

2017-06-01

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

Matsumoto, H

<http://hdl.handle.net/10026.1/9102>

---

10.1016/j.geomorph.2017.03.011

Geomorphology

Elsevier BV

---

*All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.*

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

Authors: Hironori Matsumoto<sup>1\*</sup>, Mark E. Dickson<sup>1</sup>, Gerd Masselink<sup>2</sup>

<sup>1</sup>School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

<sup>2</sup>School of Marine Science and Engineering, Plymouth University, Drake Circus, Plymouth, Devon PL4 8AA, United Kingdom

Corresponding author at: School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand.

Email Address: [hmat258@aucklanduni.ac.nz](mailto:hmat258@aucklanduni.ac.nz) (H. Matsumoto)

## 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 20<sup>th</sup>  
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 Shagoon, 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).

79

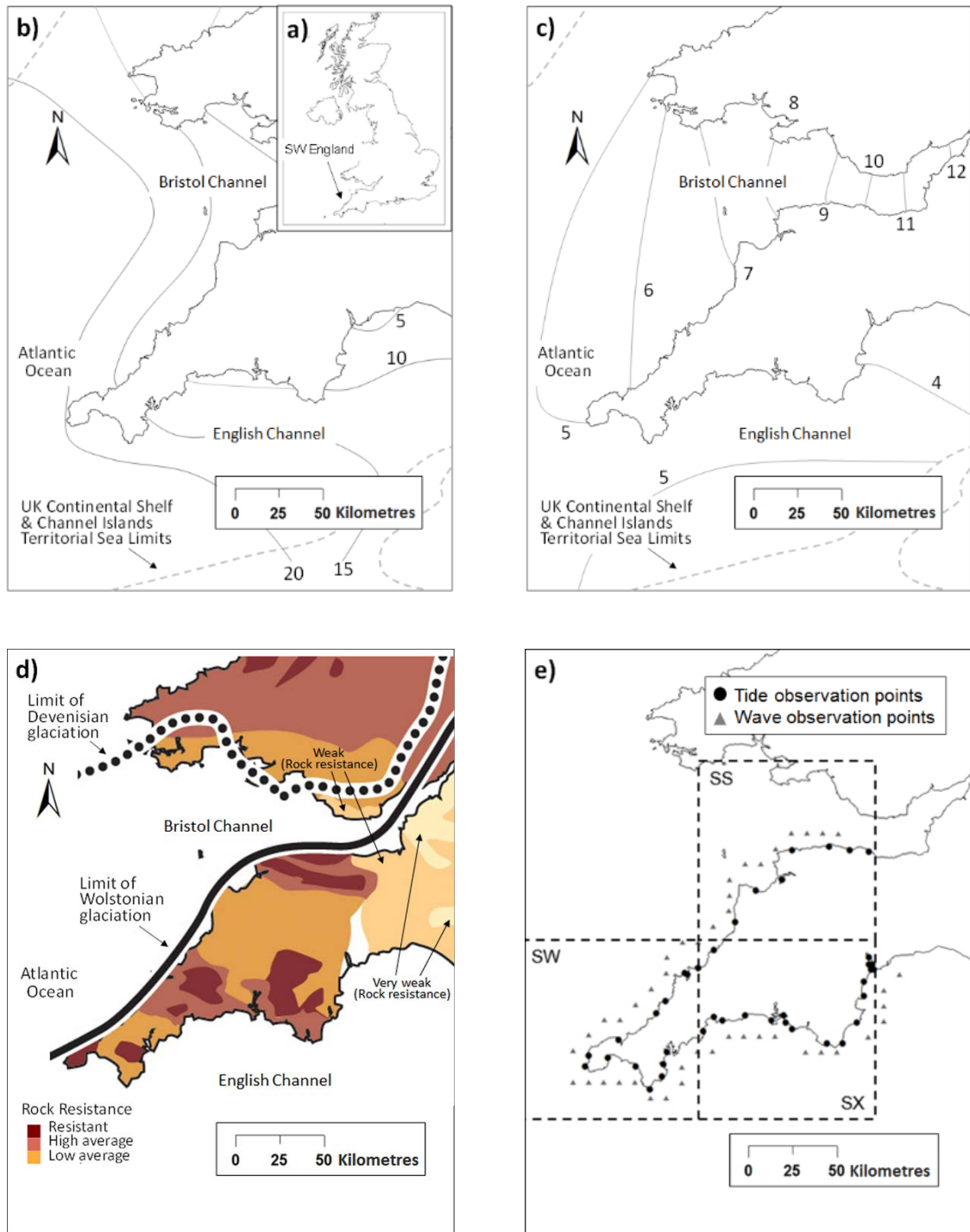


Fig. 1. a) Map of the England; b) mean wave power, based on hourly model hindcast over 7 years, modified from Scott et al. (2011); c) mean spring tidal range (based on data derived from an average tidal year), modified from Scott et al. (2011); d) resistance of geology to denudation, modified from Clayton 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  $\pm 0.1$  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  $\pm 0.03$  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%
	<b>Cliff-Rock Platform / Rock Platform</b>	<b>6,764</b>	<b>50.8%</b>
	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.  
 124



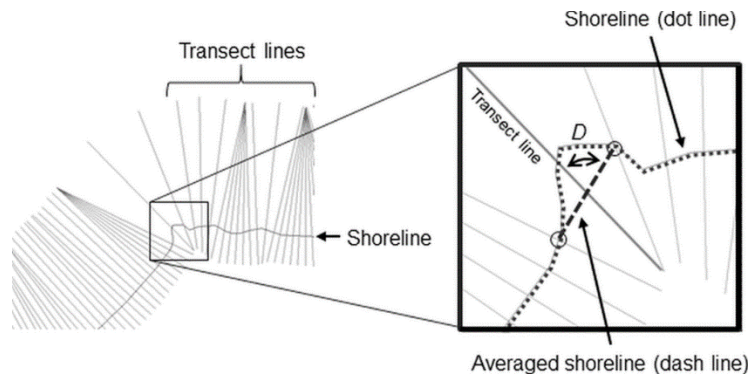


Fig. 2. Schematic view of piece-wise averaged shoreline for each transect.

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).

134

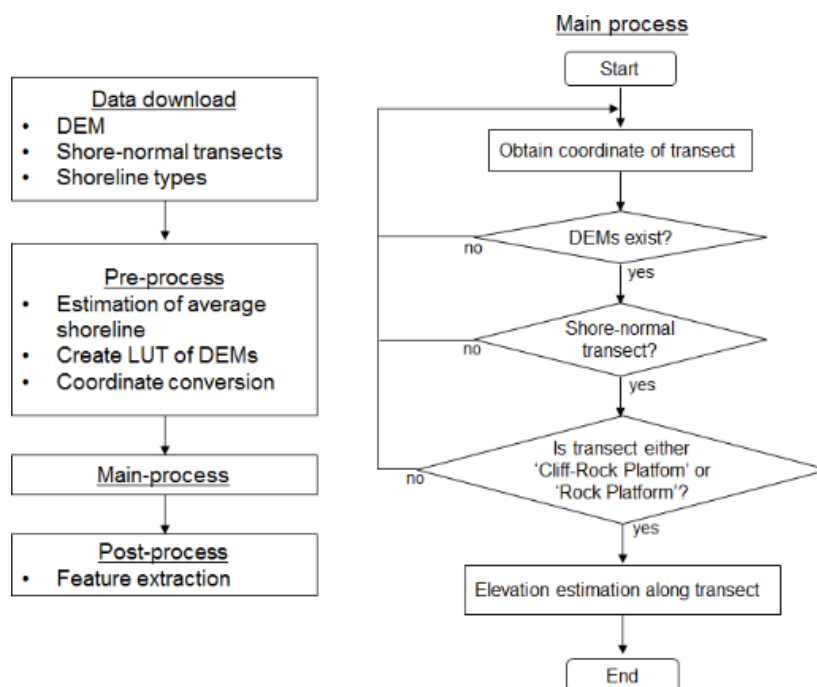


Fig. 3. Overview of semi-automated shore platform profile extraction.

135

136

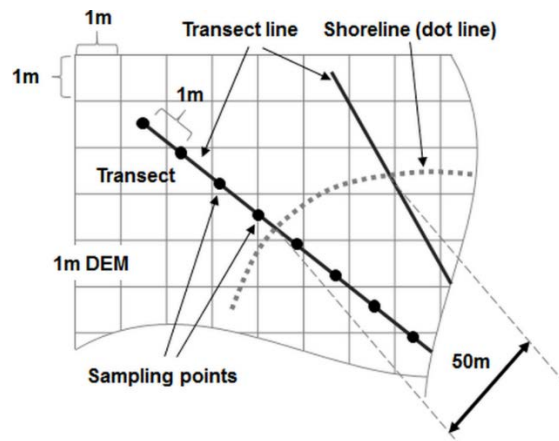


Fig. 4. Schematic view of cross-shore profile extraction from 1 m DEM. The horizontal and vertical coordinates of each sampling point are rounded off to the closest first decimal number in order to uniquely determine the elevation value.

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 6<sup>th</sup> order; hence, a 6<sup>th</sup> order polynomial line was selected for the purpose of estimating  
153 platform roughness.

154

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

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

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

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.

172

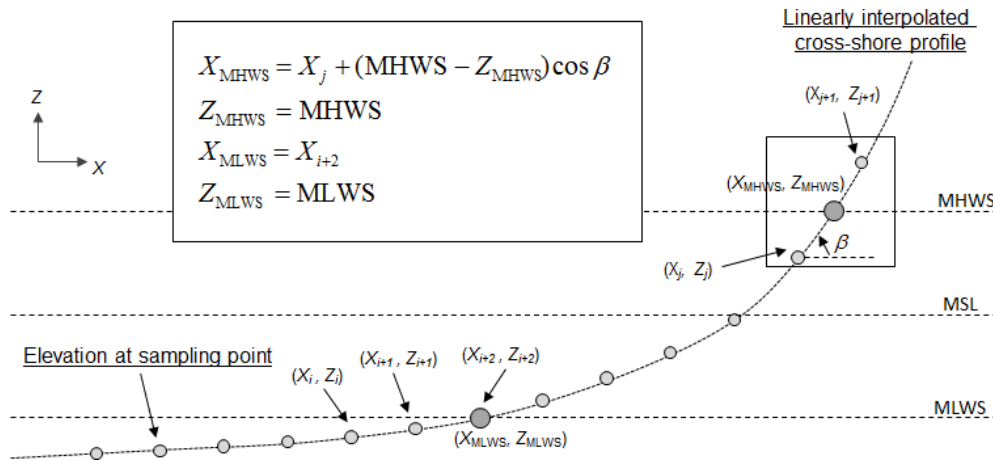


Fig. 5. Cross-sectional view of a profile with positions at MHWS and MLWS.

173

174

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 ( $\alpha$ ). To obtain the nearshore wave height, the modelled ‘deep water’ wave height was

186 simply multiplied by a multiplier  $K$ , depending on  $\alpha$ :  $K = 1$  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.  
 192

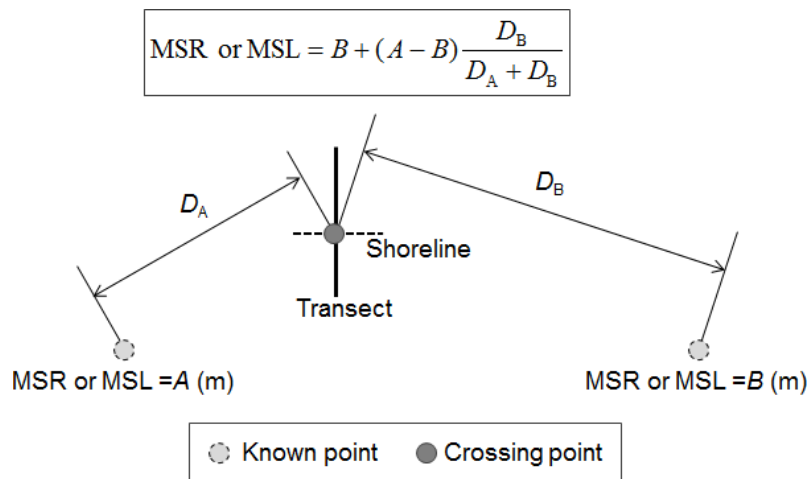


Fig. 6. Relative position of MSR/MSL-known points and crossing point with average shoreline and transect.

193  
 194

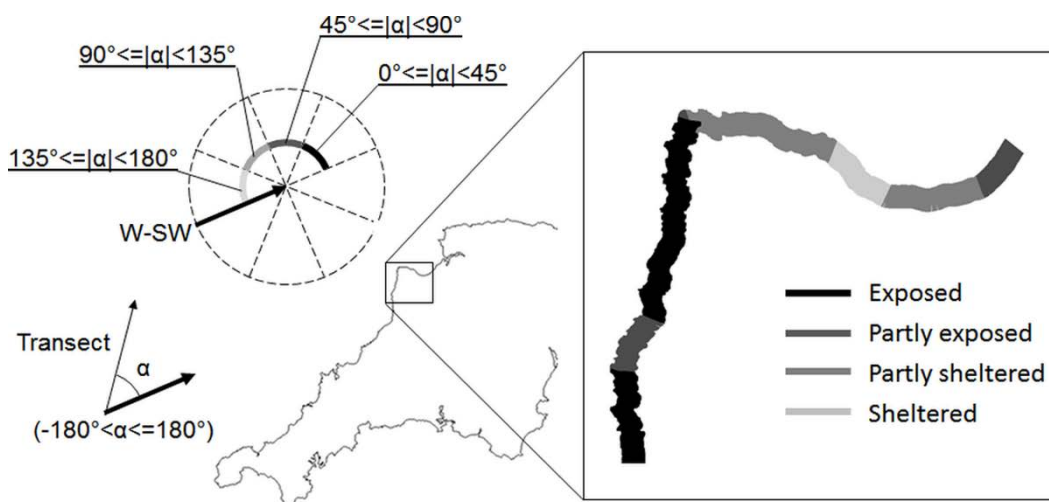


Fig. 7. Transect categorization examples in respect to wave exposure.

195

196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221

#### 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.

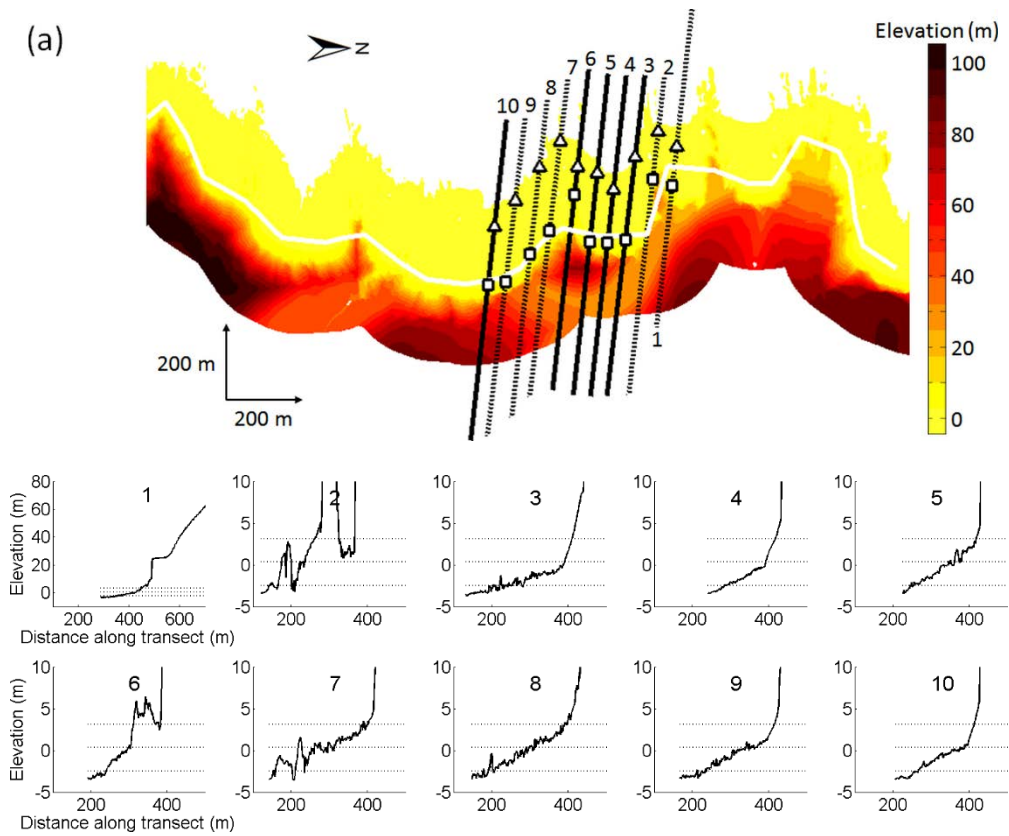
Two well-recognized shore platform sites in North Devon and Cornwall, shown in Fig. 8, were selected for the ‘ground-truthing’. Fig. 9 shows ten consecutive cross-shore profiles for each of the sites with seaward and landward margins. Table 3 shows the average PG/PW/PR values at each site. Of note, non-shore-normal 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/>)

222

223



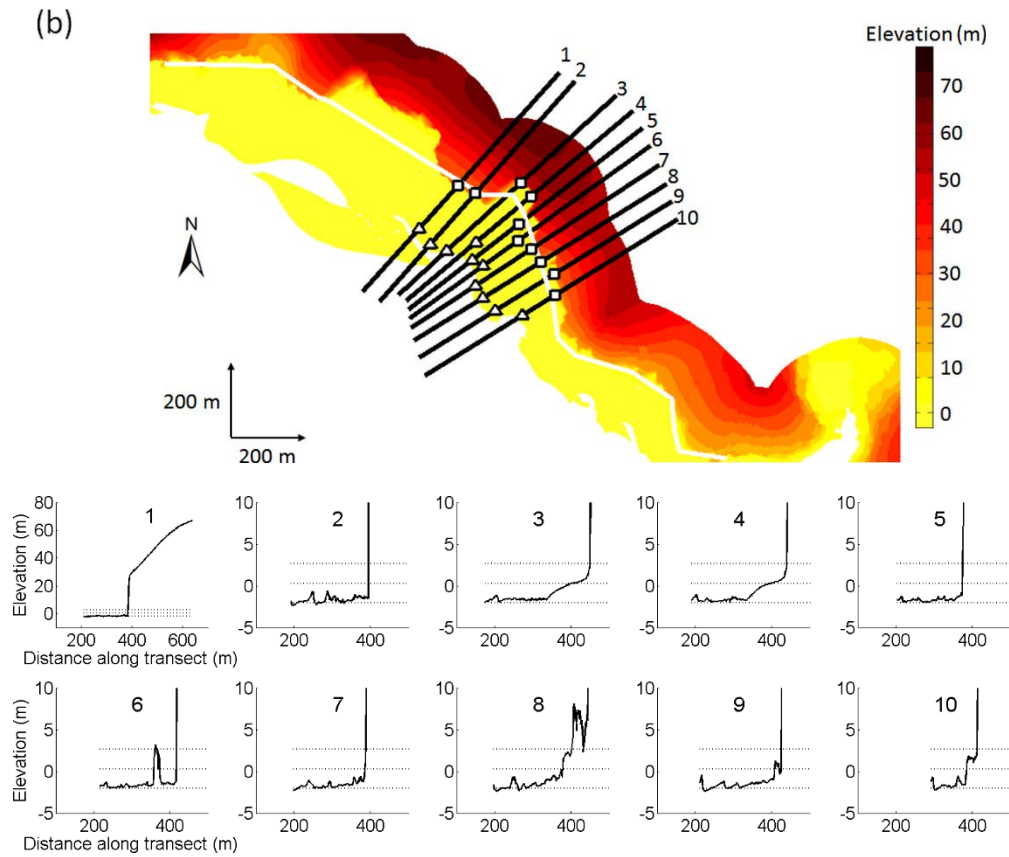


Fig. 9. DEMs with ten consecutive transects (black lines) and shoreline (white lines) and profiles at: (a) Hartland Quay and (b) Porthleven. (1) Seaward and landward margins for each transect are shown as triangles and square marks, (2) dot lines in DEMs show transects with large deviation from averaged 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).

268

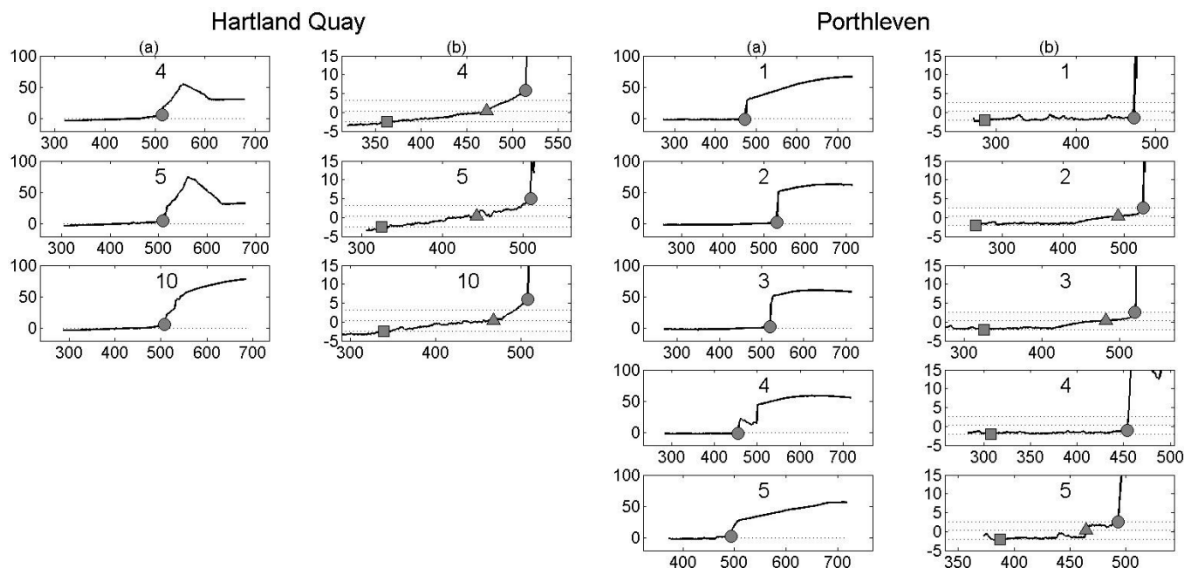


Fig. 10. Selected profiles from Hartland Quay and Porthleven: (a) whole profile and (b) intertidal profile. Number in each figure matches with those used in Figure 9. Circle, square, and triangle markers represent CP, SP and CP-MSL, respectively. Of note, (1) CP-MSL is not shown when slopes between CP 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

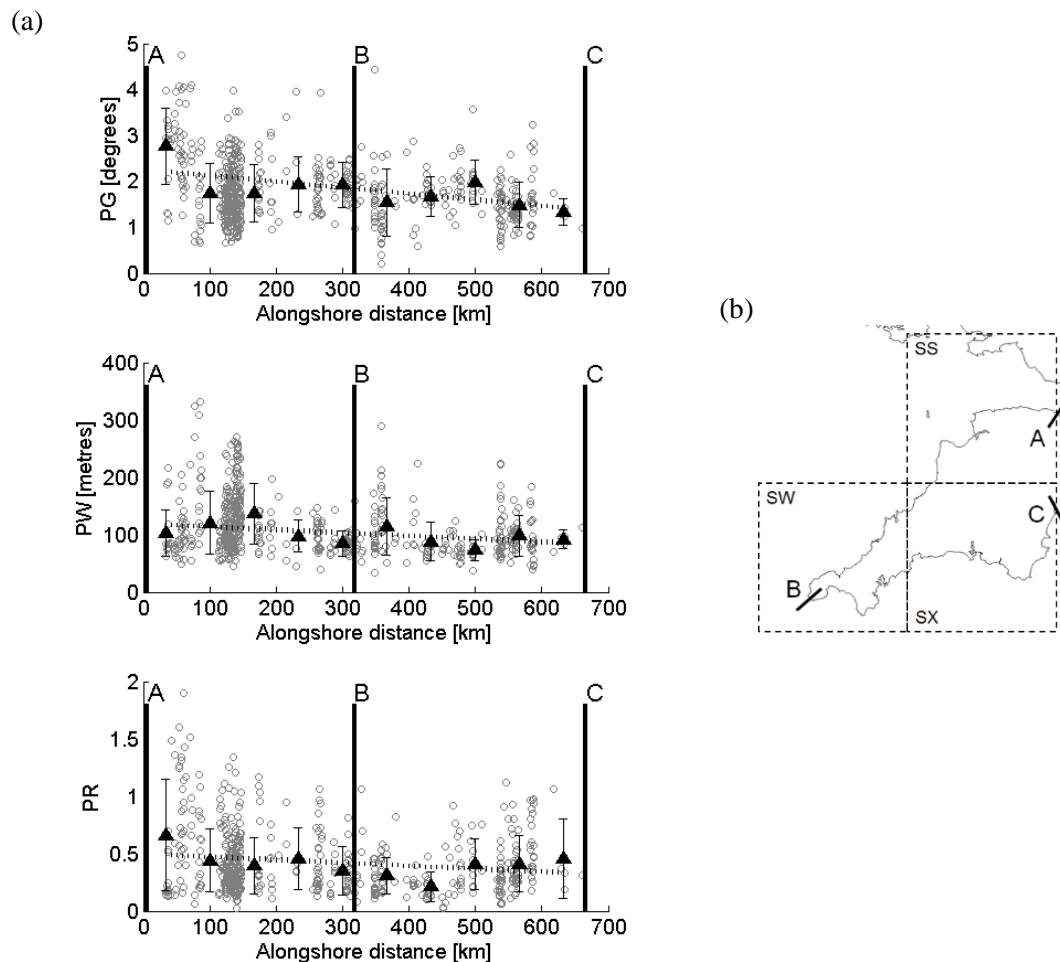


Fig. 11. (a) PG, PW and PR of shore platform profiles in SW England. Triangle markers and their error bars show mean values and standard deviations of all the data in each even

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.

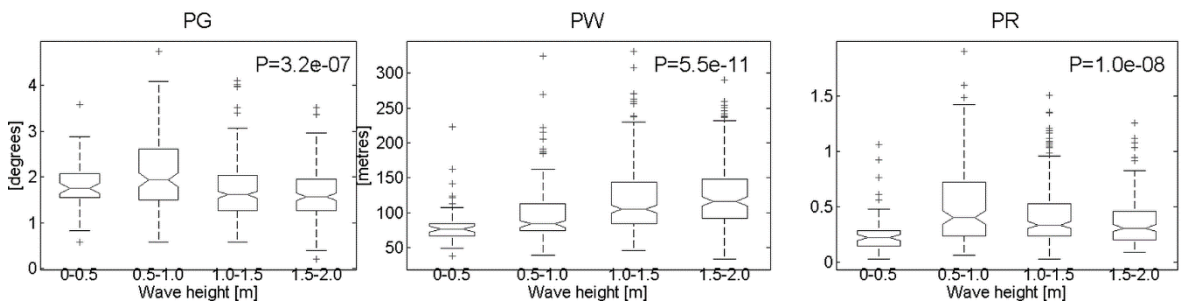
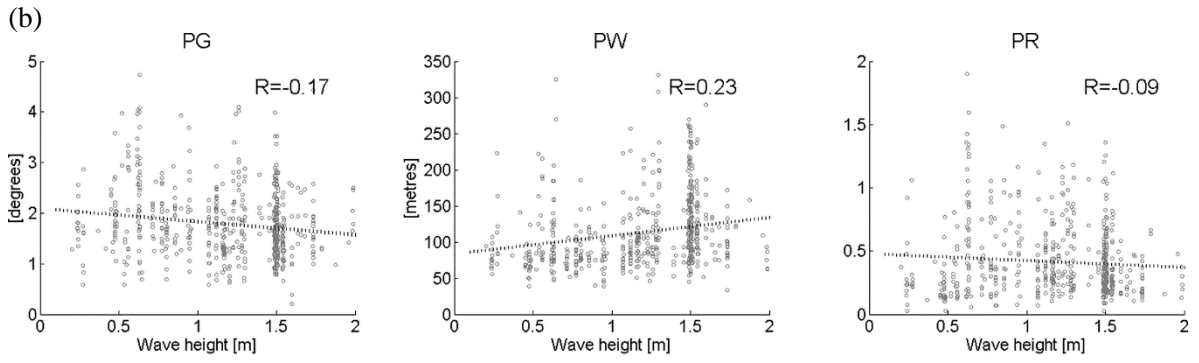
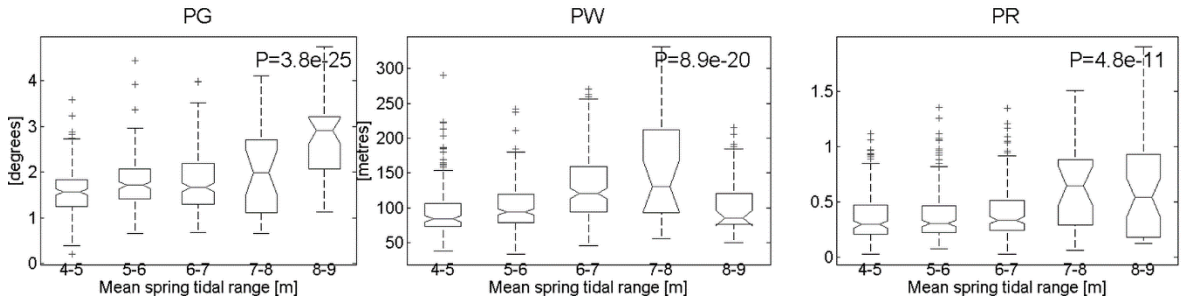
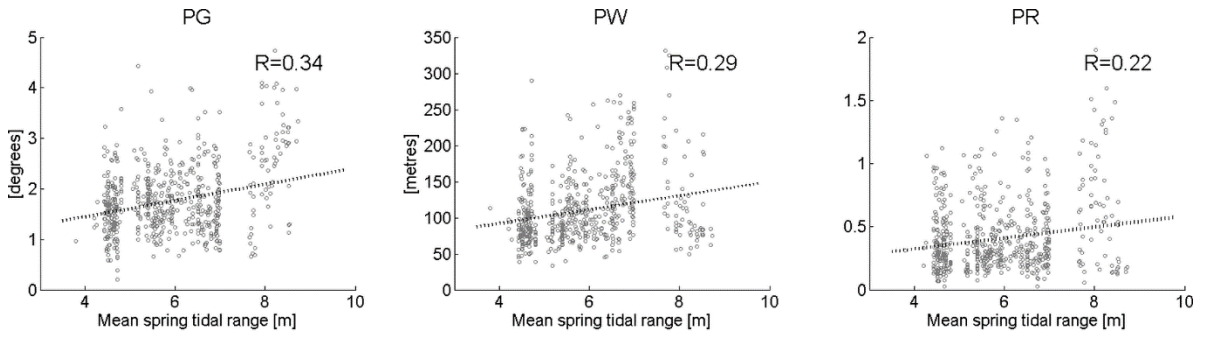
302

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)

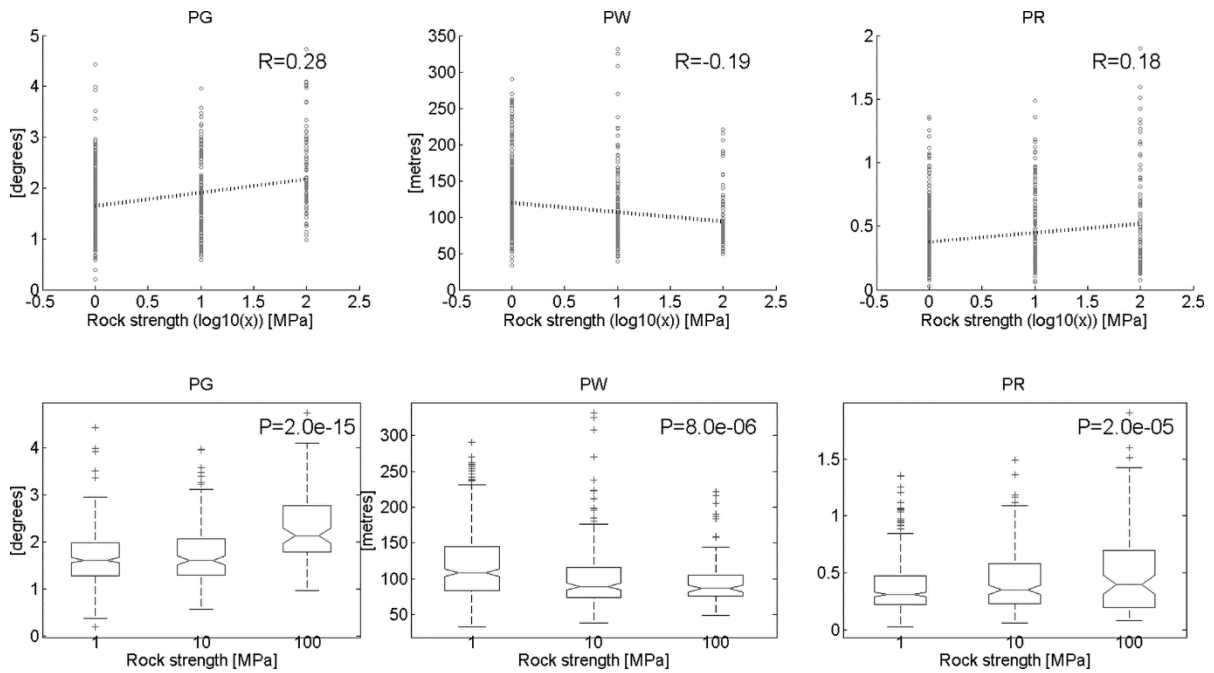


Fig. 12. Scatter plots and box plots of PG, PW and PR of shore platform profiles in relation to: (a) MSR, (b) wave height and (c) rock strength. Correlations coefficients (R) and p-values (P) are reported at the top-right of each scatter and box plot. Dot lines represent trend lines drawn from a liner 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	
$PG_{\text{single}}$	$X_1$	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		
$PG_{\text{multi}}$	$X_1$	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 ( $PG=0.26X_1$ )	<b>0.59</b>	0.70 (+10%)
$PG_{\text{single}}$	0.67 (+13%)	<b>0.65</b>
$PG_{\text{multi}}$	-	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  $PG_{\text{single}}$  fits better  
425 with SW UK data (smaller RMSE compared to the equation provided by Trenhaile, 1999),  $PG_{\text{multi}}$   
426 further reduces the RMSE of  $PG_{\text{single}}$  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

#### 456 Acknowledgments

457 Mark Dickson was part-funded by the MBIE funded Natural Hazards Research Platform through  
458 Contract C05X0907 ("Climate change impacts on weather-related hazards"). Gerd Masselink was part-  
459 funded by EPSRC grant Waves Across Shore Platforms (WASP; EP/L025191/1).

460

#### 461 References

- 462 Adams, P. N., Anderson, R. S., Revenaugh, J., 2002. Microseismic measurement of wave-energy  
463 delivery to a rocky coast, *Geology*, 30, 895–898.
- 464 Bartrum, J.A., 1926. Abnormal shore platforms. *Journal of Geology* 34, 793–807.
- 465 Bartrum, J.A., 1938. Shore platforms. *Journal of Geomorphology* 13, 266–272.
- 466 Bird, E. C. F.; Dent, O. F., 1966: Shore platforms on the south coast of New South Wales. *Aust. Geogr.*  
467 10, 71-80.
- 468 Blanco-Chao, R., Costa Casais, M., Martínez Cortizas, A., Pérez Alberti, A., Trenhaile, A.S., 2003.  
469 Evolution and inheritance of a rock coast: western Galicia, northwestern Spain. *Earth Surf. Process.*  
470 *Landf.* 28, 757–775.
- 471 Brooke, B. P., Young, R. W., Bryant, E. A., Murray-Wallace, C. V., Price, D. M. 1994. A Pleistocene  
472 origin for shore platforms along the northern Illawarra coast, New South Wales. *Australian*  
473 *Geographer*, 25, 178–185.
- 474 Channel Coastal Observatory, 2014. Specification of LiDAR surveys.  
475 ([http://www.channelcoast.org/national/procurement/Specification\\_Lidar.pdf](http://www.channelcoast.org/national/procurement/Specification_Lidar.pdf))
- 476 Clayton, K., Shamon, N., 1998. A new approach to the relief of Great Britain II. A classification of  
477 rocks based on relative resistance to denudation. *Geomorphology* 25, 155-171.
- 478 Cotton, C.A., 1963. Levels of planation of marine benches. *Zeitschrift Für Geomorphologie*, 7, 97–111.

479 Cruslock, E.M., Naylor, L.A., Foote, Y.L., Swantesson, J.O.H., 2010. Geomorphologic equifinality: A  
480 comparison between shore platforms in Höga Kusten and Fårö, Sweden and the Vale of Glamorgan,  
481 South Wales, UK, *Geomorphology* 114, 78-88.

482 Dana, J.D., 1849. Report of the United States exploration 1838-1842. Volume 10, 442.

483 Dickson, M.E., 2004. The development of talus slopes around Lord Howe Island and implications for  
484 the history of island planation. *Australian Geographer* 35(2), 223-238.

485 Dickson, M.E., 2006. Shore platform development around Lord Howe Island, southwest Pacific.  
486 *Geomorphology* 76, 295-315.

487 Dickson, M.E., and Pentney, R., 2012. Micro-seismic measurements of cliff motion under wave impact  
488 and implications for the development of near-horizontal shore platforms. *Geomorphology* 151-152,  
489 27-38.

490 Dornbusch, U., Moses, C., Robinson, D.A., Williams R., 2008. Soft copy photogrammetry to measure  
491 shore platform erosion on decadal timescale. *Journal of Coastal Conservation* 11(4), 193-200.

492 Dornbusch, U., Robinson, D.A., 2011. Block removal and step backwearing as erosion processes on  
493 rock shore platforms: a preliminary case study of the chalk shore platforms south-east England.  
494 *Earth Surface Process and Landforms* 36, 661-671.

495 Duperré, A., Raimbault, C., Le Gall, B., Authemayou, C., van Vliet-Lanoe, B., Regard, V., Dromelet,  
496 E., Vandycke, S., 2015. High-resolution onshore–offshore morpho-bathymetric records of modern  
497 chalk and granitic shore platforms in NW France, *Comptes Rendus Geoscience*.  
498 doi:10.1016/j.crte.2015.06.005

499 Earlie, C.S., Young, A.P., Masselink, G., Russel, P., 2015. Coastal cliff ground motions and response  
500 to extreme storm waves. *Geophysical Research Letters* 42, 847-854.

501 Edwards, A.B., 1941. Storm-wave platforms. *Journal of Geomorphology* 4, 223–236.

502 Edwards, A.B., 1951. Wave action in shore platform formation. *Geological Magazine* 88, 41–49.

503 Farrell, E.F., Granja, H., Cappietti, L., Ellis, J.T., Li, B., Sherman, D.J., 2009. Wave transformation  
504 across a rock platform, Belinho, Portugal. *Journal of Coastal Research* SI 56, 44-48.

505 Kanyaya, J.I., Trenhaile, A.S., 2005. Tidal wetting and drying on shore platforms: An experimental  
506 assessment. *Geomorphology* 70, 129-146.

507 Kennedy, M., 2015. Where is the seaward edge? A review and definition of shore platform morphology.  
508 Earth Surface Reviews 147, 99-108.

509 Kennedy, D.M., Ierodiaconou, D., Schimel, A., 2016. Granitic coastal geomorphology: applying  
510 integrated terrestrial and bathymetric LiDAR with multibeam sonar to examine coastal landscape  
511 evolution. Earth Surface Processes and Landforms 39, 1163-1674.

512 Lim, M, Rosser, N.J., Petley, D.N., Keen, M., 2011. Quantifying the controls and influence of tide and  
513 wave impacts on coastal rock cliff erosion. Journal of Coastal Research 27, 46–56.

514 May, V.J., 1980. Hartland Quay. Coastal Geomorphology of Great Britain 28(3), 1-6.

515 Mii, H. 1962. Coastal geology of Tanabe Bay. Science Reports of the Tokoku University, Sendai,  
516 Second Series, 34, 1–96.

517 Moses, C.A., 2014. The rock coast of the British Isles: shore platforms. Geological Society, London,  
518 Memoirs, 40(1), 39-56.

519 Naylor, L.A., Stephenson, W.J., 2010. On the role of discontinuities in mediating shore platform erosion.  
520 Geomorphology 114, 89-100.

521 Naylor, L. A., Stephenson, W. J., Trenhail, A. S., 2010. Rock coast geomorphology: Recent advances  
522 and future research directions. Geomorphology 114, 3-11.

523 Norman, E. C., Rosser, N. J., Brain, M. J., Petley, D. N., Lim, M., 2013. Coastal cliff-top ground  
524 motions as proxis for environmental processes. Journal of Geophysical Research 118(12), 6807-  
525 6823.

526 Ogawa, H., Dickson, M.E., Kench, P.S., 2011. Wave transformation on a sub-horizontal shore platform,  
527 Tatapouri, North Island, New Zealand. Continental Shelf Research 31, 1409-1419.

528 Ogawa, H., Kench, P., Dickson, M., 2012. Field measurements of wave characteristics on a near  
529 horizontal shore platform, Mahia Peninsula, Norht Island, New Zealand. Geophysical Research 50,  
530 179-192.

531 Ogawa, H. Kench, P., Dickson, M., 2016. Generalised observations of wave characteristics on near-  
532 horizontal shore platforms: Synthesis of six case studies from the North Island, New Zealand, New  
533 Zealand Geographer. doi: 10.1111/nzg.12121.

534 Orme, A.R., The raised beaches and strandlines of South Devon : field studies 1(2), 109-130.

535 Palamara, D. R., Dickson, M.E., Kennedy, D.M., 2007. Defining shore platform boundaries using  
536 airborne laser scan data: a preliminary investigation. *Earth Surface Processes and Landforms* 32,  
537 945-953.

538 Porter, N.J., Trenhaile, A.S., Prestanski, K., Kanyaya, J.I., 2010a, Patterns of surface downwearing on  
539 shore platforms in eastern Canada, *Earth Surf. Proc. Lands.* 35, 1793-1810.

540 Porter, N.J., Trenhaile, A.S., Prestanski, K., Kanyaya, J.I., 2010b, Shore platform downwearing in  
541 eastern Canada: Micro-tidal Gaspé, Québec

542 Porter, N.J., Trenhaile, A.S., Prestanski, K., Kanyaya, J.I., 2010c, Shore platform downwearing in  
543 eastern Canada: The mega-tidal Bay of Fundy, *Geomorphology* 118, 1-12.

544 Rosser, N. J., Brain, M. J., Petley, D. N., Lim, M., Norman, E.C., 2013. Coastline retreat via progressive  
545 failure of rocky coastal cliffs. *Geology* 41, 939-942.

546 Scott, T., Masselink, G., Russell, P., 2011. Morphodynamic characteristics and classification of  
547 beaches in England and Wales. *Marine Geology* 286, 1-20.

548 Stephenson, W. J. and Kirk, R. M., 1998. Rates and Patterns of Erosion on Shore Platforms, Kaikoura,  
549 South Island, New Zealand. *Earth Surf. Process. Landforms* 23, 1071-1085.

550 Stephenson, W. J., 2000. Shore platforms: a neglected coastal feature? *Progress in Physical Geography*  
551 24, 311-327.

552 Stephenson, W. J., Kirk, R. M., 2000, Development of shore platforms on Kaikouora Peninsula, South  
553 Island, New Zealand: Part Two: The role of subaerial weathering, *Geomorphology* 32, 43-  
554 56. Sunamura, T., 1992. *Geomorphology of Rocky Coasts*. John Wiley & Sons, Chichester.

555 Sunamura, T., 1978. A mathematical model of submarine platform development. *Math. Geol.* 10, 53-  
556 58.

557 Sunamura, T., 1992. *Geomorphology of Rocky Coasts*. John Wiley & Sons, Chichester.

558 Swantesson, J.O.H., Moses, C.A., Berg, G.E., Jansson, K.M., 2006. Methods for measuring shore  
559 platform micro-erosion: a comparison of the micro-erosion meter and laser scanner. *Z. Geomorphol.*  
560 144, 1-17.

561 Swirad, Z.M., Rosser, N.J., Brain, M.J., Vane-Jones, E.C., 2016. What controls the geometry of rocky  
562 coasts at the local scale? *Journal of Coastal Research, Special Issue* 75, 612-616.



563 Trenhaile, A.S., 1972. The shore platforms of the Vale of Glamorgan, Wales. Transactions of the  
564 Institute of British Geographers 56, 127–144.

565 Trenhaile, A.S., 1974. The geometry of shore platforms in England and Wales. Trans. Inst. Br. Geogr.  
566 62, 129-142.

567 Trenhaile, A.S., 1980. Shore platforms: a neglected coastal feature. Progress in Physical Geography 4,  
568 1-23.

569 Trenhaile, A. S., 1987. The Geomorphology of Rock Coasts. Oxford University Press, Oxford.

570 Trenhaile, A. S., 1999. The Width of Shore Platforms in Britain, Canada, and Japan. Journal of Coastal  
571 Research 15, 355-364.

572 Trenhaile, A.S., 2000. Modelling the evolution of wave-cut shore platforms. Mar. Geol. 166, 163-178.

573 Trenhaile, A. S., 2005. Modeling the effect of waves, weathering and beach development on shore  
574 platform development. Earth Surf. Process. Landforms 30, 613-634.

575 Trenhaile, A.S., 2008a. Modeling the role of weathering in shore platform development.  
576 Geomorphology 94, 24-39.

577 Trenhaile, A.S., 2008b. The development of subhorizontal shore platforms by waves and weathering in  
578 microtidal environments. Z. Geomorph. N.F. 52, 105-124.

579 Trenhaile, A.S., Layzell, M.G.J., 1981. Shore platform morphology and the tidal duration factor. Trans.  
580 Inst. Br. Geogr. 6, 82-102.

581 Tsujimoto, H., 1987. Dynamic Conditions for Shore Platform Initiation. Science Reports of the Institute  
582 of Geoscience University of Tsukuba A8, 45-93.

583 Young, A. P., Adams, P. N., O'Reilly, W. C., Flick, R. E., Guza, R. T., 2011. Coastal cliff ground  
584 motions from local ocean swell and infragravity waves in Southern California, J. Geophys. Res.,  
585 116, C09007, doi:10.1029/2011JC007175.

586 Young, A. P., Guza, R.T., O'Reilly, W.C., Burvingt, O., Flick, R.E., 2016. Observati ons of coastal cliff  
587 base waves, sand levels, and cliff top shaking. Earth Surface Process and Landforms.  
588 doi:10.1002/esp.3928

589 Wentworth, C.K., 1938. Marine bench-forming processes: water-level weathering. Journal of  
590 Geomorphology 1, 6–32.

