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Systematic analysis of rocky shore platform morphology at large spatial scale using LiDAR-derived digital elevation models

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Abstract

Much of the existing research on rocky shore platforms describes results from carefully selected field sites, or comparisons between a relatively small number of selected sites. Here we describe a method to systematically analyse rocky shore morphology over a large area using LiDAR-derived digital elevation models. The method was applied to 700 km of coastline in southwest England; a region where there is considerable variation in wave climate and lithological settings, and a large alongshore variation in tidal range. Across-shore profiles were automatically extracted at 50 m intervals around the coast where information was available from the Coastal Channel Observatory coastal classification. Routines were developed to automatically remove non-platform profiles. The remaining 612 shore platform profiles were then subject to automated morphometric analyses, and correlation analysis in respect to three possible environmental controls: wave height, mean spring tidal range and rock strength. As expected, considerable scatter exists in the correlation analysis because only very coarse estimates of rock strength and wave height were applied, whereas variability in factors such as these can locally be the most important control on shoreline morphology. In view of this, it is somewhat surprising that overall consistency was found between previous published findings and the results from the systematic, automated analysis of LiDAR data: platform gradient increases as rock strength and tidal range increase, but decreases as wave height increases; platform width increases as wave height and tidal range increase, but decreases as rock strength increases. Previous studies have predicted shore platform gradient using tidal range alone. A multi-regression analysis of LiDAR data confirms that tidal range is the strongest predictor, but a new multi-factor empirical model considering tidal range, wave height, and rock strength yields better predictions of shore platform gradient (root mean square error of predictions reduced by 5%). The key finding of this study is that large-scale semi-automated morphometric analyses have the potential to reveal dominant process controls in the face of small-scale local variability.

Keywords

LiDAR, DEM, shore platform, rock coast

1 1. Introduction

2 A range of landforms occur along rocky shorelines, but particular research attention has been afforded
3 to the distinctive low-gradient intertidal shore platforms that often occur in front of eroding cliffs (e.g.
4 Trenhaile, 1987; Sunamura, 1992). Early studies of shore platform geomorphology were highly
5 descriptive and focussed on a small number of platforms, distinguished in their morphology in some
6 respect (e.g., Dana, 1849; Bartrum, 1926, 1938; Wentworth, 1938; Edwards, 1951). This is because
7 slow rates of morphological change and lack of preserved evidence restricted the application of process-
8 based morphodynamic studies (Trenhaile, 1980; Stephenson, 2000). Likewise, logistics dictated that
9 most researchers could work only at a single field site, or perhaps comparing a small number of field
10 sites.

11
12 In spite of such difficulties, there have been several key morphological findings reported in the late 20th
13 Century, including: (1) a conceptual demarcation of two shore platform geometries as well as plunging
14 sea cliffs in relation to the relative force of waves and rock resistance (Tsujimoto, 1987; Sunamura,
15 1992); and (2) widespread positive correlation between mean shore platform gradient and mean spring
16 tidal range (e.g. Trenhaile, 1987, 1999). However, some key areas of morphodynamic understanding
17 remain unclear. For instance, despite recent work describing how process dominance may change
18 through time (Dickson, 2006; Trenhaile, 2008a, 2008b), it is apparent that the classical long-standing
19 debate over the relative dominance of wave and weathering processes has not been clearly resolved
20 (Stephenson, 2000). Overall, despite a great deal of research, slow developmental trajectories, a very
21 wide range of forcing conditions and local site-specific factors mean that shore platform morphology
22 remains an ambiguous indicator of process (Mii, 1962).

23
24 Recent research on shore platforms has seen emphasis move from qualitative to quantitative, facilitated
25 by high-frequency, sensitive and portable measuring devices, including pressure transducers (e.g.
26 Stephenson, 2000; Farrell et al., 2009; Ogawa et al., 2011, 2012, 2016), seismometers (e.g. Adams et
27 al., 2002; Young et al., 2011, 2016; Dickson and Pentney, 2012; Normal et al., 2013), micro-erosion
28 meters (e.g. Stephenson and Kirk, 1998, 2000; Kanyaya and Trenhaile, 2005; Swantesson et al., 2006;

29 Porter et al., 2010a, 2010b, 2010c) and laser scanners (e.g. Swantesson et al., 2006; Lim et al., 2011;
30 Rosser et al., 2013). These studies have begun to provide details on the rates of morphological change
31 and the process regime responsible for these changes. However, it is notable that these studies have
32 continued to be rather local in scale, due to measuring-range constraints. Few studies to date have
33 examined the potential of broad-scale quantitative methods for understanding rocky shore evolution.

34

35 LiDAR (light detection and ranging) is now a very widely used geomorphological research tool. On
36 rocky shores, Kennedy et al. (2014) and Duperret et al. (2015) combined LiDAR-derived elevation
37 models with bathymetric data to produce seamless onshore-offshore rocky shore profiles. They
38 demonstrated its usefulness in studying historical erosional events when sea levels are different from
39 today. Along 4.2 km of the North Yorkshire (UK) coast Swirad et al. (2016) used LiDAR data and
40 ortho-photographs to reveal weak correlations between shore platform morphology and various
41 environmental controls, suggesting that further consideration of coastal inheritance and detailed rock
42 resistance representations is required in coastal models. Palamara et al. (2007) used LiDAR-derived
43 terrain models to map 2 km of shore platform in southeastern New Zealand. The technique was capable,
44 with caveats, of automatically discerning the cliff-platform junction, seaward platform edge and an
45 upper erosional surface. Palamara et al. (2007, p946-947) noted that “If ALS data prove useful for
46 mapping shore platform morphology at this [local 2 km] scale, there is an opportunity to consider
47 evolution of rocky coast landforms at the regional scale using a single dataset”.

48

49 This study aims to systematically analyse rocky shore platform morphology at large region-wide scales
50 using LiDAR derived digital elevation models (DEMs). Our particular interest is placed on shore
51 platform gradient, width and roughness at an analysis scale afforded by LiDAR-derived DEMs with 1
52 m resolution. We describe a method to semi-automatically extract shore-normal shore platform profiles
53 and present results from an analysis of approximately ~700 km of southwest England coastline. This
54 coastline is notable particularly in respect to the broad and relatively regular transition in tidal range
55 that occurs from north (more than 10 m spring tidal range at North Devon) to south (around 4 m spring
56 tidal range at South Devon). Many other factors vary across the 700 km expanse of coast, including

57 rock strength and exposure to wave energy, but the large and regular transition in tidal range supports
58 the establishment of a simple testable proposition: is platform gradient positively correlated with tidal
59 range? The literature suggests that this should be the case (see Trenhaile, 1999), but previous studies
60 have focussed on a relatively small number of shore platform sites that had been specifically selected
61 for analysis due to cross-site variability of factors such as rock structure. Our focus therefore, is to
62 question whether an automated systematic analysis of platform morphology over a broad regional scale
63 will yield similar process relationships to those inferred from prior local site studies.

64

65 2. Study area

66 The southwest region of England is subject to a diverse coastal setting (Fig. 1) with a very large variation
67 experienced both in the wave climate and tidal regime (Scott et al., 2011). The Atlantic Ocean produces
68 a mixture of ocean swell to locally-generated wind waves to most coasts, but the significance of
69 different wave types varies owing to local orientation of the coasts and geographical setting (e.g. Bristol
70 Channel and English Channel) (Fig. 1b). The lithological setting also varies, with resistant igneous rock
71 in part of the north and southwest, in comparison to moderately-hard sedimentary rocks in other places
72 (Fig. 1d) (Clayton and Shammoun, 1998). Tidal regime also varies significantly, but, in contrast to the
73 variability in waves and lithology, the tidal regime varies systematically along the coast with mega-
74 tidal spring tide ranges of 9–10 m around the Bristol Channel and macro-tidal spring tide ranges of
75 around 4 m around the English Channel (Fig. 1c). As a result of such a diverse setting, coastal
76 geomorphology also varies considerably, but most of coasts in southwest England are characterized by
77 large expanses of rocky coastline alternated by embayed beaches, small estuaries and rocky headlands
78 (Scott et al., 2011).

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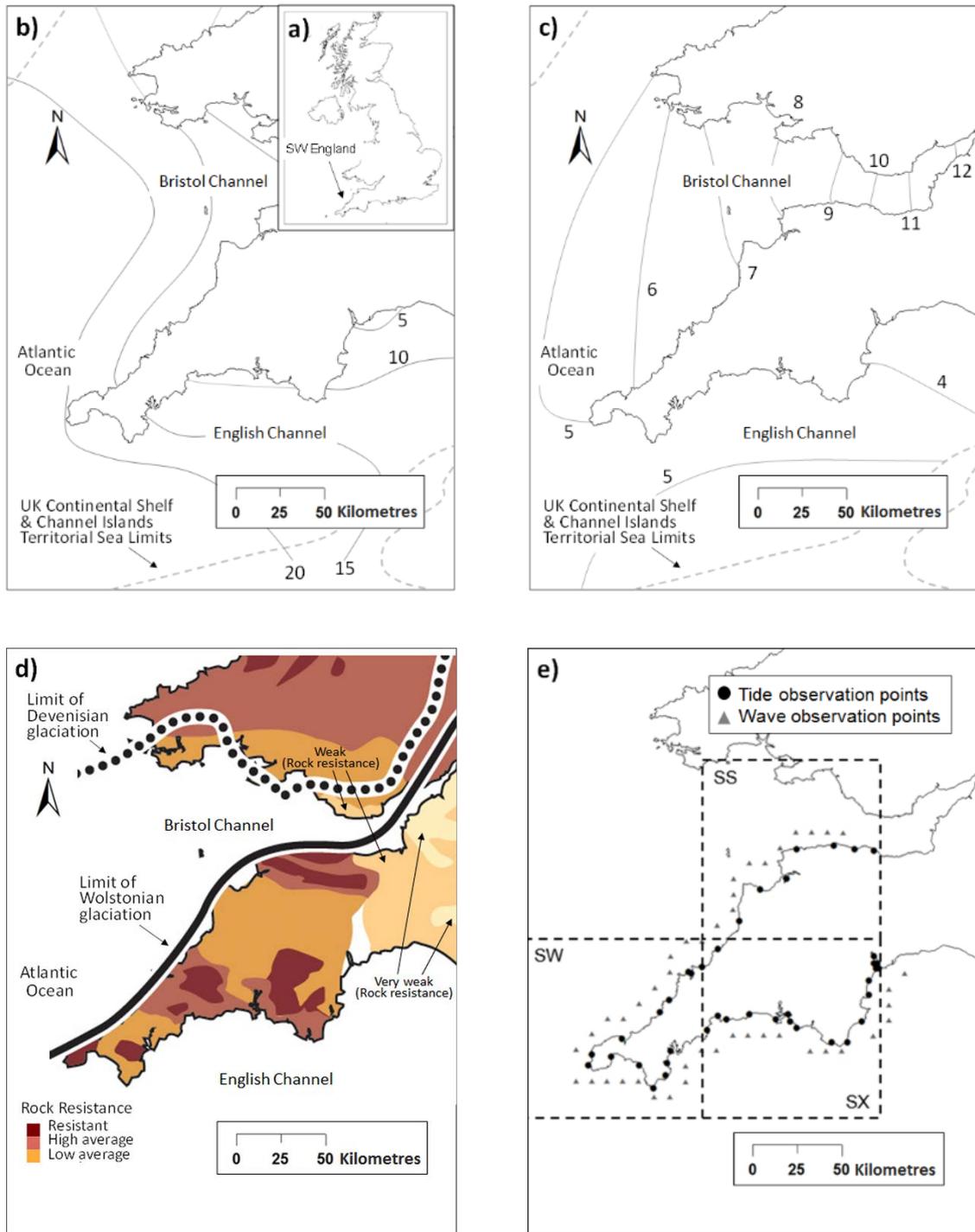


Fig. 1. a) Map of the England; b) mean wave power, based on hourly model hindcast over 7 years, modified from Scott et al. (2011); c) mean spring tidal range (based on data derived from an average tidal year), modified from Scott et al. (2011); d) resistance of geology to denudation, modified from Clayton and Shamoon (1998); and e) map of study area with hatched squares showing the location of Ordnance Survey Great Britain 1936 (OSGB36) grids in the study area and OSGB36 grid names. Circles and triangular marks in Fig. 1e show locations of points where estimates exist of wave height, mean spring tidal range (MSR) and mean sea level (MSL).

80

81

82 This study used the “SS”, “SW”, and “SX” tiles from OSGB36 which covers approximately 700 km of
83 coastline from east of Minehead in the north, to east of Exeter in the south (Fig. 1e). Fig. 1e also shows
84 the locations of points where tide and wave data used in this study were observed/estimated.

85

86 3. Methods

87 Algorithms were developed to allow (1) semi-automatic extraction of shore platform cross-shore
88 profiles from digital elevation models, and (2) morphometric analysis.

89

90 3.1. LiDAR-derived surface models

91 A digital elevation model (DEM) derived from LiDAR surveys along England coastline was provided
92 by the Channel Coastal Observatory (<http://www.channelcoast.org/>). DEMs were captured using an
93 OPTEC GEMINI and OPTEC ALTM 3100 system coupled with a dual frequency carrier phase global
94 navigation satellite system for positioning. Cleaning (e.g., removing spurious points such as flying birds
95 or fog, etc.) and filtering (e.g., removing seawater, building and vegetation) had already been applied
96 to the raw digital surface elevation (Channel Coastal Observatory, 2014). The resulting processed
97 DEMs were provided as a form of 1000 m or 500 m square tile on the OSGB36 grid, with 1 m spatial
98 resolution containing either 1000 x 1000 or 500 x 500 elevation values, referenced to the Ordnance
99 Datum Newlyn with minimum vertical accuracy of ± 0.1 m. This was achieved through ground-truthing
100 using hard surface and/or features with known elevation, surveyed using real time kinematic (RTK)
101 global positioning system which yields vertical accuracy of ± 0.03 m, which took place every 10-15 km
102 alongshore distance (Channel Coastal Observatory, 2014).

103

104 3.2. Data mining

105 The Channel Coastal Observatory provided shore-normal transect lines at approximately 50 m intervals
106 around the southwest England shoreline. These transects are ideal locations to extract elevation data
107 from the DEMs, because most of the transects have an accompanying shoreline classification, such as:
108 rock platform, beach, rock platform with beach, and various engineering features (e.g. groynes,
109 breakwaters). Table 1 shows a general breakdown of transect categorization in the currently studying

110 area. Our analysis focussed on the rock (shore) platform categorisation; transects were omitted if they
 111 were categorized other than ‘Rock Platform’ or ‘Cliff-Rock Platform’, or had no categorisation, more
 112 than one categorisation, or engineering features. As a result, 6,764 transect lines were obtained as
 113 potentially useful shore platform transects (Table 1)
 114

Table 1. Breakdown of the number of shoreline types along the southwest England coastline.

Shoreline classification	Type	Number of transects	Ratio
Natural features	Cliff / Cliff with others such as beach	3,758	28.2%
	Cliff-Rock Platform / Rock Platform	6,764	50.8%
	Beach (including barrier / shingle beach)	386	2.9%
	Dune / Inter-tidal / Spit / Inlet Entrance	75	0.6%
Natural features plus coastal defences	Cliff/Rock Platform - Rock Revetment/Seawall	282	2.1%
	Beach-Embankment/Revetment/Seawall/Groyn	457	3.4%
Coastal defences	Breakwater / Embankment / Revetment / Seawall	105	0.2%
No or more than one categorization		1,489	11.2%
Total		13,316	100%

115
 116 Each transect line was extended 1.2 km in length to ensure that it encompassed the seaward and
 117 landward extent of the landform of interest. Some transects were found to deviate significantly from
 118 the shore-normal orientation of the coast, particularly where the coastline was rugged in planform.
 119 These profiles were excluded by estimating the average shoreline bearing for each transect (on the basis
 120 of the crossing points between shoreline and the two adjacent transects) and eliminating transects if D
 121 $< 60^\circ$ or $D > 120^\circ$, where D ($0^\circ \leq D \leq 180^\circ$) was the angle between the transect and the average
 122 shoreline bearing (Fig. 2). As a result, 1,223 transects out of potentially useful 6,764 transects were
 123 excluded.
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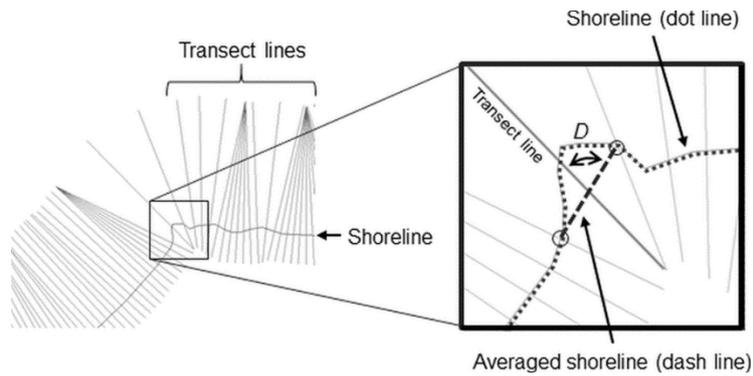


Fig. 2. Schematic view of piece-wise averaged shoreline for each transect.

125

126 Fig. 3 shows a process flow of the profile-extraction methodology. DEMs, shore-normal transects and
 127 shoreline types were manually downloaded from the Channel Coastal Observatory. Computer programs
 128 were developed to automatically store coordinate information of DEMs in a look-up table (LUT) and
 129 extract cross-shore profile elevation data. For each transect, the corresponding DEM(s) was(were)
 130 retrieved using a look-up table, and transect orientation and shoreline type were examined to select
 131 “true” shore-normal shore platform transects. Elevation values were estimated at 1 m spacing across
 132 transects by interpolating the values of the DEM cell within which each sampling point occurred, and
 133 in the eight surrounding DEM cells (Fig. 4).

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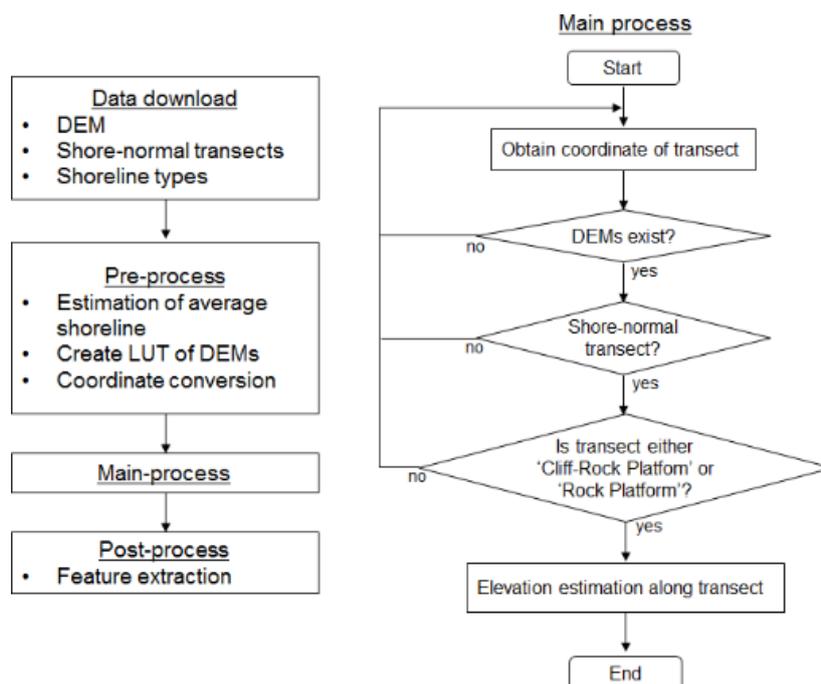


Fig. 3. Overview of semi-automated shore platform profile extraction.

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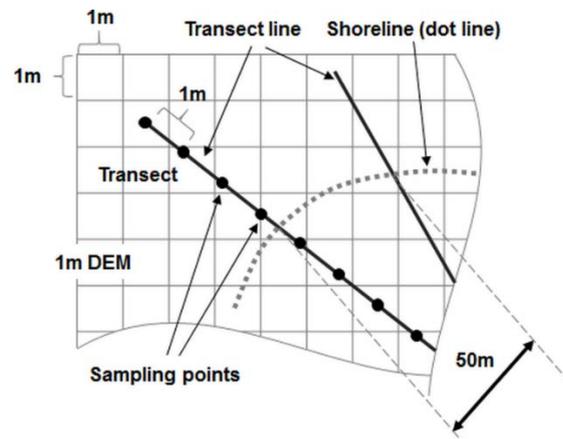


Fig. 4. Schematic view of cross-shore profile extraction from 1 m DEM. The horizontal and vertical coordinates of each sampling point are rounded off to the closest first decimal number in order to uniquely determine the elevation value.

137

138 3.3. Morphometric description

139 Many different aspects of meso-scale shore platform morphology have been described in the research
140 literature (e.g. see Trenhaile, 1987), and more recently there has been focus on micro-scale
141 morphological descriptions (e.g. Dornbusch et al., 2008; Dornbusch and Robinson, 2011). For this study
142 we focussed on automatically characterising meso-scale morphology; the mean intertidal platform
143 gradient (PG), intertidal platform width (PW) and intertidal platform roughness (PR). These metrics
144 were determined for each cross-shore platform profile using three equations (Eq. (1)-(3)), where N is
145 the total number of sampling elements along the transect, and F is an approximate line extending
146 between mean high water spring (MHWS) and mean low water spring (MLWS) elevations. Shore
147 platform roughness was estimated by analysing the variability in a polynomial regression line fitted
148 through sampling points between MHWS and MLWS. The order of the polynomial regression line used
149 in analysis was selected by systematically increasing the order (1, 2, 3...) and examining roughness
150 values. The mean and standard deviation of roughness values decreased as the order of the polynomial

151 regression increased, but almost no difference in mean and standard deviation of roughness values was
152 detected above 6th order; hence, a 6th order polynomial line was selected for the purpose of estimating
153 platform roughness.

154

$$155 \quad PG = \tan^{-1} \left((Z_{\text{MHWS}} - Z_{\text{MLWS}}) / (X_{\text{MHWS}} - X_{\text{MLWS}}) \right) \quad \text{Eq. (1)}$$

$$156 \quad PW = X_{\text{MHWS}} - X_{\text{MLWS}} \quad \text{Eq. (2)}$$

$$157 \quad PR = \sqrt{\sum_i (Z_i - F_i)^2 / N} \quad \text{Eq. (3)}$$

158

159 Positions on the profile of the MHWS and MLWS tidal levels were calculated by linearly interpolating
160 their elevation, as shown in Fig. 5. Morphometric estimations were excluded when there were no
161 elevation points extending up to MHWS or down to MLWS. Owing to across-shore profile variation in
162 platform morphology, some profiles had more than one MHWS or MLWS elevation intersection. In
163 these cases the seaward-most MHWS and MLWS positions of profiles which extended up to and down
164 to MHWS and MLWS were selected for morphometric calculations. Shore platform profiles sometimes
165 exhibit across-shore curvature with more steep and gentle slopes at higher and lower intertidal
166 elevations (e.g. Trenhaile, 1974; Blanco-Chao et al., 2003). For this reason, PG, PW, and PR were also
167 evaluated for upper, lower, and central intertidal profiles, as described in Table 2. Describing PG and
168 PW requires identification of the outer (seaward) margin of the shore platform. Kennedy (2015) has
169 described the difficulties faced with field researchers making this decision. We defined the outer margin
170 as the seaward point on a profile corresponding with MLWS elevation, because in the absence of field-
171 survey, a repeatable classification method was necessary.

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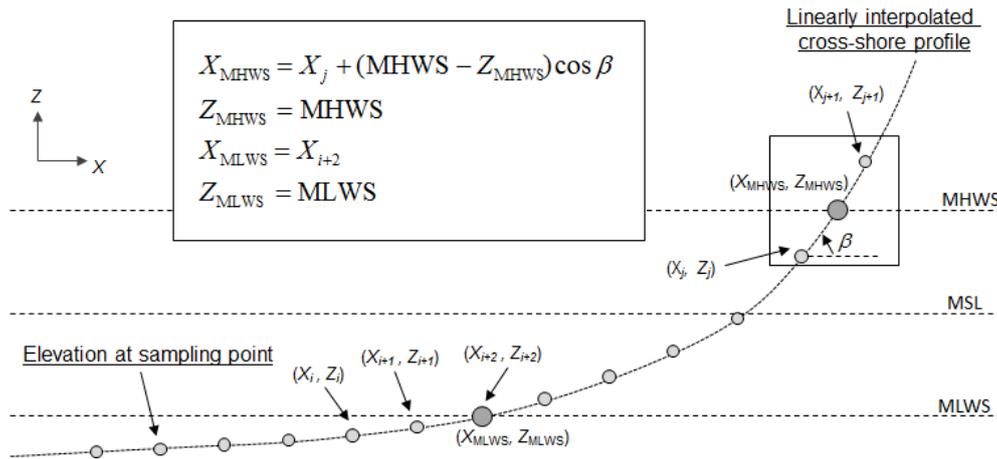


Fig. 5. Cross-sectional view of a profile with positions at MHWS and MLWS.

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Table 2. Upper and lower limit of profile elevation of whole, upper, lower, and central intertidal profiles.

	Whole	Upper	Lower	Central
Upper limit of profile elevation	MHWS	MHWS	MSL	MSL+MSR/4
Lower limit of profile elevation	MLWS	MSL	MLWS	MSL-MSR/4

175

176 3.4. Process-regime description

177 The MSR and MSL were estimated for each transect by linearly extrapolating observed MSR and MSL
 178 at two points with exact coordinates to the nearest transect line, obtained from Admiralty Tide Tables
 179 (2016) (Fig. 6). Mean wave height variations for each transect were estimated in a similar way, using
 180 modelled data provided by the UK Met Office (representing waves in 20–30 m water depth and obtained
 181 from their 8 km grid model) for the 2011-2013 period along the southwest coast of England. Nearshore
 182 wave transformation was not modelled for this study. Instead, each transect was automatically
 183 categorized as exposed, partly-exposed, partly-sheltered or sheltered, depending on the relative
 184 orientation between the transect (from seaward to landward) and the prevailing WSW wave direction
 185 in the study area (α). To obtain the nearshore wave height, the modelled ‘deep water’ wave height was
 186 simply multiplied by a multiplier K , depending on α : $K = 1$ for $0^\circ \leq |\alpha| < 45^\circ$; $K = 0.75$ for $45^\circ \leq |\alpha| < 90^\circ$;

187 $K = 0.5$ for $90^\circ \leq |\alpha| < 135^\circ$; $K = 0.25$ for $135^\circ \leq |\alpha| < 180^\circ$) (Fig. 7). Detailed geological information was
 188 not available for each transect. Instead, the work of Clayton and Shamoon (1998) was used to manually
 189 locate the coordinates of boundary points that divide geological areas of ‘high’ rock strength, ‘high
 190 average’, and ‘low average’, with values of 100, 10, and 1MPa, respectively, assigned to these
 191 categories.
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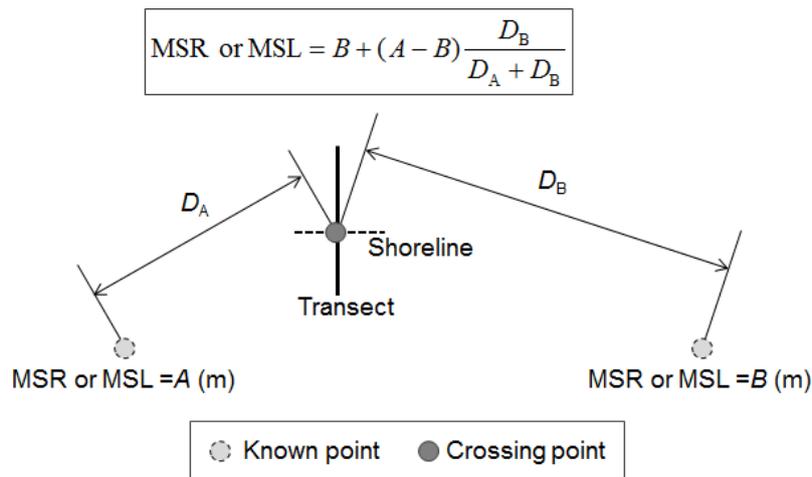


Fig. 6. Relative position of MSR/MSL-known points and crossing point with average shoreline and transect.

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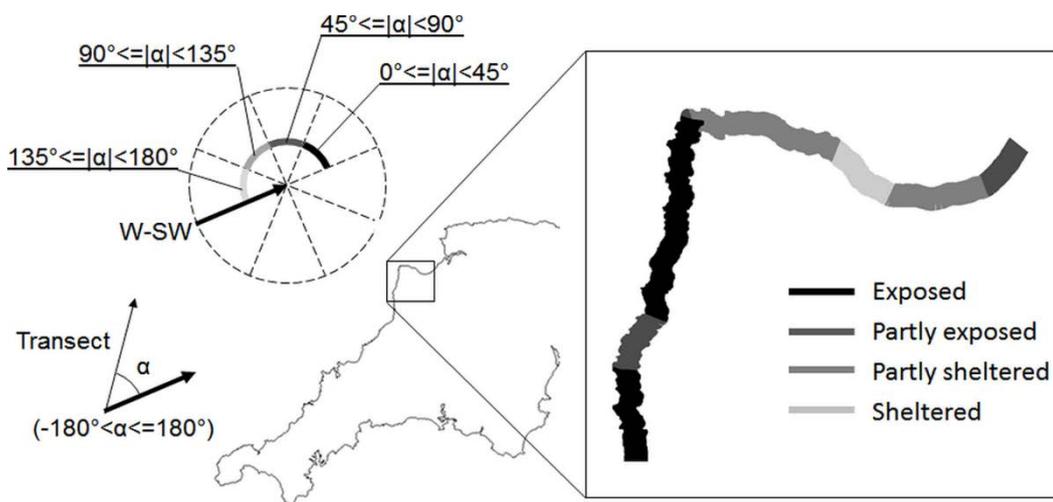


Fig. 7. Transect categorization examples in respect to wave exposure.

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4. Methodology: development of a semi-automated method for shore platform morphometric description

This section describes a new method for selecting and extracting the morphometric characteristics of shore platform profiles from a large DEM dataset. The method is dependent on the existing shoreline classification provided by the Coastal Channel Observatory. In this classification we believe that some profiles that are mapped as shore platforms (presumably in a desk-top aerial photograph exercise) may in fact be low-slope, but very ‘rough’ rocky foreshores that might not be typically identified for research investigation by field workers interested in shore platforms. It is important that our study is comparable with the existing shore platform literature. Hence, to examine the comparability of the proposed method, we conducted a preliminary application of the method to selected shore platform sites in southwest England known to the authors.

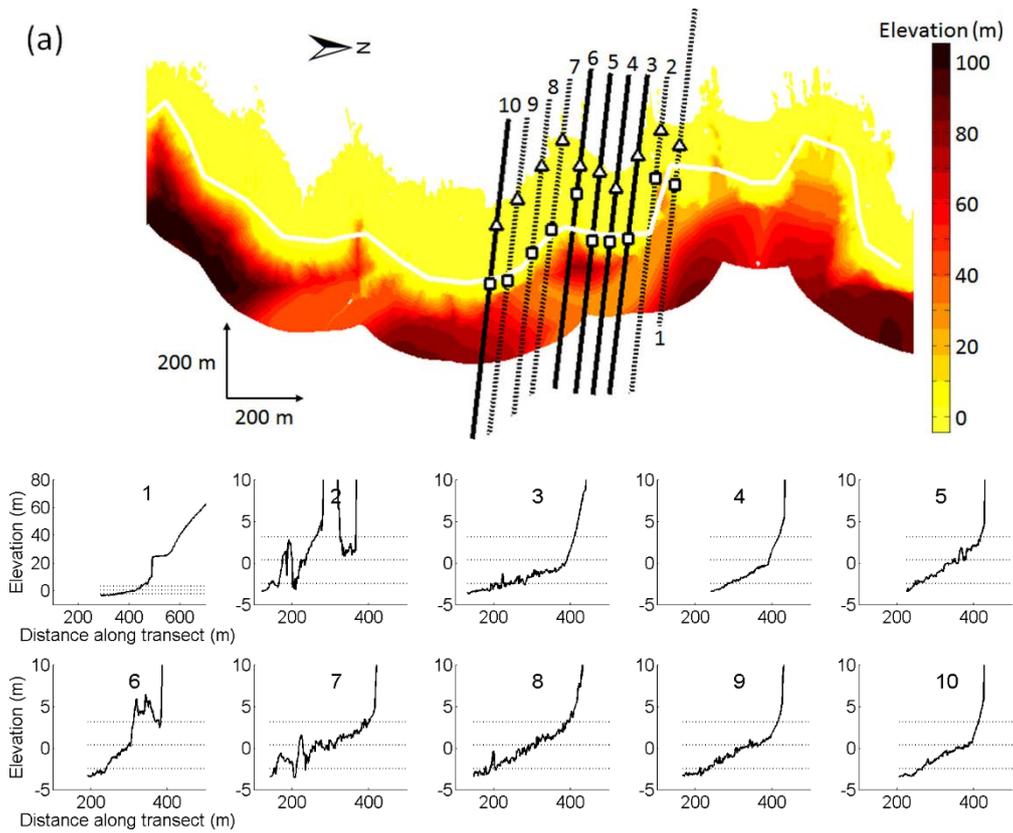
Two well-recognized shore platform sites in North Devon and Cornwall, shown in Fig. 8, were selected for the ‘ground-truthing’. Fig. 9 shows ten consecutive cross-shore profiles for each of the sites with seaward and landward margins. Table 3 shows the average PG/PW/PR values at each site. Of note, non-shore-normal profiles (dot lines) are excluded in the calculations presented in Table 3. Most of the extracted cross-shore profiles exhibit a low-gradient intertidal slope, extending from seaward at around the MLWS elevation to a cliff-platform junction between MSL and MHWS elevations, particularly at Hartland Quay (Fig. 9a). Gradually sloping cross-shore profiles at Porthleven often occur at lower intertidal elevations, and cliff-platform junctions sometimes occur even below MSL, resulting in very steep cliff profiles or narrow ramps/ledges at upper intertidal elevations (Fig. 9b). Examples of very rough intertidal profiles, which vary markedly at intertidal elevations, occur at both sites (e.g. No.2 and No.6 profiles in Hartland Quay and No.6 profile in Porthleven), and should be categorized as non-platform profiles.



Fig. 8. Shore platforms at a) Hartland Quay in North Devon and b) Porthleven in Cornwall
(Photos from Google Earth: <https://www.google.com/earth/>)

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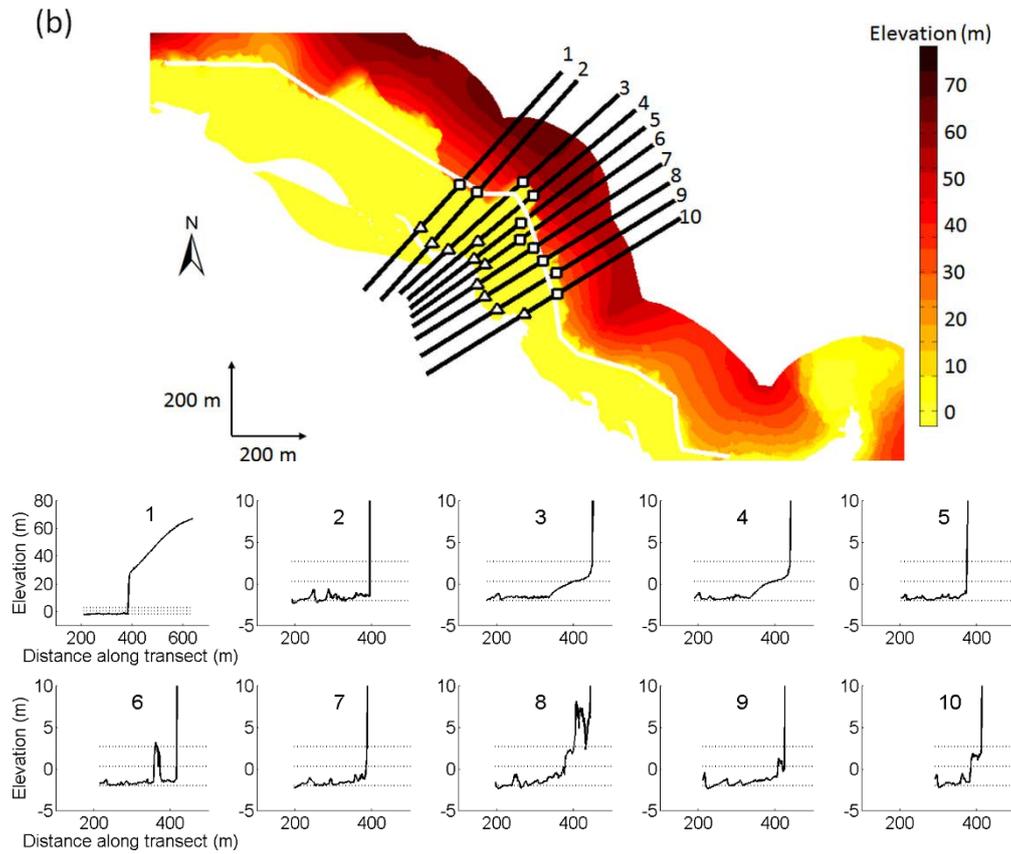


Fig. 9. DEMs with ten consecutive transects (black lines) and shoreline (white lines) and profiles at: (a) Hartland Quay and (b) Porthleven. (1) Seaward and landward margins for each transect are shown as triangles and square marks, (2) dot lines in DEMs show transects with large deviation from averaged shoreline which are removed in the average estimations presented in Table 3, and (3) dot lines in cross-shore profiles indicate MHWs, MSL, and MLWS elevations respectively. Of note, different horizontal and vertical scales are used to show both whole cross-shore (transect 1) and intertidal cross-shore profiles (transects 2-10).

224

225

Table 3. Summary of average intertidal profile characteristics of shore-platform transects in Hartland Quay - North Devon and Porthleven. Note that average calculation only considers 'shore-normal' profiles (excluding dot lines).

	North Devon			Porthleven		
	PG [degrees]	PW [metres]	PR	PG [degrees]	PW [metres]	PR
Whole	2.5	146	0.18	1.6	174	0.27
Upper	6.3	36	0.11	32.0	17	0.08
Central	2.6	69	0.12	16.8	80	0.15
Lower	1.7	110	0.13	0.9	158	0.18

226

227 The average PG of the whole, central and lower intertidal profiles at Hartland Quay is between 1.7 and
228 2.6°, whereas the upper intertidal profile slopes at 6.3° on average, because of the influence of a steeper
229 gravel/boulder beach at the site (Table 3 and Fig. 8a). At Porthleven the PG of the lower intertidal
230 profiles is less than 1 degree, whereas the cross-shore profile slopes steeply in upper and central portions
231 (32.0° and 16.8° respectively), due to the presence of the cliff face at upper intertidal elevations (Fig.
232 9b). The average PR at both sites is highest for the whole intertidal profile and lowest for the upper
233 intertidal section, but there is no clear consistency in PRs found between the two sites (PRs at different
234 elevations were almost consistent in North Devon whereas there was an increasing trend of PR with the
235 elevation at Porthleven). It should also be noted that most of the PR values exceed the minimum vertical
236 accuracy of the DEMs used in this study. Hence, the roughness estimates are unreliable and cannot be
237 used to inform observations of micro-surface morphology (e.g. see Dornbusch et al., 2008; Dornbusch
238 and Robinson, 2011).

239

240 Initial ground truthing revealed that calculations using profile points at particular tidal levels (e.g. MSL,
241 MHWS) occasionally resulted in inappropriate estimates of shore platform features; for instance, due
242 to the presence of non-shore platform features such as gravel/boulder beaches, steep cliffs or
243 ramps/ledges at upper intertidal elevations. To appropriately extract shore platform profiles, we
244 developed a method to automatically identify the cliff-platform junction (CP) and subsequently
245 characterize the shore platform morphology by analysing the section of profile extending between CP
246 and the seaward-most point (SP) corresponding with MLWS. Several conditions were used to find the
247 CP in relation to some SP and a landward point (LP) on the profile. (1) The width between CP and SP
248 and the gradient of the CP-SP slope were set as > 100 m and $< 10^\circ$, respectively, so that the CP occurs
249 at a wide range of elevations, without tidal elevational constraints, up to about 17 m ($\sim \tan 10^\circ \times 100$ m)
250 above MLWS. (2) The height and the gradient of CP-LP slope was set as > 3 m and $> 45^\circ$, respectively,
251 as we focused on shore platforms backed by a moderately higher and steeper cliff. Of note, the search
252 for the LP was conducted up to 3 m horizontal distance from CP due to computational efficacy. The
253 resulting CPs were often found at elevations above higher intertidal elevations, even with the possible
254 occurrence of high tide beaches in profiles. To remove the possible effect of beaches at higher intertidal

255 elevations, a landward-most point at MSL (CP-MSL) was used as the CP when (1) CP elevation was
 256 higher than MSL or (2) CP-LP slope was $> 5^\circ$ assuming that CP-LP slope was non-shore platform slope
 257 ($< 5^\circ$). When all CP/CP-MSL, SP, and LP were found, PG, PW, and PR were estimated using a profile
 258 extending between CP/CP-MSL and SP.

259

260 In total 612 transects out of possible 5541 transects (11%) were identified as shore-normal shore
 261 platform profiles with clear cliff-platform junctions. A large reduction of possibly useful shore platform
 262 profiles occurred because the CPs occur in a variety of geometric conditions in nature, whereas the CP-
 263 search was conducted automatically with a fixed geometric rule. We also verified the modified method
 264 by manually checking all the profiles, and confirmed that the selected 612 profiles and their SP and CP
 265 locations were sensible. For example, possible high tide beaches at higher intertidal elevations in No.4
 266 and No.10 profiles from Hartland Quay were removed with the automated method, whereas the CP
 267 below MSL in No.1 and No.4 profiles from Porthleven were appropriately selected (Fig. 10).

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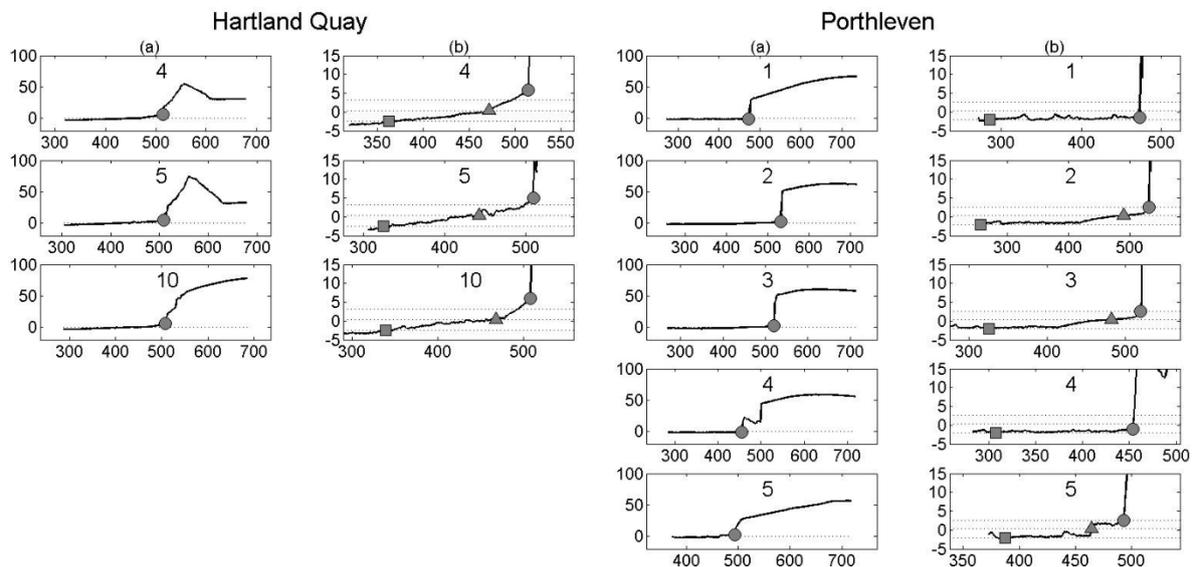


Fig. 10. Selected profiles from Hartland Quay and Porthleven: (a) whole profile and (b) intertidal profile. Number in each figure matches with those used in Figure 9. Circle, square, and triangle markers represent CP, SP and CP-MSL, respectively. Of note, (1) CP-MSL is not shown when slopes between CP and SP slope are used in calculation, (2) horizontal and vertical axis represent distance along transect in metres and elevation in metres, and (3) dot lines in intertidal profiles indicate MHWS, MSL, and MLWS elevations.

269

270 5. Results

271 This section examines the morphology of 612 shore platform profiles identified around the southwest
272 coast of England in respect to geographical location and possible environmental controls on
273 morphological development.

274

275 5.1. Region-wide comparison of shore platform morphology

276 The estimated PG, PW, and PR of the selected 612 shore platform profiles along about 700 km of
277 coastline from north to south are plotted in Fig. 11. We further divided the coastline into ten even
278 segments and plotted the mean and standard deviation of each segment. The trend lines were estimated
279 based on a linear regression analysis using the mean values of the segments.

280

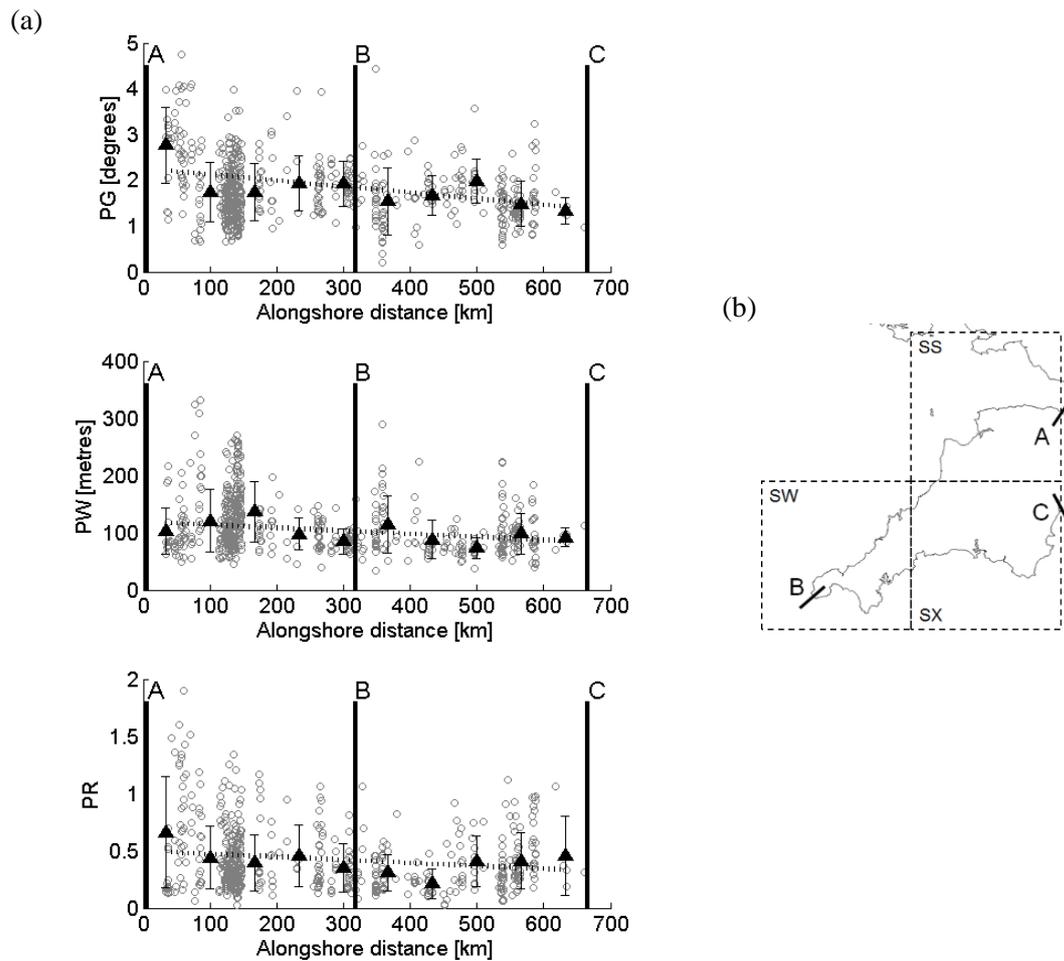


Fig. 11. (a) PG, PW and PR of shore platform profiles in SW England. Triangle markers and their error bars show mean values and standard deviations of all the data in each even

segment, and dots lines show linear trend lines. (b) A map of south west England with area lines indicating the relative position of A, B and C.

281

282

283 Results are scattered, and the standard deviation is high, but there are general region-wide trends
284 observed in shore platform morphology. For example, there is a gradual decreasing alongshore trend in
285 PG from the north (line A) to south-west (line B) and south-east (line C). A similar decreasing trend is
286 apparent both in PW and PR, although the trend is less clear, particularly with PR contrastingly
287 increasing from south-west (B) to south-east (C). In very general terms, the data indicate that from north
288 (A) to south-west (B) and south-east (C), shore platforms become flatter, narrower, and smoother. Some
289 clustering of data points is apparent in Fig. 11, particularly between 100-150 km distance alongshore.
290 Testing confirms that when those points are omitted the same decreasing PG/PW/PR trends still occur.

291

292 5.2. Correlation with environmental conditions

293 Statistical analyses were undertaken to explore potential relationships between shore platform
294 morphology and MSR, wave height and rock strength. It is important to note at the outset that the quality
295 of data available for these analyses varies: the estimate of MSR and MSL for each transect is relatively
296 reliable, whereas only offshore wave conditions and transect orientations were considered to estimate
297 nearshore wave conditions, and rock strength data are coarse with no account taken of local structural
298 controls (e.g., strike, dip, thickness of beds, and fracturing). Fig. 12 presents scatter plots and box plots
299 of PG/PW/PR calculated across the shore platform profiles, in relation to MSR, wave height and rock
300 strength; trend lines calculated using a linear regression analysis and correlation coefficients, and p-
301 values calculated using an analysis of variance (ANOVA) are also reported in the same figure.

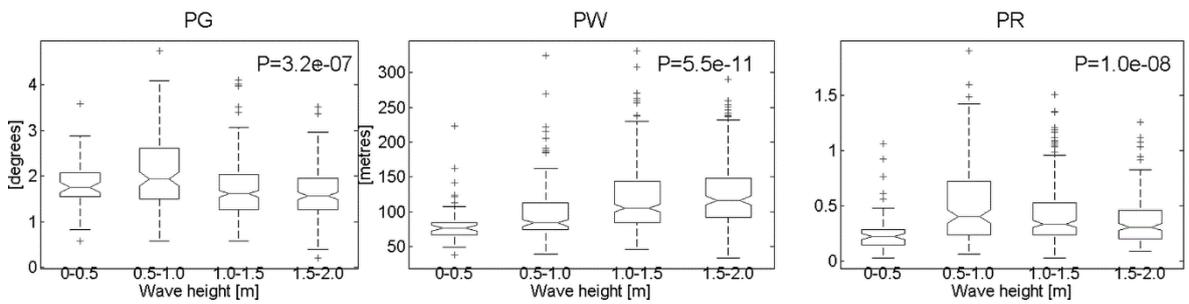
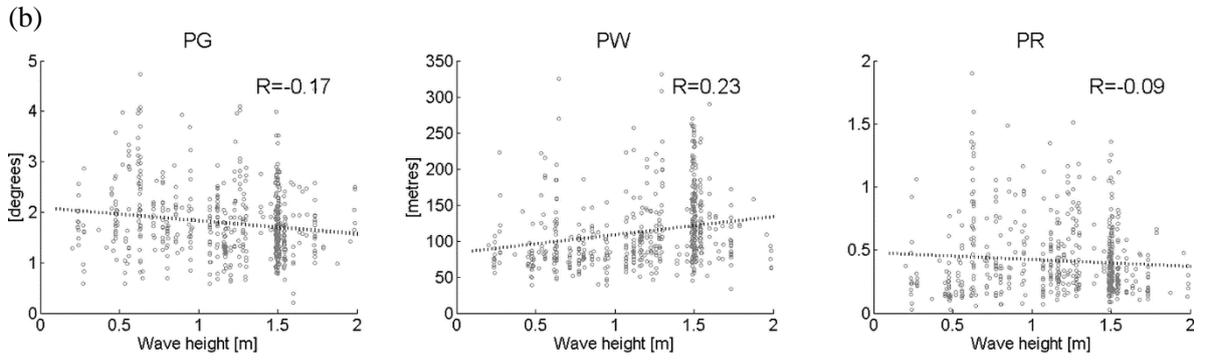
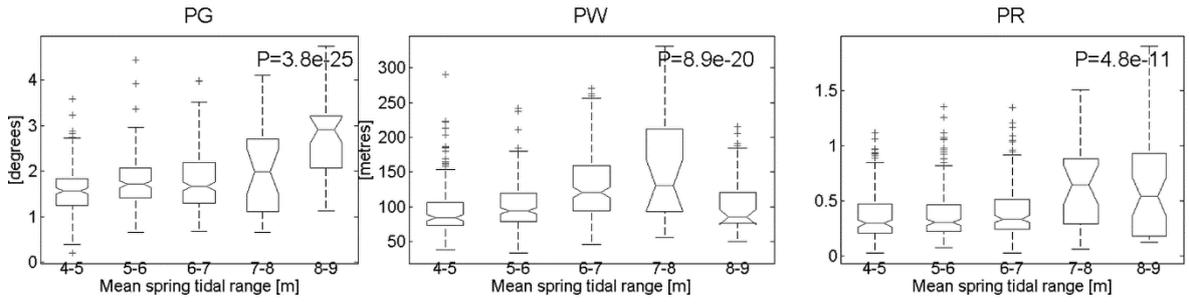
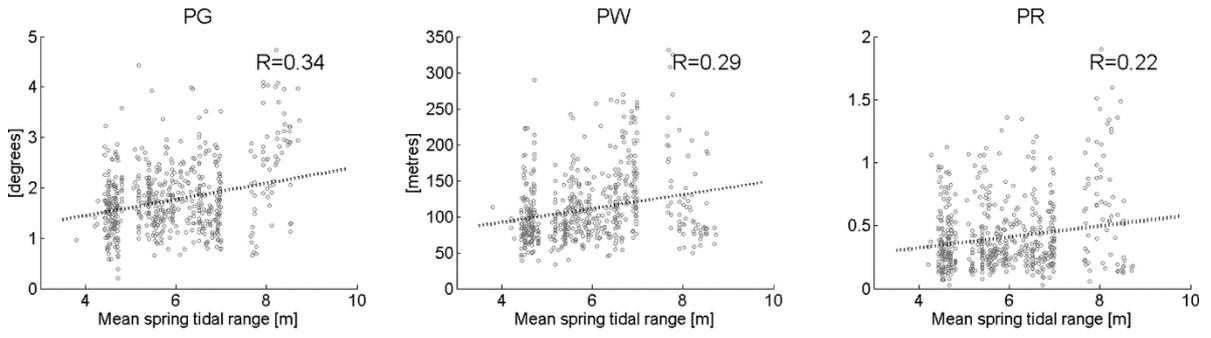
302

303 Trends exist between platform morphology and the different potential process controls (MSR, wave
304 height and rock strength). However, there is considerable scatter and correlation coefficients are
305 generally around 0.3 or less. As Fig. 12 shows, many relationships have very small p-values, implying
306 statistical significance (e.g. PG-MSR relation), but significance should be interpreted cautiously given
307 that there is a low degree of correlation, and that p values are influenced strongly by large sample sizes.

308 Overall, however, there are interesting trends in the relations investigated. For example, PG increases
309 with both MSR and rock strength. This relationship is also demonstrated by the box plots, although it
310 is notable that, when grouped, increases in MSR/rock strength result in a stepped rather than regular
311 increase in PG, raising the possibility of threshold effects (for instance, compare box-plots above and
312 below 7 m MSR and 10 MPa or below and 100 MPa rock strength). In contrast, a negative decreasing
313 trend was detected between PG and wave height. Generally, the data indicate that flatter platforms occur
314 where the tidal range is smaller, rock strength is weaker, and where there are larger waves. The PW
315 trend line also increases with MSR, but in contrast to PG, it increases with wave height and decreases
316 with rock strength. These results are physically sensible (e.g. wider platforms occur where waves are
317 bigger, tidal range is larger, and rocks are weaker), and exists despite difficulties associated with
318 usefully measuring PW. For instance, PW in some instances is calculated as the horizontal distance
319 between SP and CP, but in other instances, it is the horizontal distance between SP and CP-MSL (e.g.
320 when possible high tide beach profiles occur). PR increases with MSR and rock strength, in contrast to
321 a negative trend between PR and wave height. Correlation coefficients and p-values are smaller and
322 larger, respectively, in the PR-related relations, but, again in a broad view, there is physical sense to the
323 direction of trends: rougher platforms occur where there are harder rocks, smaller waves and larger tidal
324 ranges (because wave attack operates for less time across a larger band of rocks).

325

(a)



(c)

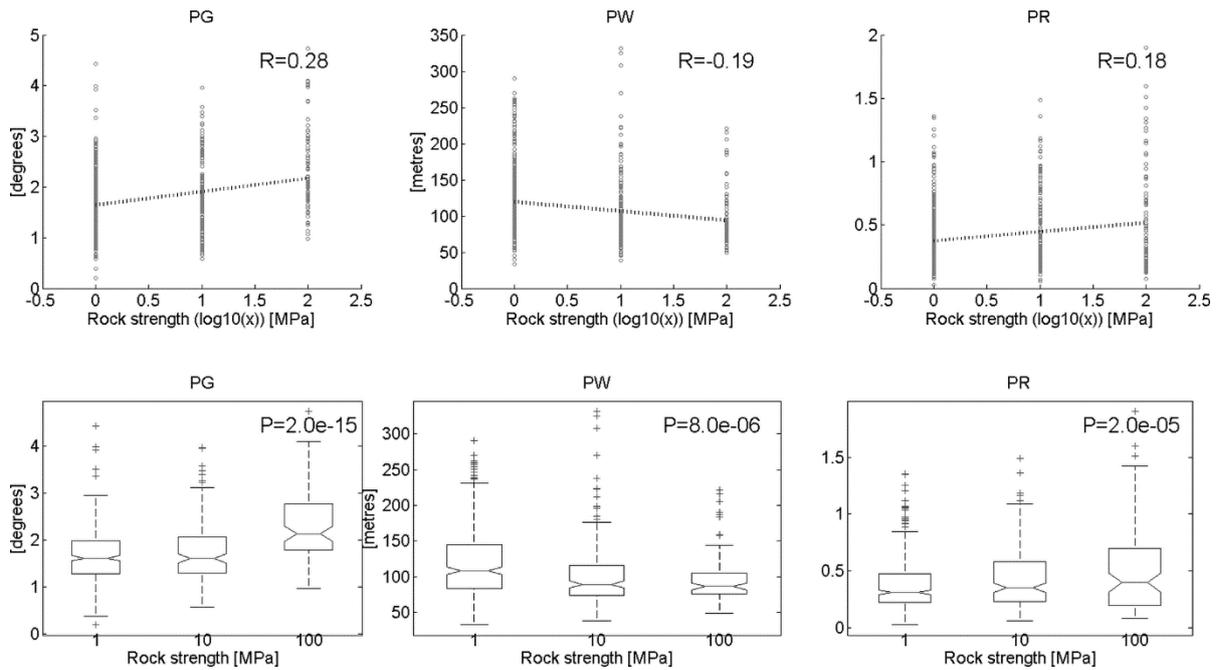


Fig. 12. Scatter plots and box plots of PG, PW and PR of shore platform profiles in relation to: (a) MSR, (b) wave height and (c) rock strength. Correlations coefficients (R) and p-values (P) are reported at the top-right of each scatter and box plot. Dot lines represent trend lines drawn from a liner regression analysis. Box plot shows median values (mid lines in the boxes), 25 and 75 percentile values (box outline), minimum and maximum values excluding outliers (whiskers), and 1.5 interquartile range (IQR) outliers (plus markers).

326

327

328 6. Discussion

329 The results from this paper demonstrate that LiDAR-derived DEMs can be used to systematically
 330 extract and analyse shore platform morphology at regional scales (i.e. hundreds of kilometres). This is
 331 a new spatial scale of analysis in rocky shore studies; the vast majority of previous work has focussed
 332 on descriptions of profile morphology across hundreds of metres to tens of kilometres at discrete field
 333 sites. The discussion below (1) considers process controls on shore platform development in the study
 334 area (~700 km of coast in southwest England), (2) describes a new simple empirical model describing
 335 shore platform gradient, and (3) examines the potential broader applicability of the method described
 336 in this paper for studies of rocky shore geomorphology.

337

338 6.1. Process controls on shore platform morphology

339 Previous field and modelling studies have suggested associations between platform morphology (e.g.
 340 PG, PW, PR) and various aspects of the process environment (Table 4). Perhaps the most widely known
 341 of these is a general positive correlation noted in field surveys by Trenhaile (1972, 1974, 1987, 1999)
 342 between PG and MSR. In addition, positive correlations have been noted between PG and rock strength
 343 (e.g. Trenhaile, 2005), PW and MSR (e.g., Trenhaile and Layzell, 1981; Trenhaile, 2000, 2005), and
 344 PW and wave intensity (e.g., Sunamura, 1978; Trenhaile, 1999, 2005). Trenhaile (2005) also showed
 345 that PG decreases with PR, which indirectly suggests a positive correlation between PR and MSR.
 346

Table 4. Examples of previous studies regarding environmental controls on platform morphology and the trends in this study

Shore platform morphology	Process	Trend observed in this study	Trend found in previous study	Reference	Study type
PG	MSR	Positive	Positive	Trenhaile (1972, 1974, 1987,1999)	Field observations
	Rock strength	Positive	Positive	Trenhaile (2005)	Modelling study
PW	MSR	Positive	Positive	Trenhaile and Layzell (1981), Trenhaile (2000, 2005)	Modelling study
	Wave intensity	Positive	Positive	Sunamura (1978), Trenhaile (2005)	Modelling study
		Positive	Positive	Trenhaile (1999)	Field observations
PR	MSR	Positive	Positive	Trenhaile (2005)	Modelling study

347
 348 Direct quantitative comparison of the trends observed in field studies with those found in this study is
 349 difficult, owing to different classification and description methods. However, the overall qualitative
 350 consistency between previous findings and our systematic and automated analysis of LiDAR data is
 351 noteworthy. The results are also somewhat surprising (in the sense that trends exist at all) because: (1)
 352 there are many potential sources of variability that exist from transect to transect; and (2) we have only
 353 taken very approximate representations of the process environment at each site.
 354

355 Observed relationships between shore platform morphology and controlling processes (i.e. MSR, wave
356 height, and rock strength) exhibit considerable scatter (Fig. 12), and caution needs to be exercised in
357 any attempt to link correlation with causation. It is unsurprising that scatter exists given the approximate
358 way in which environmental conditions were estimated at each transect. For example, offshore wave
359 conditions mediated by shoreline orientation were used to estimate nearshore wave conditions, whereas
360 complex transformations in wave energy are known to occur as waves transform inshore toward each
361 transect, and these are not fully accounted for in our analysis. Our analysis also neglects any possible
362 formative role for storm waves, which have been linked to erosion on many rocky coasts (e.g. Bartrum,
363 1926; Edwards, 1941, 1951; Cotton, 1963; Sunamura, 1978; Trenhaile, 1980) including the southwest
364 of England (Earlie et al., 2015). Further, Trenhaile (1987) highlighted that in nature sometimes opposite
365 trends occur between platform morphology and the expected environmental control owing to factors
366 such as local variability in rock structure (e.g. bedding orientation, joint density, presence/absence of
367 faults, etc.) which can be locally dominant (e.g. Trenhaile, 1972; Dickson et al., 2004; Naylor and
368 Stephenson, 2010; Cruslock et al., 2012; Moses, 2014). It is evident that local rock structure in the
369 studied coasts is highly varied (e.g., May, 1980) and must account for a least some of the scatter in the
370 results.

371

372 Inheritance of platform morphology from previous sea-level positions can also result in unusual
373 relationships between platform morphology and various aspects of the process environment. For
374 example, Bird and Dent (1966) noted that in southeast Australia, wider shore platforms sometimes occur
375 in more sheltered embayments. Brooke et al. (1994) showed that some platforms on this coast are
376 inherited from previous sea-level highstands, and that these inherited platforms are sometimes wider in
377 sheltered environments as they have suffered less erosion of their seaward edge during the present sea-
378 level highstand. The role of inheritance in shaping the geomorphology of contemporary shore platforms
379 in the southwest of England is not clear; however, there is an abundance of evidence for the presence
380 of raised shore platforms from previous inter-glacial period(s) (Orme, 1960). These highstand platforms
381 'merge' with the contemporary platforms and this may have contributed additional scatter to the
382 correlations observed in this study.

383

384 Factors such as varied rock resistance and inheritance lead Mii (1962) to conclude that shore platform
385 morphology is a very ambiguous indicator of process. This statement has often been repeated (e.g.
386 Stephenson 2000). We have not attempted to account for complex potential sources of uncertainty in
387 our analysis, so the fact that trends can be seen between platform morphology and various indicators of
388 the process environment likely stems from the large spatial scale of analysis. For example, despite the
389 overall consistency, there are many local inconsistent trends seen in Fig. 11. It appears therefore that
390 selectively but systematically observing morphology over a large spatial area, encompassing a wide
391 range of forcing processes, it is possible to observe the general nature of process-form dependency.

392

393 The present study illustrates that shore platform morphology is dependent on multiple controls: all of
394 the three controls we analysed had some association to platform morphology, and there will be other
395 controls that we did not study that are likely to be important as well (e.g. storm waves, weathering
396 processes, inheritance from former sea-level positions). Below we describe a simple empirical model
397 to describe shore platform gradient based on the three controls studied in this paper.

398

399 6.2 Empirical model of shore platform gradient

400 Several empirical models exist describing shore platform morphology, including the wave erosion
401 models of Tsujimoto (1987) and Sunamura (1992), which demarcates the development of sloping type-
402 A and sub-horizontal type-B shore platforms in relation to the relative forces of wave erosion and rock
403 strength. Here we examine the empirical model of Trenhaile (e.g. 1999), which predicts mean PG in
404 relation to MSR. The field data included in Trenhaile's (1999) analysis cover a wide spectrum of tidal
405 regimes from micro to mega tides. A strong correlation exists between PG and MSR across the entire
406 MSR space, although scatter in the data mean that this correlation would not be obvious if analyses
407 were conducted across a narrow tidal range (see Fig. 2 in Trenhaile, 1999).. An improved model of PG
408 for these data might benefit from consideration of additional environmental controls (beyond MSR). To
409 examine this possibility, single- and multi-linear regression analyses were undertaken, considering
410 MSR, wave height and rock strength assuming no co-correlation among independent variables.

411

412 Equation 4 and 5 provide models of PG with no intercept, similar to the empirical model by Trenhaile
 413 (e.g. 1999), where X_1 , X_2 and X_3 represent MSR in metres, wave height in metres, and rock strength in
 414 MPa. Table 5 shows statistical summaries of the single- and multi-linear regression analysis with an
 415 ANOVA analysis, and Table 6 compares root mean square errors (RMSE) of PG models including
 416 Trenhaile’s (1999) with respect to field data from Trenhaile (1999) and SW UK using LiDAR DEMs.

417

418
$$PG_{\text{single}} = 0.30X_1 \tag{Eq. (4)}$$

419
$$PG_{\text{multi}} = 0.31X_1 - 0.13X_2 + 0.19\log_{10}(X_3) \tag{Eq. (5)}$$

420

Table 5. Statistical summary of single- and multi-linear regression analysis (left) and ANOVA analysis.

Estimated coefficients						Anova					
		Estimate	Standard Error	tStat	pValue	SumSq	DF	MeanSq	F	pValue	
PG_{single}	X_1	0.30	0.01	68.13	1.4e-289	Total	332.4	612	0.54		
						Model	72.9	1	72.93	172.05	8.1e-35
						Residual	259.4	611	0.42		
PG_{multi}	X_1	0.31	0.01	22.81	9.3e-84	Total	341.9	612	0.56		
	X_2	-0.13	0.06	-2.20	2.8e-02	Model	98.7	3	32.89	82.66	7.0e-45
	X_3	0.19	0.04	5.27	1.9e-07	Residual	242.7	610	0.40		

421

Table 6. RMSE of various models using field data from Trenhaile (1999) and SW UK (LiDAR DEMs). Bold values represent RMSEs of single-factor best fit linear models, and values in the brackets show percent deviation relative to the RMSE of single-factor best fit linear models.

	Data from Trenhaile (1999)	Data from SW UK using LiDAR DEMs
Trenhaile’s model ($PG=0.26X_1$)	0.59	0.70 (+10%)
PG_{single}	0.67 (+13%)	0.65
PG_{multi}	-	0.62 (-5%)

422

423 Table 5 shows that the estimated coefficients and the models themselves are significant at 5%
424 significance level (p-values < 0.05). More importantly, Table 6 shows that, although PG_{single} fits better
425 with SW UK data (smaller RMSE compared to the equation provided by Trenhaile, 1999), PG_{multi}
426 further reduces the RMSE of PG_{single} by 5%. A 5% reduction in RMSE is not particularly large, but this
427 is not at all unexpected given the coarse estimates of wave height and rock strength used. Our
428 expectation is that improved estimates (measurements and/or modelling) of a range of environmental
429 controls, coupled with large-scale morphometric analyses, would achieve better quantitative
430 understanding of the relative importance of different controls on rocky coast morphology development.

431

432 7. Conclusions

433 This study describes a new semi-automatic method for analysing shore platform morphology over large
434 spatial scales using LiDAR-derived surface elevation models. DEMs with 1 m spatial resolution and
435 0.1 m RMSE are sufficiently detailed to enable algorithmic calculation of shore platform gradient and
436 platform width (but not platform roughness). Our results from 700 km of coast in southwest England
437 are broadly consistent with previous field studies undertaken at a relatively small number of selected
438 sites in which it has been shown that shore platform gradient is positively correlated with tidal range.
439 In addition, we find that shore platform gradient varies with wave height and lithology and conclude
440 that in southwest England, shore platform gradient is best predicted using an empirical model that
441 considers tidal range, wave height and rock strength. There is considerable scatter in the relationships
442 but this is not surprising given the extent of local variability that exists along the coast, and the very
443 coarse way that process controls have been represented in our study (particularly wave height and rock
444 strength). Rocky shore geomorphology is known to be influenced by many factors that we have not
445 considered (e.g. storm waves, local geological discontinuities, morphological inheritance from previous
446 sea-level positions, etc.). In this regard it is encouraging that general relationships can be seen between
447 shore platform geometry and metrics of tidal regime, wave climate and geology. We conclude that this
448 is likely attributable to the very large scale of analysis conducted. Given the widespread availability of
449 high resolution coastal DEMs, it should be possible to conduct even larger scale analyses of rocky shore
450 landforms and formative environmental controls, particularly if it is possible to combine such analyses

451 with more detailed information (modelled or field) relating to process-controls, such as nearshore wave
452 energy and geological/lithological/structural variability. In this way, large-scale analysis of coastal
453 DEMs might address the call from Naylor et al. (2010) for rocky shore evolution models to improve
454 calibration of model coefficients using field data.

455

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460

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