levels.

Rebound values from sites experiencing abrasion were up to almost 20 points higher than for sites at the same tidal elevation that do not experience abrasion (Fig. 6) (Table 3). The only exceptions were at one station at Oia North, near the mean low tidal level, and another at Miadelo, close to the mid-tidal level. At both stations, the evidence for abrasion included the presence of abrasive tools, polished rock surfaces, and the lack of biological coverage. The station at Oia North is in a shallow, polished joint channel in which a few clasts have been trapped. These clasts have remained in the channel for years, and although movement has been observed, it is very episodic and punctuated by long periods of inactivity. At the Miadelo station, some abrasion occurs around a pocket of sand and gravel at

Table 2
t-test for the difference in surface rock hardness between abrading and non-abrading sites (for all sites combined)

	No abrasion	Abrasion
Min	27.50	34.00
Max	53.79	67.60
Mean	37.86	51.9
S.D.	5.55	7.69
t-statistic	−8.7 [a]	

[a] Indicates significant difference ($p=0.05$).

Table 3
Differences in Hammer Rebound values (*R*) between abrading and non-abrading stations at the same tidal elevation

With abrasion			Without abrasion			Difference
Tidal elevation (m)	Station	*R* value	Tidal elevation (m)	Station	*R* value	
Oia North profile						
1.45	ON-Ab10	34	1.43	ON 1	34.7	−0.7
2.13	ON-Ab5	47.34	2.13	ON 9	33	14.34
2.29	ON-Ab11	57.3	2.32	ON 15	40.68	16.62
2.57	ON-Ab3	59.9	2.53	ON 4	40.68	19.22
2.7	ON-Ab6	49.13	2.69	ON 11	38.5	10.63
3.07	ON-Ab4	54.7	2.95	ON 16	47.96	6.74
3.47	ON-Ab7	54.35	3.46	ON 17	53.79	0.56
3.73	ON-Ab12	46.23	3.7	ON 5	43.54	2.69
Oia South profile						
2.28	OS-Ab7	51.9	2.28	OS7	35.3	16.6
Miadelo profile						
2.25	Mia-Ab33	34.6	2.38	Mia20	39.9	−5.3
2.35	Mia-Ab36	59.7	2.38	Mia20	39.9	19.8
2.63	Mia-Ab40	54.2	2.64	Mia15	44.6	9.6
2.73	Mia-Ab34	53.8	2.82	Mia14	45.7	8.1
3.04	Mia-Ab37	48.1	3.05	Mia19	37.6	10.5
3.3	Mia-Ab42	56.5	3.38	Mia23	41.7	14.8
3.9	Mia-Ab39	52.3	4.18	Mia24	44.1	8.2

The lowest low tide is at 0 m and the highest high tide is at 4.2 m. Comparisons were only made between stations that were essentially at the same elevation (±15 cm). At Corrubedo, all the abrasion stations are at higher elevations where abrasion is absent.

the foot of a rock scarp; it is unclear why the rock is weaker at this abrasional site than at similar locations elsewhere.

Two groups of stations can be distinguished from those that are experiencing abrasion today (Fig. 6). Although large and small clasts often occur together, stations that tend to have small, mobile clasts cluster around the neap high tidal level, where there is most frequent wave action. Stations that generally have larger clasts are at higher elevations, as much as 1 m above the neap, high tidal duration maximum. These clasts are less mobile than those in the first group, and many can only be moved by the most powerful waves, which have low tidal duration values and tend to occur when high winds raise the water level. Clast movement has been monitored in the Oia–Miadelo sector since summer 2004, based on observations made in autumn, winter and spring. Swell waves produce strong run-up that facilitates clast movement on beachfaces (Carter and Orford, 1984), and it has been noted that most clast movement, and presumably therefore abrasion, takes place when there are long, high swell waves in autumn and winter.

In addition to differences in rebound values according to whether or not stations experience abrasion, differences are also apparent when Hammer rebound

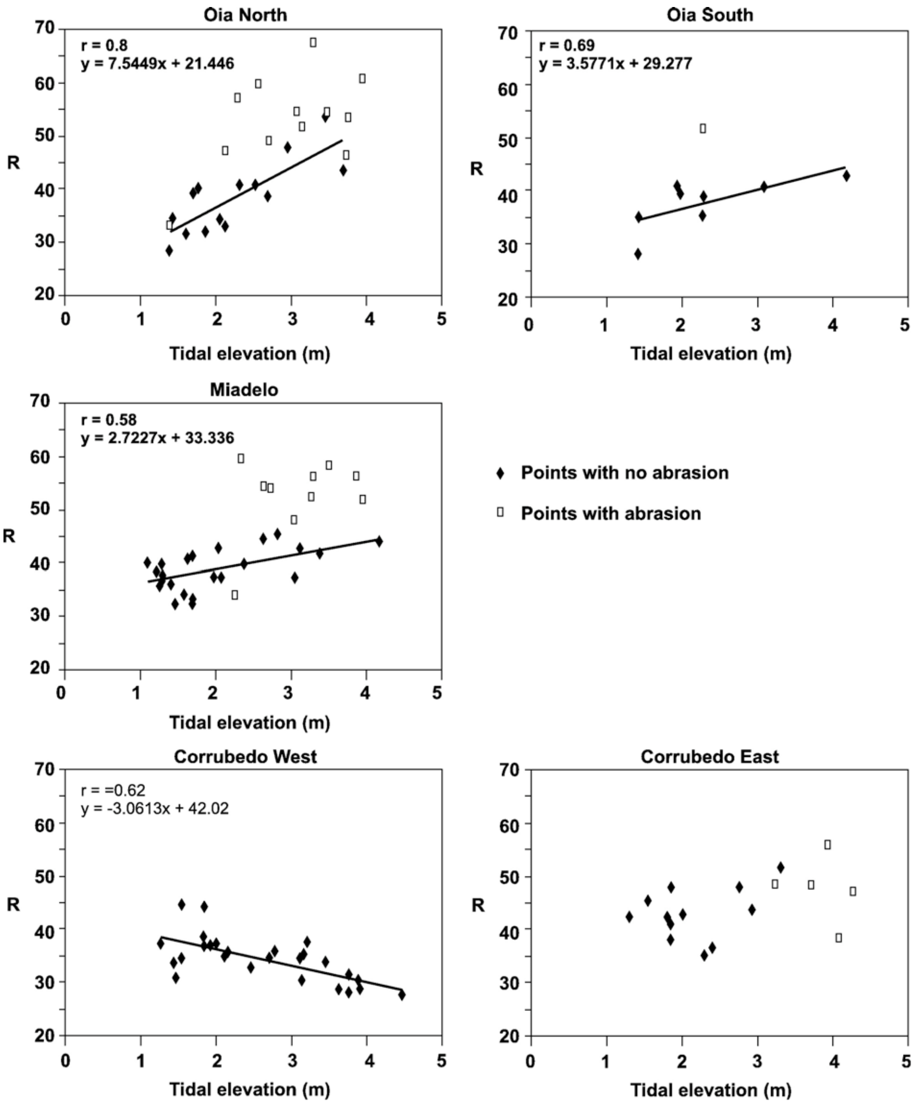

Fig. 7. Rebound values (R) and station elevation. The regression lines are for all the points in each sector that are not experiencing abrasion today. All correlations are significant.

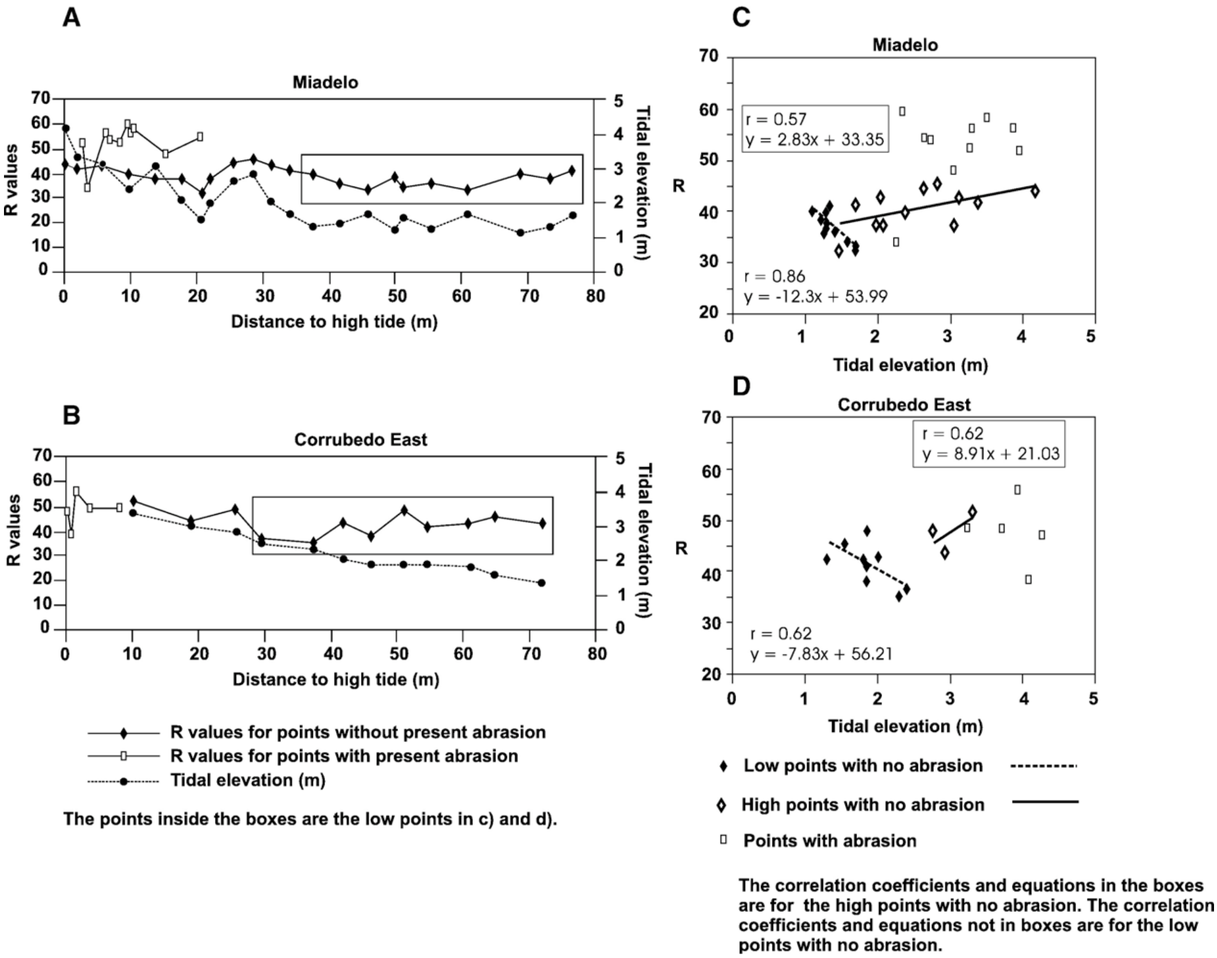

Fig. 8. Distance of rebound sites from the mean spring high tidal level at A) Miadelo and B) Corrubedo East. Regression lines for rebound values against elevation at C) Miadelo and D) Corrubedo East: regression lines for the low points with no abrasion corresponding to those shown in the boxes in A) and B).

values are correlated against station elevation (Fig. 7). Correlations are lower and insignificant for stations that are experiencing abrasion today, and generally higher and statistically significant for stations that are not experiencing abrasion (Table 1). With the exception of Corrubedo West, rock strength at sites that are not experiencing abrasion increases shorewards in the study areas. The data suggest, however, that the opposite relationship may occur at elevations below about 1.7 m at Miadelo and 2.5 m at Corrubedo East (Fig. 7). Although some low sites are in deep channels in the more landward portions of the two platforms, most sites at lower elevation are located further seawards, where the surfaces are rougher and less regular than at higher elevation (Fig. 8). Analysis of these sites confirmed that rock strength decreases shorewards in about the lower 37 to 80 m of the platform at Miadelo, and approximately in the lower 30 m to 75 m of the platform at Corrubedo East (Fig. 8). A *t*-test confirmed that the differences in rock hardness between the points at high and low elevation at Miadelo and Correbudo East are statistically significant (Table 4).

Table 4
Statistical values and *t*-test for differences in rock hardness between low and high points in Miadelo and Corrubedo East

	Miadelo		Corrubedo East	
	Low points	High points	Low points	High points
Min	32.8	32.1	35.1	43.8
Max	40.9	45.7	48.0	51.7
Mean	36.8	40.6	41.4	47.9
S.D.	2.9	3.88	4.17	3.95
t-statistic	−2.5 [a]		−2.3 [a]	

[a] Indicates significant difference ($p=0.05$).

There are few quantitative field data on the role of abrasion on shore platforms. Robinson (1977a) found that abrasion by sand and gravel lowered a shale platform at a median rate of 5.79×10^{-3} cm/tide, corresponding to a rate of about 4.25 cm yr^{-1}. This abrasion rate is much higher than measured rates of downwearing by weathering, which usually range from 0 up to a few millimeters per year (Robinson, 1977b; Gill and Lang, 1983; Mottershead, 1989; Stephenson and Kirk, 1998; Foote et al., 2001; Andrade et al., 2002; Trenhaile and Kanyaya, 2004).

During the first year of measurement, mean downwearing rates at each of the 12 TMEM stations in the northern embayment at Oia ranged from a low of 0.13 mm yr^{-1} at a roughly horizontal station (TMEM-005) in a shallow groove at about the mid-tidal level, to a high of 1.8 mm yr^{-1} at a near vertical station (TMEM-007) on the lower wall of a structural channel containing pebbles and small cobbles (5–10 cm). There was high spatial variability in the amount of downwearing recorded at some stations, including a difference of 1.5 mm yr^{-1} between the highest and the lowest of the 3 readings at station TMEM-007: this may reflect the way that abrasion wears down the coarse-grained granites. Close examination of the rock surface reveals numerous small pits and other features that suggest that abrasion largely occurs through clast impact and the resultant removal of large quartz and feldspar grains, producing much greater spatial variability in short-term downwearing rates than if abrasion were accomplished by polishing.

5. Discussion

The shore platforms in the study areas consist of fairly homogeneous rocks with little variation in structure or lithology. Therefore, one of the main factors responsible for local variations in rock strength is the degree of weathering by tidally-induced wetting and drying, salt weathering and possibly other processes. Stephenson and Kirk (2000a) suggested that weathering is probably most effective in the zone of most frequent tidal wetting and drying: this extends from the height of the lowest high tide to the height of the highest low tide (Trenhaile, 2003). Experimental work has shown that the duration of the drying period is more important than wetting and drying frequency, however, and consequently wetting and drying is most effective in the zone extending from the mid- to the high tidal level (Kanyaya and Trenhaile, 2005; Trenhaile, 2006). The present study has demonstrated that rock strength, as represented by Rock Hammer rebound values, also varies according to whether a surface has been abraded (Fig. 7). The general occurrence of stronger rock surfaces in the upper part of the intertidal zone therefore suggests that abrasion plays an important role in removing weak, weathered material, thereby exposing the strong, fresh rock below.

Higher wetting and drying efficacy in the upper half of the intertidal zone suggests that, in the absence of abrasion, rebound values should decrease with elevation within the intertidal zone. This is consistent with variations in rock strength and downwearing rates on platforms in other areas that that have not been exhumed from beneath coarse materials (Stephenson and Kirk, 2000a; Kanyaya and Trenhaile, 2005). This situation occurs at Corrubedo West, which because of its distance from the mountains was never covered by continental deposits and, therefore, never received an abundant supply of abrasives (Fig. 7).

Where there is a clastic beach, abrasion along its seaward edge may cause rock strength to increase with elevation near the high tidal level. Rock strength in the study areas, however, generally increases with elevation throughout the intertidal zone (Fig. 7). This raises the possibility that abrasion, which is largely restricted to the upper portions of the platforms today, may have been active at lower elevations in the past, particularly in the Oia–Miadelo sector.

A number of studies have demonstrated that at least the upper parts of some shore platforms in western Galicia were exhumed during the Holocene transgression (Pérez Alberti et al., 1998b; Trenhaile et al., 1999; Blanco Chao and Costa Casais, 2001; Blanco Chao et al., 2002, 2003). With rising sea level, erosion of thick and extensive continental deposits supplied large amounts of clasts: this was the main, and often the only, source of sediments for coarse-grained beaches. As the sediment cliffs retreated, the zone of abrasion at the foot of the accumulating beaches migrated landwards. Older polished surfaces formed by intense abrasion were abandoned and they began to be weathered by wetting and drying, salt weathering and other tidally-induced weathering processes. Waves were eventually unable to continue eroding the cliff foot once sea level had stabilized because of wave attenuation over the exhumed platforms and the protection afforded by the eroded sediments. This ended the supply of new sediment to the foreshore, and continued abrasion then depended on there being suitably sized material on the platform and sufficient wave energy to move it. According to this hypothesis, the tendency for Hammer rebound values to increase landward is an inherited property associated with the recent evolution of a para-periglacial system (Fig. 9A).

Increasing rock strength with elevation above the 1.7 m tidal level at Miadelo and above the 2.5 m tidal elevation at Corrubedo East, suggests that these areas were once affected by abrasion, whereas abrasion did not occur at lower elevations where rock strength decreases with increasing elevation (Fig. 8). This

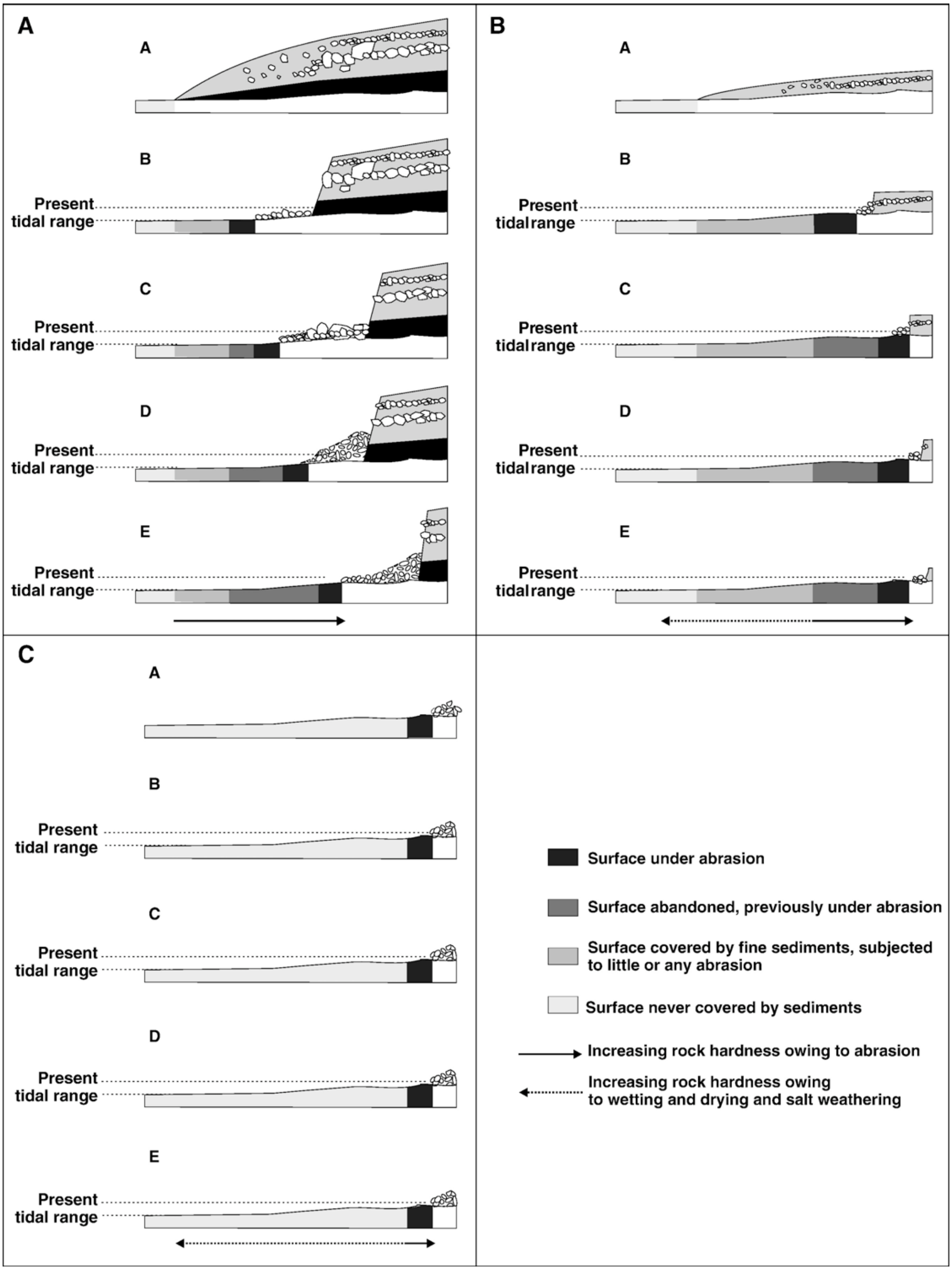

Fig. 9. Model of the migration of the abrasion zone during Holocene sea level rise: A) platform covered by thick, coarse sediment (Oia North); B) platform partially covered by fairly thin, fine deposits (Miadelo); and C) platform never covered by continental deposits (Corrubedo).

conclusion is consistent with the occurrence of much smoother and more uniform rock surfaces above 1.7 m at Miadelo and above 2.5 m at Corrubedo East, than at lower elevations. At Miadelo, where there were thin and mainly fine-grained continental deposits, either the deposits, and therefore abrasion, only extended down to about 1.7 m (Fig. 9B), or weathering has subsequently removed the evidence of abrasion from lower areas: the latter explanation is considered less plausible because of the abrupt transition between the two regression lines and between the occurrence of smooth and rough surfaces. At Corrubedo East, which was not covered by continental deposits, there is some abrasion today from localized deposits of sand and cobble, and evidence along a narrow strip at a lower elevation of some abrasion in the recent past (Fig. 9C). Surface roughness and decreasing rock hardness with elevation suggest that abrasion has never been effective in the lower part of this platform.

The question remains why smooth platform surfaces have been able to persist in areas that are no longer being abraded today. There are no precise data on changing relative sea level in western Galicia in the Holocene. Scarce data for the Atlantic coasts of the Iberian Penninsula suggest that eustatic sea level reached its present position between 5000 and 2500 BP (Bao et al., 1999; Dias et al., 2000; Delgado et al., 2003). Maximum Holocene sea levels on the Portuguese coast and on the northeastern coast of Spain recorded prior to 5000 BP (Dias et al., 2000; Freitas et al., 2003; Leorri and Cearreta, 2004) were driven by tectono-isostatic movements, while the Galician coast remained stable (Blanco Chao et al., 2002, 2003). Radiocarbon dated material from cliff sediments suggests that the cliffs retreated until very recent times, even after sea level reached its present position. Furthermore, radiocarbon dates from the Oia–Miadelo area and from similar settings elsewhere on the coast of Galicia, have shown that there were phases of continental sedimentation up to 500 years ago, which suggests that the front of the deposits and their associated abrasion zones, were still retreating until very recently (Trenhaile et al., 1999; Blanco Chao et al., 2002, 2003).

Kanyaya and Trenhaile (2005) ran a series of long-term experiments on the effects of tidally-induced wetting and drying. Most of this work was conducted on basalts, sandstones and argillites, but a smaller number of granite and granite–gneiss samples experienced downwearing rates between 0 and 0.0026 mm yr^{-1} and 0 to 0.004 mm yr^{-1}, respectively. The data also suggested that downwearing rates decrease with the compressive strength of the rock. Based on the Hammer rebound values (40–60), the freshly abraded and unweathered granites of the study areas have equivalent cube compressive strengths ranging from 40 to more than 70 MNm^{-2}. Kanyaya and Trenhaile's analysis implies that downwearing rates in these rocks by wetting and drying would be only between about 0.016 and 0.004 mm yr^{-1}. Predicted rates of Galician granite downwearing by wetting and drying are, therefore, much lower than rates measured on weaker rocks by Kanyaya and Trenhaile (2005), and much lower than the abrasion rates measured with a TMEM at Oia North. The assumption that downwearing rates by weathering are very low in Galicia is also consistent with the occurrence, on the upper portions of the shore platforms, of Eemian beach remnants that are at roughly the same elevation as the surrounding rock surface (Trenhaile et al., 1999; Blanco Chao et al., 2003). The persistence of former abrasion surfaces can, therefore, be partly attributed to fairly recent continental sedimentation, and partly to slow rates of downwearing and surface modification by weathering.

The slope of the regression lines showing a positive relationship between rock strength and elevation at stations that are not experiencing abrasion today, becomes lower from Oia North to Miadelo, and reverses at Corrubedo West, from sectors with thick sedimentary deposits and large amounts of stony abrasive material to sectors with little or no sedimentary deposits and few abrasives. This suggests that differences in the phases of abrasion are probably related to variations in the thickness and facies of the deposits in each area, and consequently to the volume of sediment released by erosion. The platform at Oia North probably remained covered longer than in the other areas because of the time required to erode its thick cover of stony deposits. The first stages of marine erosion probably only eroded fine, distal sediments, and abrasion only started when sea level had reached the coarse facies farther landwards. The finer sediments at Oia South contained fewer clasts and probably retreated faster than in the north. Similar conditions existed at Miadelo, where there were also fine deposits. Consequently, even if these areas did experience a phase of abrasion, it would have finished earlier than at Oia North, and consequently the previously abraded surfaces at Oia South and Miadelo would be more weathered. At Corrubedo East, abrasion is mainly caused by gravels and coarse sand derived from recent continental sedimentation which partly covers the Eemian boulder crest. Therefore, the former occurrence of abrasion at the three stations above 2.5 m, which recorded an increase in rock strength with elevation, could be attributed to migration of the small beach edge over year or decade time-scales (Fig. 8).

6. Conclusions

The main conclusions of this paper are as follows:

(i) Abrasion removes the products of tidally-induced weathering on the shore platforms of western Galicia.
(ii) The importance of abrasion on the Galician coast varies according to the thickness and facies of the sediments deposited during the last marine regression.
(iii) In para-periglacial systems, the relationship between intertidal rock strength and tidal level may be a function of the occurrence, and nature of, continental slope deposits that impinged on the coastal domain. With rising Holocene sea level, erosion and retreat of sedimentary cliff deposits caused abrasion zones to migrate landwards, as the coarse sediments were released from the deposits; the effect of this migration may be preserved today in the form of a positive relationship between rock hardness and intertidal elevation.

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