

1 **Spatial variability in beach biogeomorphology in a tropical archipelago**

2

3 Shannon Gore¹, J. Andrew G. Cooper², Derek W. T. Jackson², Lianna Jarecki³

4

5 1. Coastal Management Consulting, P. O. Box 3252 PMB #1103, Road Town, Tortola
6 VG1110, British Virgin Islands

7 2. Centre for Coastal and Marine Research, School of Environmental Sciences,
8 University of Ulster, Coleraine, Northern Ireland, BT52 1SA, United Kingdom.

9 3. Guana Science, 257 Park Ave. S. #700, New York, NY 10010.

10

11 **ABSTRACT**

12

13 Beaches of tropical island coasts exhibit high levels of diversity in composition and form
14 in comparison with their continental counterparts. To investigate the nature and origin of
15 this diversity, individual beach morphology and sedimentology was investigated in the
16 British Virgin Islands (BVI), a Caribbean archipelago of > 60 high volcanic and low reef
17 islands. The islands exhibit a diversity of orientations (some facing the Atlantic and
18 some the Caribbean), elevation and gradient, rock type and wave energy. An
19 examination of 100 beaches in the archipelago revealed a first order division into sand
20 (70 beaches) and coral rubble (30 beaches). These beaches occur in seven planform
21 types (determined by the antecedent geological framework) and are further subdivided
22 according to shoreface type (seagrass, sandy shoreface, or reef). Mainland-attached

23 headland-embayment beaches are the most common form of sand beach while coral
24 rubble beaches usually occur as barriers that enclose salt ponds and wetlands.

25

26 Among sand beaches, carbonate content is greatest on Atlantic-facing beaches, and
27 coral rubble beaches are more common on Caribbean-facing beaches. Grain size
28 characteristics on sandy beaches are highly variable and range from fine to very coarse
29 sands while coral rubble beaches range up to boulder-sized clasts. The local source
30 material is a primary determinant of sediment composition.

31

32 The local factors such as the underlying geology, source and availability of sediments
33 are the primary determinants of beach form, composition and texture in the BVI.
34 Oceanographic and climatic conditions such as the prevailing easterly trade winds and
35 waves which seasonally range in direction from east-northeast to southeast as well as
36 beach orientation to Atlantic or Caribbean facing waves also contribute to the variability,
37 but in a secondary role.

38

39 **INTRODUCTION**

40 The morphology of a beach reflects a variety of interacting variables including sediment
41 texture and composition, wave energy and geologic setting (Pilkey et al., 2011, Loureiro
42 et al., 2012). A number of studies have examined the interaction between sediment
43 texture and wave conditions (e.g. Wright and Short, 1984) to develop generic models of
44 beach morphology and beach behaviour. The geological influence on beach form
45 (geologic setting and sediment volume) has received comparatively less attention and

46 yet is known to be an important determinant of beach form and behaviour (Jackson et
47 al., 2005; Jackson and Cooper, 2009; Short, 2010). On tropical beaches, the influences
48 of biogeomorphology (via reefs and seagrass beds) and sediment texture (imparted by
49 a diversity of bioclastic shape and size) are likely to be particularly important influences
50 on beach form (Gallop et al., 2013).

51

52 With a few notable exceptions (e.g. Bush et al., 1995; Woodroffe, 2002; Wong, 2003;
53 Kench and Brander, 2006; Duvat, 2007) the geomorphology of beaches on small
54 tropical islands has received comparatively little attention. The British Virgin Islands
55 (BVI) (Figure 1) contains a large number of beaches of variable form and texture within
56 a relatively small area. Despite many beaches in the BVI having ecological, economic
57 and socio-cultural importance; they are severely threatened by development of
58 commercial and residential properties and beach management is in the early stages of
59 implementation (Gore, 2007).

60

61 In this paper, we seek to examine the nature and origin of beach form diversity in
62 tropical island settings and look at individual beach morphology and sedimentology
63 using the BVI as a case study. Specifically, we focus on spatial variability in beach form
64 throughout the region of over 60 islands. The objective is to provide a first-order
65 baseline classification of the beaches and to interpret their distribution and form in terms
66 of their oceanographic and geological setting.

67

68

69 **METHODS**

70 Field investigations of 70 sandy and 30 coral rubble beaches (See Figures 2-6 for
71 localities) were conducted between 2005 and 2009. Selection of beaches was based
72 primarily on ease of access by land or sea. Foreshore characteristics, terrestrial
73 environments adjacent to the beach and planforms were first identified from both the
74 BVI Coastal Resource Atlas (CRI) (Blair Meyers et al., 1992) and 2002 aerial photos
75 (1:2500).

76

77 Remotely sensed site characteristics were verified by field visits that also involved
78 beach sediment sampling and snorkelling observations in the area immediately seaward
79 of the beach. The subtidal foreshore was characterised based on morphology between
80 the shoreline and 20 m depth, where the forereef is generally located. Three different
81 foreshore morphologies were identified (see Figures 10-13 for examples): headland-
82 attached linear reef; terrace flat (with or without reef or marine vegetation); and graded
83 reef (with or without reef or marine vegetation).

84

85 Surface sand samples were collected at 70 sandy beaches. At each beach samples
86 (~100 g) were collected from the swash zone, mid-beachface and berm. All 210
87 samples were taken from the centre of the beach planform. A semi-automated settling
88 tube was used for sediment analysis (Johansen and Larsen, 1998). Carbonate
89 percentages were determined by weight-loss acid digestion (Molnia, 1974). A
90 multivariate statistical analysis of sandy beaches was carried out using K-means
91 clustering analysis (MacQueen, 1967) based on grain size, sediment composition and

92 foreshore characteristics. Foreshore characteristics were assigned numerical values (1-
93 yes, 2-no) for direction to prevailing wind and wave regimes and a second numerical
94 value was assigned for each a fronting reef, sand or seagrass bed. All results were
95 mapped using ArcGIS 9.3.

96

97 Mean clast size at each of 30 coral rubble beaches was determined using Wolman's
98 (1954) sampling technique for coarse bed surfaces. This method determines grain sizes
99 based on relative area covered instead of relative weight. A 50m transect measuring
100 tape was laid shore-parallel mid-way up the beachface of each coral rubble beach.
101 Clasts directly below the transect line at 1 m intervals were measured at their b-axis
102 with a total sample size of 50 clasts per beach.

103

104 **STUDY AREA**

105 The British Virgin Islands (BVI) comprise a small volcanic archipelago (Figure 1)
106 bounded by the Atlantic Ocean to the north and the Caribbean Sea to the south. The
107 BVI has a total land area of 151 km² and human population of 35,015 (CIA, 2017). The
108 Territory consists of over 60 high volcanic islands. Anegada, the second largest island
109 in the Territory, however, is a reef platform with a maximum elevation of 8m (Martin-
110 Kaye, 1959; Atwater et al., 2012). The ~6km-wide Sir Francis Drake channel (maximum
111 depth 50m) divides the BVI into two high island chains. Northeast of Tortola and
112 southwest of Anegada is a shallow carbonate bank (average depth 25m) (Figure 1). A
113 number of low-lying mangrove cays occur on coral reef/rubble flats along the southern
114 coast of Tortola and Beef Island. One previously vegetated sand cay (vegetation

115 removed by a recent category 5 hurricane) exists as part of an incipient tombolo (Sandy
116 Spit) and an unvegetated sand cay is forming on a narrow reef flat off Necker Island.

117

118 The BVI has a total coastline length of ~420km consisting of beaches (of sand, gravel,
119 and boulder-sized clasts) of both terrigenous and carbonate sediment, interspersed with
120 red mangroves (*Rhizophora mangle*), steep rocky cliffs or man-made bulkheads and
121 riprap. The island shorelines vary in orientation, underlying geology, and have a
122 diversity of adjacent marine features (coral reefs, marine vegetation, and carbonate
123 platforms).

124

125 The area is microtidal (0.29m during neaps to 0.65m during spring tides). The trade
126 winds blow from ENE during winter (Dec.-Feb.), E during spring (Mar.-May) and SE
127 during summer and fall (June-Nov.). Maximum wind speeds occur during winter with a
128 minimum during the fall (Figure 7).

129

130 The Atlantic offshore wave climate is dominated by a persistent north-easterly to south-
131 easterly wave regime with deep-water significant wave heights averaging 1.7m with an
132 average period of 8 seconds (NOAA's WAVEWATCH III models between 1997-2010,
133 location 19N and 65W with a 1.0 X 1.25-degree grid resolution). Swells, from the north
134 to northwest are occasionally generated from storms in the North Atlantic Ocean
135 between December and May (Cooper et al., 2013). Additionally, the BVI lies within the
136 Atlantic hurricane belt. The hurricane season extends from June to November, with

137 August and September being most active (Hubbard, 1989). High-energy waves
138 generated from these storms may approach the islands from any direction (Figure 7).

139
140 The Caribbean Sea wind and wave regime is characterised by its generally benign yet
141 persistent mean conditions forced by the easterly trade winds. Mean wave height and
142 period are 1.34m and 4.9s, respectively. The semi-enclosed Caribbean Sea is
143 sheltered from distant Atlantic swells and dominated by locally produced wind waves
144 (Stopa et al., 2013). Storms control extreme conditions with intensity and frequency
145 variations increasing across the basin from south to north (Calverley et al., 2001). While
146 some hurricane activity is generated in the eastern Atlantic, hurricanes may also
147 originate within the Caribbean Sea.

148
149 Only a few of the studied beaches are directly exposed to swell waves and even then,
150 this is seasonal. They include Long Bay - Belmont, Larmer, Cooper, Rogues, Trunk,
151 Josiah's and Lambert Bays on Tortola; North Beach, Guana Island; North Bay, Great
152 Camanoe; Wedgeo Bay, Ginger; South Sound and Handsome Bay on Virgin Gorda.
153 Extreme waves such as those produced from hurricanes may affect a wider range of
154 beaches, at least temporarily, as hurricanes may pass the islands from any direction,
155 although usually on an east-west track. Two known hurricanes (Category 4 Hurricane
156 Lenny ~90km south of the BVI in 1999 and Category 3 Hurricane Omar ~60k south of
157 the BVI in 2008) have passed on an anomalous west-east direction. Hurricanes may
158 pass either to the north or south of the island chain. Since 1871, ten hurricanes have
159 made a direct landfall on the BVI with only one category 5 hurricane (NOAA, 2011;

160 Cangialosi et al., 2018). In contrast, swells approaching from a north-westerly direction
161 may last for a few days and expose beaches on west or north-west coasts.

162

163 **BEACH MORPHOLOGY & PLANFORM**

164 The 100 beaches in this study were categorized according to both planform and
165 nearshore (profile) characteristics since beach planform provides insight into a range of
166 characteristics such as wave exposure, water transport pathways, formation of littoral
167 cells, temporal morphologic changes and sedimentary characteristics (Bowman et al.,
168 2009). In this study, beach planforms in the BVI were divided into three categories:
169 mainland-attached beaches (64 examples), barriers (33 examples) and spits (3).
170 Mainland-attached and barrier categories were further sub-divided into linear, embayed
171 or cusped forms (Figure 8 and Table 1).

172

173 Mainland-attached beaches are by far the most common type of beach in the BVI with
174 sediment having been driven onshore over steeply dipping bedrock into small coastal
175 re-entrants. These beaches are often dissected by freshwater drainage pathways locally
176 called 'ghuts' that drain directly into the sea and provide a source of terrigenous
177 sediments from pebble to boulder size terrigenous rock.

178

179 Linear beaches are relatively straight and continuous beaches of sand or coral rubble.
180 They are best developed on Anegada where the beach forms a continuous rim around
181 the island (approximately 48km) as either mainland-attached or barrier beaches. Since
182 the high islands have irregular coastlines, linear beaches are not common. However, a

183 few mainland-attached linear beaches exist on smaller volcanic islands with lower relief,
184 such as Pelican Island, and along the southern coast of Tortola.

185
186 Embayed beaches consist of discrete sedimentary units bounded by headlands. They
187 vary in morphology according to headland spacing and orientation, bay indentation,
188 length and sediment characteristics (Klein and Menezes, 2001), but typically assume a
189 concave planform controlled by wave refraction and diffraction around adjacent
190 headlands. Beaches in these embayments tend to be swash-aligned (Woodroffe,
191 2002). Embayed beaches bounded by bedrock outcrops are the most common form in
192 the BVI.

193
194 Cuspate beaches are formed from converging or drift aligned waves influenced by
195 nearshore bathymetry. Barrier cuspate beaches in the BVI exist as small cuspate
196 forelands. These develop as a sequence of ridges formed at a high angle to the overall
197 beach orientation (McNinch and Luettich, 2000). They often enclose lagoons and
198 marshes (Woodroffe, 2002). A series of well-developed cuspate forelands are located
199 on the south-western coast of Anegada at Pomato Point as well as on the northern side
200 of Dead Chest (Figure 8).

201
202 Barrier beaches are widely developed around the BVI coast. On the volcanic islands
203 they enclose salt ponds or wetlands and are associated with areas of lower gradient
204 bedrock. The barriers are typically composed of coral rubble that occasionally has a
205 veneer of sand. Barrier beaches form as a result of a linear reef developing across the

206 entrance of a bay. With the rapid growth rates of corals such as *Acroporids* (Lidtz and
207 Shinn, 1991; Jarecki, 2004), the reef crest may become exposed over time (Cox et al.,
208 2000). Red mangroves (*Rhizophora mangle*) then colonize the reef crest to form a
209 complex network of roots that trap mangrove peat and sediments (Ellison and
210 Farnsworth, 1996). Sediments that have accumulated on these barrier frameworks
211 range in size from medium sand to boulder-sized coral clasts. Back-barrier lagoons are
212 important influences on beach behaviour in that they capture fine sediment from
213 inflowing streams (MacDonald et al., 1997) and provide space for potential landward
214 retreat of barriers.

215

216 Mainland-attached cusped beaches in the BVI occur as tombolos that connect two solid
217 outcrops. Tombolos form when the distance between the two outcrops is equal to or
218 less than 1.5 times the width of the offshore structure (Sunamura and Mizuno, 1987). In
219 the BVI, they form between islands, rock outcrops or reefs. Sandy Spit is an incipient
220 tombolo (Figure 9) developing between Green Cay and some shallowly submerged
221 beachrock outcrops. Three spits were identified, two composed of coralline boulders
222 (The Bluff at South Sound, Salt Island and South Sound Spit, Virgin Gorda) and one
223 composed of sand (Sprat Point, Beef Island).

224

225 **FORESHORE/SHOREFACE MORPHOLOGY**

226 Most temperate beaches have a sandy shoreface. In the tropics, however, shoreface
227 development is often inhibited by the presence of biogenic structures (Short, 2006).
228 Some BVI beaches are fronted by sandy shorefaces while others are fronted by coral

229 reefs or seagrass meadows. The absence of a mobile shoreface influences the
230 potential for morphological change to the beachface and backbeach in response to
231 changing wave conditions. A classification of BVI beaches based on
232 shoreface/nearshore morphology (Figure 7) identifies an initial split between beaches
233 with sandy shorefaces and those without. Those that lack a shoreface further divide
234 into those fronted by one of three types of fringing reef or those fronted by seagrass
235 beds.

236

237 **Coral reef foreshores**

238 The majority of reefs around the high volcanic islands of the BVI are fringing reefs that
239 have developed close to shore on a narrow shelf between the low tide shoreline and the
240 20m bathymetric contour. Anegada's Horseshoe Reef covers approximately 133km²
241 and is composed of two distinctive facies, a high-energy reef front on the north-north-
242 eastern windward side of the island, and a series of systematically distributed patch
243 reefs along the island's southern leeward side (Brown and Dunne, 1980). The fringing
244 reef on the north side of Anegada extends beyond the eastern end of the island to the
245 southeast for ~14km. This entire reef system is the largest contiguous reef in the BVI
246 and is a major source of the carbonate sediments found on the Anegada Bank between
247 Anegada and Tortola. Many of the fringing reefs in the high volcanic islands of the BVI
248 lack an identifiable reef crest.

249

250 Fringing reefs fronting beaches are common throughout the BVI and our study shows
251 that there is further variability in form of fringing reefs backed by beaches. Three types

252 of fronting reef exist in conjunction with BVI beaches: headland-attached reefs, terrace
253 flats and graded reefs.

254

255 *Headland-attached linear reefs* are < 500 m offshore and usually extend across an
256 embayment (Figure 11). Such reefs have a distinct reef crest, originally composed of
257 *Acropora palmata* but since the outbreak of white-band disease in the late 1970s
258 (Aronson and Precht, 2001), *Orbicella annularis* has become the dominant reef species
259 in the BVI. The reef crest may be partially exposed on extremely low tides and depth in
260 the lagoon can exceed 5 m. These reefs intercept much of the incoming wave energy
261 but secondary waves and wind waves form in the fetch-limited back-reef area.

262

263 *A terrace flat* is a backreef environment or reef flat, although it does not always have a
264 fronting reef but instead a broad shallow seagrass or carbonate bank. A terrace flat is a
265 low-gradient, broad and shallow lagoon, composed of unconsolidated sediments,
266 seagrasses, small patch reefs and/or most often coral rubble (Figure 12). The irregular
267 seafloor topography exerts a strong control on contemporary wave behaviour. Strong
268 energy dissipation occurs over the initial fore reef, substantially reducing the total
269 energy contained in the wave forms. Subsequent wave energy reduction occurs through
270 shoaling processes over the shallow (<1-5 m) waters of the reef flats. Short (2006)
271 noted several such beaches in tropical Australia where the reef flat extended to the
272 shore.

273

274 *Graded reefs* differ from reef flats in that the cross-shore profile is steeper so less
275 energy is dissipated through breaking and shoaling (Figure 13). Coral relief and
276 coverage is commonly higher than on reef flats but there is no distinctive reef crest. The
277 reef may cover the entire seabed or be dissected by sand-filled channels (spur and
278 groove formations).

279

280 **Seagrass meadow foreshores**

281 The presence of seagrass on the foreshore plays an important morphological function
282 on adjacent beaches. Seagrass beds attenuate wave energy (Fonesca and Cahalan,
283 1992; Koch, 1996; Verduin and Backhaus, 2000), stabilize bottom sediments (Fonseca,
284 1989), and interact with hydrodynamics restricting morphological response during
285 storms to the beachface and berm (Basterretxea et al., 2004; Vacchi et al., 2017). An
286 additional influence on beach morphology occurs through the accumulation of leaf litter
287 forming banquettes which may enhance dune formation on the backshore (Hemminga
288 and Nieuwenhuize, 1990; Kirkman and Kendrick, 1997) or foreshore, depending on the
289 exposure to dominant waves (Simeone and Falco, 2012). Extensive seagrass meadows
290 occur throughout the BVI, with several bays exhibiting high densities of *Thalassia*
291 *testudinum*, *Syringodium filiforme*, *Halodule wrightii* and/or more recently the invasive
292 species, *Halophila stipulacea*. A distinctive beach step is usually developed at the
293 junction of seagrass bed and beachface.

294

295 **Sandy shorefaces**

296 Several sandy beaches on the north east coast of Tortola lack offshore reefs and are
297 exposed to high Atlantic wave energy. These are the only beaches to have a mobile
298 sandy shoreface. Observations during large swell events (Cooper et al., 2013) show
299 that these beaches suffer backshore erosion, reduction in gradient and development of
300 nearshore bars during high wave energy. Post-storm recovery involves the transfer of
301 sediment from nearshore bars to the beachface, as in unconstrained temperate
302 beaches (Wright and Short, 1984).

303

304 **BEACH COMPOSITION**

305 From a textural perspective, beaches in the BVI may be broadly divided into sand and
306 coral rubble. There is, however, additional variability in carbonate content and sediment
307 texture. These variations and the distribution of such beaches around the archipelago
308 are described below.

309

310 **Coral rubble beaches**

311 Numerous beaches throughout the BVI are composed of coral rubble ranging in size
312 from fine to coarse gravel (4mm to >64mm). In many cases, this is augmented by
313 coarse terrigenous clasts from adjacent headlands and cliffs, and a few beaches have a
314 partial and temporary cover of sand. Clasts range from smooth well-rounded corals no
315 longer identifiable as a particular coral species to angular, identifiable pieces of coral
316 that have simply been broken from the reef and thrown onto the beach. Twelve of the
317 30 coral rubble beaches in this study were backed by multiple coral rubble ridges.

318

319 In the BVI, coralline rubble beaches occur in all seven of the planforms described
320 above. Figure 8 displays a mainland-attached linear beach (Oil Nut Bay, Virgin Gorda),
321 embayed barrier (South Sound, Salt Island) and cusped forelands (Dead Chest). Figure
322 14 shows the remaining three planforms not previously shown.

323

324 The largest mean clast sizes were recorded at the Bluff at South Sound, Virgin Gorda
325 (280mm) and South Sound, Salt Island (247mm), both of which are spits. The longest
326 coral rubble beach (1.8km) is at Banana Wharf, Beef Island (Figure 14) and the widest
327 is 80m at the Bluff South Sound, Salt Island).

328

329 **Sand beaches**

330 Sand beaches on the high islands in the BVI occur in embayments along the Atlantic-
331 facing (northern) side of both the north and southern island chains. Few sandy beaches
332 occur on the southern (Caribbean facing) side of the islands. Except for beaches on the
333 northeast shore of Tortola (where they reach 50-80m wide) sand beaches are generally
334 less than 30m wide.

335

336 Carbonate content of the 70 sandy beaches varied from 10%-99% (Table 1). In general,
337 the highest carbonate content was on Atlantic-facing beaches, with the majority being
338 on Anegada and the northern chain of islands. Beaches with the lowest carbonate
339 content were generally located on the southern island chain. There, deeply weathered
340 bedrock made a significant contribution of terrigenous material to the beach sand
341 volume.

342

343 Sand beach mean grain size ranged from fine to very coarse. The finest grain sizes
344 (0.19mm-0.23mm) in the swash zone were found on north shore beaches on Tortola.
345 Very coarse sand (1.02mm to 1.30mm) in the swash zone was primarily found on the
346 southern island chain. The mid beachface sediments ranged from fine to very coarse
347 sands but medium sand was most common. Berm grain sizes ranged from fine to
348 coarse sand. The northern Tortola beaches had fine-grained sands on the berm.

349

350 Multivariate analysis (using SPSS 19.0 statistical software) was used to identify
351 potential groupings of beaches based on carbonate content, grain size, and foreshore
352 geomorphology (fringing reefs; seagrasses and sandy shorefaces. Using the data
353 collected, a K-means clustering with Minikowski as a distance measure (n=3) revealed
354 three stable clusters with centroids that classified the data set with 85.4% of variance
355 being explained within the clusters (SSB/(SSW+SSB)). The external consistency
356 between the clusters was strong with $t(c1-c2) = 8.71$; $t(c1-c3) = 5.64$ and $t(c2-c3) =$
357 2.89 and $p < 0.01$ for all tests, indicating solid separations between clusters. For all three
358 clusters, the foreshore geomorphology variable did not indicate significance. The
359 distribution of beaches in each cluster is shown in Figure 15.

360

361 The first cluster identified two beaches that had coarse sand in the swash zone
362 (0.905mm mean grain size, $p < 0.05$); fine sand on the berm (0.276 mean grain size,
363 $p < 0.05$) and significantly less carbonate content than the other clusters (20.2%
364 carbonate, $p < 0.05$). These two beaches, Salt Bay, Salt Island and South Sound, Virgin

365 Gorda, both in the southern high island chain, have different orientations, Atlantic- and
366 Caribbean-facing respectively, but both are flanked by deeply weathered bedrock which
367 makes a significant contribution to the beach sediment supply.

368
369 The second cluster had 52-member beaches and accounted for 74.3% of the
370 observations. Distinctive features of this group of beaches were fine sand in the swash
371 zone (0.527mm, $p < 0.05$) and high carbonate content (89.355%, $p < 0.05$). The majority
372 of these beaches are located along Atlantic-facing shores on the northern island chain.
373 Some have fringing reefs and others have mobile sandy shorefaces.

374
375 The third cluster had 16 members (22.9% of the beaches). These beaches had coarser
376 grain sizes in the mid-beachface (0.483mm, $p < 0.05$) and berm (0.423mm, $p < 0.05$). The
377 mean percentage of carbonate fell between the other two clusters (58.47%, $p < 0.05$).
378 The majority of these beaches (except for Trellis Bay and Sprat Point on Beef Island)
379 are located in the southern high island chain.

380
381 Foreshore geomorphology did not appear to influence carbonate composition. The north
382 shore of Tortola has three types of fringing reefs, and some beaches lack a reef but
383 there was no correlation between the percentage of carbonate found on beaches and
384 the nearshore topography. Neither did foreshore geomorphology influence grain size.

385

386 **DISCUSSION**

387 Beach morphology in the BVI is exceedingly variable and reflects the combined
388 influence of dynamic and geological factors. The entire region is microtidal and wave
389 action is thus concentrated in a narrow band, except during hurricanes when surges
390 elevate the water level and shift the focus of wave energy. Modally energetic waves
391 occur on the Atlantic-facing shores, while the Caribbean-facing shores are
392 characterised by low wave energy. All, shorelines, however, are affected by episodic
393 hurricanes. Modally high wave energy on the Atlantic shorelines coincides with the
394 distribution of carbonate-rich sandy beaches and points to a causative relationship. We
395 suggest that on these shorelines, the breakdown of carbonate material into finer size
396 grades is accomplished under modal wave conditions. Consequently, hurricanes deliver
397 the pre-abraded sand fraction to the shoreline.

398

399 In contrast, hurricanes on the sheltered Caribbean shorelines, impact on reefs that have
400 not been subject to the same degree of abrasion under modal conditions and thus large
401 clasts are broken off and delivered to the high tide shoreline to create the coral rubble
402 beaches and ridge complexes. Geister (1977, 1980) noted that more sheltered
403 Caribbean reefs have a higher degree of *Acropora palmata* development on the reef
404 crest, which is consistent with the high proportion of this species in rubble beaches.
405 Coral rubble may derive either from corals broken in situ in depths up to 12m
406 (Hernandez-Avila et al., 1977) or from offshore zones in which coral rubble previously
407 accumulated. Characteristics of foreshore slope and morphology, shelf width, and water
408 depth determine whether or not coral rubble is transported onshore or offshore,
409 (Hughes, 1999). Descriptions of coral rubble beaches elsewhere in the Caribbean and

410 Pacific (Scoffin, 1993; Bries et al., 2004; Morton et al., 2008, Scheffers et al., 2009)
411 focus on coarse clastic deposition during storm or tsunami events in which coralline
412 rubble is transported onshore to create ridges, and over time, ridge complexes.

413

414 The lower proportion of carbonate in sandy beaches on the southern island chain is also
415 consistent with the lower rates of sand production in modally lower energy conditions.
416 Consequently, there is dilution of carbonate by terrigenous sediment input from steep
417 weathered slopes.

418

419 The underlying geologic framework determines the physical boundaries within which a
420 beach forms and evolves (Jackson and Cooper, 2009) while physical wave processes,
421 currents and sediment transport, shape the beach within these constraints. In tropical
422 settings, the underlying geological framework is particularly important in constraining the
423 beach and influencing the sediment source, as well as modifying wave dynamics
424 (particularly through the presence/absence of reefs or simply through the degree of
425 shelter offered by beach orientation). All beaches exhibit some degree of geological
426 control on beach planform. Most are located between distinct headlands which set
427 longshore limits to beach extent. Both sand and rubble beaches occur in seven
428 planform types all of which are dictated by the antecedent coastal morphology and the
429 availability of sediment. The same range of planform types was noted on neighbouring
430 Puerto Rico (Bush et al., 1995). Only on Anegada are extensive, linear beaches
431 prevalent.

432

433 The beaches are nearly all constrained in the vertical dimension by some form of
434 fronting biogenic structure (reef or seagrass bed) that precludes development of a
435 mobile shoreface and limits beach development to the beachface, berm and backbeach.
436 Fringing reefs fronting beaches are common in Australia where they were identified as a
437 distinctive beach type (Short, 2006). Incoming wave energy is significantly attenuated
438 by coral reefs (e.g. Roberts, 1975; Young, 1989) and this exerts an important influence
439 on beach form (Short, 2006). This also limits the spatial mobility of such beaches during
440 wave events compared to those with shorefaces (De Alegria-Arzaburu et al., 2012).

441

442

443 **Conclusions**

444 Beach morphology ($n > 100$) in the BVI archipelago is characterised by seven planforms
445 and several profile categories based on a sandy shoreface, fronting seagrass bed or
446 one of three reef profiles. These are the result of antecedent geology and
447 biogeomorphology, which sets horizontal (planform) and vertical (profile) constraints on
448 accommodation space available for beach development and controls the limits of
449 mobility of unconsolidated beach sediment.

450

451 Beaches are composed of sand or coral rubble. Coral rubble beaches dominate the
452 modally low energy Caribbean-facing shorelines while sand dominates those facing the
453 high-energy Atlantic-facing shores. This paradoxical primary textural division (sand and
454 rubble associated with modally high and low energy, respectively) is explained by the
455 varying reef morphology and the ability of hurricanes to break large clasts from modally

456 low energy environments whose energy-attenuating ability is minimal. Modally high-
457 energy reefs in contrast have greater wave energy dissipation.

458

459 Sand beaches vary in carbonate content, with significant terrigenous components on
460 several volcanic islands with adjacent deeply weathered and steep slopes. Carbonate
461 content is almost 100% on most Atlantic-facing beaches, irrespective of whether they
462 have a fronting reef.

463

464 Three main textural and compositional groups of sand beach are identified by cluster
465 analysis. These have a clear spatial distribution with high carbonate content beaches on
466 Atlantic-facing beaches; intermediate carbonate levels on islands in the southern Island
467 chain; and very low carbonate beaches in locations adjacent to deeply weathered
468 bedrock sources. The pattern of distribution of grain sizes across the beach was
469 broadly consistent within each of these categories and differed between them.

470

471 Geological inheritance and sediment source are important determinants of beach form,
472 composition and texture in this tropical archipelago. Dynamic influences (wave height
473 and direction, and storm occurrence) also contribute the variability, but in a secondary
474 role.

475

476 **REFERENCES**

477 Aronson, R.B. and Precht, W.F., 2001. White-band disease and the changing face of
478 Caribbean coral reefs. *Hydrobiologia*, 460, 25–38. DOI: 10.1023/A:1013103928980

479
480 Atwater, B. F., ten Brink, U. S., Buckley, M., Halley, R. B., Jaffe, B. E., López-Venegas,
481 A. M., Reinhardt, E. G., Tuttle, M. P., Watt, S., and Wei, Y. 2012. Geomorphic and
482 stratigraphic evidence for an unusual tsunami or storm a few centuries ago at Anegada,
483 British Virgin Islands. *Nat. Hazards*, 63, 51–84. DOI: 10.1007/s11069-010-9622-6
484
485 Basterretxea, G. Orfila, A. Jordi, A. Casas, B. Lynett, P. Liu, P. L. F. Duarte, C. M. and
486 Tintoré, J., 2004. Seasonal Dynamics of a Microtidal Pocket Beach with *Posidonia*
487 *oceanica* Seabeds (Mallorca, Spain). *Journal of Coastal Research*, 20, 1155 – 1164.
488 DOI: 10.2112/03-0027R
489
490 Blair Myers, C.N., Sheppard, C.R. C. and Bythell, J.C., 1992. A Coastal Resource Atlas
491 of the British Virgin Islands. Chatham, United Kingdom: Natural Resources Institute. 4pp
492 and 22 maps.
493
494 Brown, B.E. and Dunne, R.P., 1980. Environmental Controls of Patch-reef Growth and
495 Development. *Marine Biology*, 56, 85-96. DOI: 10.1007/BF00390598
496
497 Bowman, D., Guillén, J., López, L. and Pellegrino, V., 2009. Planview Geometry and
498 Morphological Characteristics of Pocket Beaches on the Catalan Coast (Spain),
499 *Geomorphology*, 108,191-199. DOI: 10.1016/j.geomorph.2009.01.005
500

501 Bries, J.M., Debrot, A.O. and Meyer, D.L., 2004. Damage to the leeward reefs of
502 Curacao and Bonaire, Netherlands Antilles from a rare storm event: Hurricane Lenny,
503 November 1999. *Coral Reefs*, 23, 297-307. DOI: 10.1007/s00338-004-0379-9
504

505 Bush, D.M., Webb, R.M.T., Liboy, J.G., Hyman, L. and Neal, W.J. 1995. Living with the
506 Puerto Rico Shore. Duke University Press, Durham, North Carolina, 193pp.
507

508 Calverley, M. J., D. Szabo, V. J. Cardone, E. A. Orelup, and M. J. Parsons, 2002: Wave
509 climate study of the Caribbean Sea. *Proc. Seventh Int. Workshop on Wave Hindcasting
510 and Forecasting*, Banff, AB, Canada, Environment Canada. [Available online at
511 http://www.waveworkshop.org/7thWaves/Papers/Calverly_etal.pdf.]
512

513 Cangialosi, J.P., Lato AS, Berg R. 2018. Tropical Cyclone Report - Hurricane Irma.
514 National Hurricane Center, 2018. 111pp.
515

516 Central Intelligence Agency (CIA), 2017. The CIA World Fact Book. Available at:
517 <https://www.cia.gov/library/publications/the-world-factbook/geos/vi.html> (Accessed 24
518 Feb. 2018)
519

520 Cooper, J.A.G. Jackson, D.W.T. and Gore, S. 2013. A groundswell event on the coast
521 of the British Virgin Islands: variability in morphological impact. *Journal of Coastal
522 Research*, Special Issue 65, 696-701. DOI: 10.2112/SI65-118.1
523

524 Cox, R., Atkinson, R. K., Bear, B. R., Brandriss M. E., Chokel, C. B., Comstock, J. C.,
525 Gutmann, E.D., Interest, L.B., Schildgen, T.F., Teplitzky S.J. and Willis, M.P., 2000.
526 Changes in a fringing reef complex over a thirty-year period: Coral loss and lagoon
527 infilling at Mary Creek, St. John, U. S. Virgin Islands. *Bulletin of Marine Science*, 66,
528 269-277.

529

530 De Alegria-Arzaburu, A. R., Mariño-Tapia, I., Enriquez, C., Silva-Casarín, R., &
531 González-Leija, M. (2012). Morphodynamics of a Caribbean beach fringed by a coral
532 reef. *Coastal Engineering Proceedings*, 1(33), sediment-119. DOI:
533 10.9753/icce.v33.sediment.119

534

535 Duvat, V., 2007. Proposition de typologie des plages coralliennes (océan Indien
536 occidental). *Zeitschrift für Geomorphologie*, 51, 307-325. DOI: 10.1127/0372-
537 8854/2007/0051-0307

538

539 Ellison, A.M. and Farnsworth, E.J., 1996. Spatial and temporal variability in growth of
540 *Rhizophora* mangrove saplings on coral cays: links with variation in insolation, herbivory,
541 and local sedimentation rate. *Journal of Ecology*, 84, 717-731. DOI: 10.2307/2261334

542

543 Fonseca, M. S., 1989. Sediment stabilization by *Halophila decipiens* in comparison to
544 other seagrasses. *Estuarine, Coastal and Shelf Science*, 29, 501–507. DOI:
545 10.1016/0272-7714(89)90083-8

546

547 Fonesca, M.S. and Cahalan, J.A., 1992. A preliminary evaluation of wave attenuation by
548 four species of seagrass. *Estuarine, Coastal and Shelf Science*, 35, 565-576. DOI:
549 10.1016/S0272-7714(05)80039-3
550

551 Gallop S. L., Bosserelle C., Eliot I., Pattiaratchi C.B., 2013. The influence of coastal
552 reefs on spatial variability in seasonal sand fluxes. *Marine Geology*, 344, 132-143.
553 doi:10.1016/j.margeo.2013.07.016.
554

555

556 Geister, J., 1977. The influence of wave exposure on the ecological zonation of
557 Caribbean coral reefs. *Proceedings of Third International Coral Reef Symposium Vol. 2:*
558 *Geology*. Miami, Florida: Rosenstiel School of Marine and Atmospheric, 1, 23-29.
559

560 Geister, J., 1980. Calm-water reefs and Rough Water Reefs of the Caribbean
561 Pleistocene. *Acta Palaeontologica Polonica*, 25, 541-561.
562

563 Gore, S., 2007. Framework development for beach management in the British Virgin
564 Islands. *Ocean & Coastal Management*, 50, 732-753. DOI:
565 10.1016/j.ocecoaman.2007.03.004
566

567 Hernandez-Avila, M.L., Roberts, H.H., Rouse, L.J., 1977. Hurricane generated waves
568 and coastal boulder rampart formation. *Proceedings of the 3rd International Coral Reef*
569 *Symposium*, Miami2, 72-78.

570

571 Hemminga, M.A. and Nieuwenhuize, J., 1990. Seagrass wrack induced dune formation
572 on a tropical coast (Banc d'Arguin, Mauritania). *Estuarine Coastal and Shelf Science*,
573 31, 499-502. DOI: 10.1016/0272-7714(90)90040-X

574

575 Hughes, T.P., 1999. Off-reef transport of coral fragments at Lizard Island, Australia.
576 *Marine Geology*, 157, 57-72. DOI: 10.1016/S0025-3227(98)00187-X

577

578 Hubbard, D.K., 1989. Modern Carbonate environments of St. Croix and the Caribbean:
579 A general overview. In: Hubbard, D.K., (Ed). *Terrestrial and Marine Geology of St.*
580 *Croix, US Virgin Islands. West Indies Laboratory Special Publication*, 9, 85-94.

581

582 Jackson, D.W.T., Cooper, J.A.G., and del Rio, L., 2005. Geological control of beach
583 morphodynamic state. *Marine Geology*, 216, 297–314. DOI:
584 10.1016/j.margeo.2005.02.021

585

586 Jackson, D.W.T. and Cooper, J.A.G., 2009. Geologic Control on Beach Form:
587 Accommodation Space and Contemporary Dynamics. *Journal of Coastal Research*, SI
588 56, 69-72.

589

590 Jarecki, L., 2004. Salt Ponds of the British Virgin Islands: Investigations in an
591 unexplored ecosystem. Canterbury, United Kingdom: University of Kent. Unpublished
592 PhD thesis. 183 pp.

593

594 Johansen, C., Larsen, T. 1998. Measurement of settling velocity of fine sediment using
595 a recirculated settling column. *Journal of Coastal Research*, 14, 132-139.

596

597 Kench, P.S. and Brander R.W., 2006. Response of reef island shorelines to seasonal
598 climate oscillations: South Maalhosmadulu Atoll, Maldives. *J. Geophys. Res.* 111,
599 F01001, doi: 10.1029/2005JF000323.

600

601 Kirkman, H. and Kendrick, G.A., 1997. Ecological Significance and Commercial
602 Harvesting of Drifting Beach-Cast Macro-Algae and Seagrasses in Australia: A review.
603 *Journal of Applied Phycology*, 9 (4). P 311-26. DOI: 10.1023/A:100796550

604

605 Klein, A.H.F. and Menezes, J.T. 2001. Beach Morphodynamics and Profile Sequence
606 for a Headland Bay Coast. *Journal of Coastal Research*, 17, 814-835.

607

608 Koch, E.W., 1996. Hydrodynamics of a shallow *Thalassia testudinum* bed in Florida,
609 USA. In: Kuo, J., Phillips, R.C., Walker, D.I., Kirkman, H., (Eds). *Seagrass Biology:*
610 *Proceedings International Workshop, Rottnest Island, Western Australia, 25–29 January*
611 *1996. Crawley, Australia: Faculty of Sciences, University of Western Australia, 105-110.*

612

613 Lidz, B. and Shinn E.A., 1991. Paleoshorelines, reefs, and a rising sea: South Florida,
614 U.S.A. *Journal of Coastal Research*, 7, 203-229.

615

616 Loureiro C., Ferreira O., Cooper J.A.G., 2012. Geologically constrained morphological
617 variability and boundary effects on embayed beaches. *Marine Geology*, 329-331, 1-15.
618 DOI: 10.1016/j.margeo.2012.09.010

619

620 MacDonald, L.H., Anderson, D.M. and Dietrich, W.E., 1997. Paradise threatened: Land
621 use and erosion on St. John US Virgin Islands. *Environmental Management*, 21, 851-
622 863. DOI: 10.1007/s002679900072

623

624 MacQueen, J., 1967. Some methods for classification and analysis of multivariate
625 observations. In: LaCam, L.M., Neyman, J., (Eds). *Proceedings of the Fifth Berkeley*
626 *Symposium on Mathematical Statistics and Probability*. Berkeley, California: University
627 of California Press, 281–297.

628

629 Martin-Kaye, P. H. A., 1959. Reports on the geology of the Leeward and British Virgin
630 Islands. Castries, St. Lucia: Voice Publishing. 117pp.

631

632 McNinch, J.E., Richard, A. and Luettich, Jr., 2000. Physical processes around a cusped
633 foreland: implications to the evolution and long-term maintenance of a cape-associated
634 shoal. *Continental Shelf Research*, 20, 2367-2389. DOI: 10.1016/S0278-
635 4343(00)00061-3

636

637 Molnia, B.F., 1974. A Rapid and Accurate Method for the Analysis of Calcium
638 Carbonate in Small Samples. *Journal of Sedimentary Petrology*, 44, 589-590. DOI:
639 10.1306/74D72A9F-2B21-11D7-8648000102C1865D
640

641 Morton, R.A., Richmond, B.M., Jaffe, B.E. and Gelfenbaum, G. 2008. Coarse-clast ridge
642 complexes of the Caribbean: a preliminary basis for distinguishing tsunami and storm-
643 wave origins. *Journal of Sedimentary Research*, 78, 624–637. DOI:
644 10.2110/jsr.2008.068
645

646 NOAA (National Oceanographic and Atmospheric Administration) 2011. National
647 Hurricane Center Data Archive, “Best-track” database (HURDAT). Available at:
648 <http://www.nhc.noaa.gov/pastall.shtml>. (Accessed 12 June 2011).
649

650 Pilkey, O.H., Neal, W.J., Kelley, J.T., & Cooper, J.A.G. 2011. *The World’s Beaches*.
651 Berkeley, California: University of California Press, 283p.
652

653 Roberts, H.H., 1975. Physical processes in a fringing reef system. *Journal of Marine*
654 *Research*, 33, 233–260.
655

656 Scheffers, S.R., Havisser, J., Browne, T. and Scheffers, A., 2009. Tsunamis, hurricanes,
657 the demise of coral reefs and shifts in prehistoric human populations in the Caribbean.
658 *Quaternary International*, 195, 69-87. DOI: 10.1016/j.quaint.2008.07.016
659

660 Scoffin, T.P., 1993. The geological effects of hurricanes on coral reefs and the
661 interpretation of storm deposits. *Coral Reefs* 12, 203–221. DOI: 10.1007/BF00334480
662

663 Short, A.D., 2006. Australian Beach systems- nature and distribution. *Journal of*
664 *Coastal Research*, 22, 11-27.
665

666 Short, A.D., 2010. Role of geological inheritance in Australian beach morphodynamics.
667 *Coastal Engineering*, 57, 92-97. DOI: 10.1016/j.coastaleng.2009.09.005
668

669 Simeone, S., De Falco, G., 2012. Morphology and composition of beach-cast *Posidonia*
670 *oceanica* litter on beaches with different exposures. *Geomorphology* 151–152,
671 224–233. DOI: 10.1016/j.geomorph.2012.02.005
672

673 Stopa, J. E., K. F. Cheung, H. L. Tolman, and A. Chawla, 2013: Patterns and cycles in
674 the Climate Forecast System reanalysis wind and wave data. *Ocean Modell.*, 70, 207–
675 220, DOI:10.1016/j.ocemod.2012.10.005.
676

677 Sunamura, T. and Mizuno, O., 1987. A study on the depositional shoreline forms behind
678 an island. *Annual Report of the Institute of Geoscience, University of Tsukuba*, 13, 71-
679 73.
680

681 Vacchi, M., De Falco, G., Simeone, S., Montefalcone, M., Morri, C., Ferrari, C., &
682 Bianchi, C. N. (2017). Biogeomorphology of the Mediterranean *Posidonia oceanica*

683 seagrass meadows. *Earth Surface Processes and Landforms*, 42(1), 42–54. DOI:
684 10.1002/esp.3932
685
686 Verduin, J.J. and Backhaus, J.O., 2000. Dynamics of plant-flow interactions for the
687 seagrass *Amphibolis antarctica*: Field Observations and Model Simulations. *Estuarine*
688 *Coastal and Shelf Science*, 50,185-204. DOI: 10.1006/ecss.1999.0567
689
690 Wright, L.D. and Short, A.D., 1984. Morphodynamic variability of surf zones and
691 beaches: a synthesis. *Marine Geology*, 56, 93-118. DOI: 10.1016/0025-3227(84)90008-
692 2
693
694 Wolman, M.G. 1954. Method of sampling coarse river bed material. *Transactions,*
695 *American Geophysical Union*, 35, 951-956. DOI: 10.1029/TR035i006p00951
696
697 Wong, P.P., 2003. Where have all the beaches gone? *Singapore Journal of Tropical*
698 *Geography*, 24, 111-132. DOI: 10.1111/1467-9493.00146
699
700 Woodroffe, C.D., 2002. *Coasts: form, process and evolution*. Cambridge: Cambridge
701 University Press. 623 pp.
702
703 Young, I.R., 1989. Wave transformation over coral reefs. *Journal of Geophysical*
704 *Research*, 94, 9779– 9789. DOI: 10.1029/JC094iC07p09779
705

706 **Figure Captions**

707 Figure 1. Map of the larger islands in the British Virgin Islands and the country's location
708 within the greater Caribbean region.

709

710 Figure 2. Beach names and locations in the NW section of the BVI. Map indicates
711 sandy beaches with dots and coral rubble beaches with asterisks. Coral rubble beaches
712 listed are also italicized.

713

714 Figure 3. Beach names and locations in the north central section of the BVI. Map
715 indicates sandy beaches with dots and coral rubble beaches with asterisks. Coral rubble
716 beaches listed are also italicized.

717

718 Figure 4. Beach names and locations in the SW section of the BVI. Map indicates
719 sandy beaches with dots and coral rubble beaches with asterisks. Coral rubble beaches
720 listed are also italicized.

721

722 Figure 5. Beach names and locations in the SE section of the BVI. Map indicates sandy
723 beaches with dots and coral rubble beaches with asterisks. Coral rubble beaches listed
724 are also italicized.

725

726 Figure 6. Beach names and locations in the NE (Anegada) section of the BVI. Dots
727 mark location of sandy beaches.

728

729 Figure 7. Wind and wave conditions around the BVI. Upper panel shows wind and
730 wave roses for Atlantic shorelines. (Source: NOAA's WAVEWATCH III global model;
731 location 19N and 65W with a 1.0 X 1.25 degree grid resolution; Feb 1997-Sept 2010).
732 Central panel shows hurricane tracks (1960-2017) within 100km of the BVI. Lower panel
733 shows Caribbean wind and wave roses. (Source: NOAA Station ID: 42060; location 16N
734 and 63W; April 2013-Oct. 2017).

735

736 Figure 8. Classification of beach planforms in the BVI.

737

738 Figure 9. Incipient tombolo at Sandy Spit. Panel A (May 2008) shows Green Cay and
739 Sandy Spit with prevailing waves from the northeast. Panel B (July 2005) shows
740 exposed beachrock.

741

742 Figure 10. Classification of BVI beaches based on nearshore/shoreface morphology.

743

744 Figure 11. Headland-attached linear reef at Oil Nut Bay, Virgin Gorda. From the beach
745 to the reef crest is approximately 500m or less and depth may be greater than 5m. Red
746 arrow identifies the reef crest.

747

748 Figure 12. A terrace flat is a shallow, broad portion of the foreshore without a distinctive
749 reef crest that extends no more than 500m offshore. Low relief corals and seagrasses
750 are common but the flat may also be composed only of sand. (Carrot Bay, Tortola).

751

752 Figure 13. A graded reef lacks a prominent reef crest and slopes steeply to depths
753 greater than 20m (North Thatch, Great Thatch).

754

755 Figure 14. 1). Banana Wharf, Beef Island – Linear barrier coral rubble beach. 1a is a
756 close-up of the pond in the upper right-hand corner of (1). 2) Tombolo formed between
757 Pelican Cay and Little Jost Van Dyke (Source: BVI Survey Department). 2a shows the
758 rubble accumulated between the two islands. 3) NW side of JVD and 3a, a close-up of
759 the beach and ridges.

760

761 Figure 15. Location and results of multivariate analysis on 70 sand beaches in the BVI
762 classified on mean carbonate content and mean grain sizes along the swash, mid and
763 berm zones of the beach.

764