Spatial variability in beach biogeomorphology in a tropical archipelago

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ABSTRACT

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

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

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

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

INTRODUCTION

The morphology of a beach reflects a variety of interacting variables including sediment texture and composition, wave energy and geologic setting (Pilkey et al., 2011, Loureiro et al., 2012). A number of studies have examined the interaction between sediment texture and wave conditions (e.g. Wright and Short, 1984) to develop generic models of beach morphology and beach behaviour. The geological influence on beach form (geologic setting and sediment volume) has received comparatively less attention and yet is known to be an important determinant of beach form and behaviour (Jackson et al., 2005; Jackson and Cooper, 2009; Short, 2010). On tropical beaches, the influences of biogeomorphology (via reefs and seagrass beds) and sediment texture (imparted by a diversity of bioclastic shape and size) are likely to be particularly important influences on beach form (Gallop et al., 2013).

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

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

METHODS

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

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

Surface sand samples were collected at 70 sandy beaches. At each beach samples (~100 g) were collected from the swash zone, mid-beachface and berm. All 210 samples were taken from the centre of the beach planform. A semi-automated settling tube was used for sediment analysis (Johansen and Larsen, 1998). Carbonate percentages were determined by weight-loss acid digestion (Molnia, 1974). A multivariate statistical analysis of sandy beaches was carried out using K-means clustering analysis (MacQueen, 1967) based on grain size, sediment composition and foreshore characteristics. Foreshore characteristics were assigned numerical values (1-yes, 2-no) for direction to prevailing wind and wave regimes and a second numerical value was assigned for each a fronting reef, sand or seagrass bed. All results were mapped using ArcGIS 9.3.

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

STUDY AREA

The British Virgin Islands (BVI) comprise a small volcanic archipelago (Figure 1) bounded by the Atlantic Ocean to the north and the Caribbean Sea to the south. The BVI has a total land area of 151 km^2 and human population of 35,015 (CIA, 2017). The Territory consists of over 60 high volcanic islands. Anegada, the second largest island in the Territory, however, is a reef platform with a maximum elevation of 8m (Martin-Kaye, 1959; Atwater et al., 2012). The ~6km-wide Sir Francis Drake channel (maximum depth 50m) divides the BVI into two high island chains. Northeast of Tortola and southwest of Anegada is a shallow carbonate bank (average depth 25m) (Figure 1). A number of low-lying mangrove cays occur on coral reef/rubble flats along the southern coast of Tortola and Beef Island. One previously vegetated sand cay (vegetation removed by a recent category 5 hurricane) exists as part of an incipient tombolo (Sandy Spit) and an unvegetated sand cay is forming on a narrow reef flat off Necker Island.

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

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

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

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

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

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

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

BEACH MORPHOLOGY & PLANFORM

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

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

Linear beaches are relatively straight and continuous beaches of sand or coral rubble. They are best developed on Anegada where the beach forms a continuous rim around the island (approximately 48km) as either mainland-attached or barrier beaches. Since the high islands have irregular coastlines, linear beaches are not common. However, a few mainland-attached linear beaches exist on smaller volcanic islands with lower relief, such as Pelican Island, and along the southern coast of Tortola.

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

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

Barrier beaches are widely developed around the BVI coast. On the volcanic islands they enclose salt ponds or wetlands and are associated with areas of lower gradient bedrock. The barriers are typically composed of coral rubble that occasionally has a veneer of sand. Barrier beaches form as a result of a linear reef developing across the entrance of a bay. With the rapid growth rates of corals such as *Acroporids* (Lidtz and Shinn, 1991; Jarecki, 2004), the reef crest may become exposed over time (Cox et al., 2000). Red mangroves (*Rhizopora mangle*) then colonize the reef crest to form a complex network of roots that trap mangrove peat and sediments (Ellison and Farnsworth, 1996). Sediments that have accumulated on these barrier frameworks range in size from medium sand to boulder-sized coral clasts. Back-barrier lagoons are important influences on beach behaviour in that they capture fine sediment from inflowing streams (MacDonald et al., 1997) and provide space for potential landward retreat of barriers.

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

FORESHORE/SHOREFACE MORPHOLOGY

Most temperate beaches have a sandy shoreface. In the tropics, however, shoreface development is often inhibited by the presence of biogenic structures (Short, 2006). Some BVI beaches are fronted by sandy shorefaces while others are fronted by coral reefs or seagrass meadows. The absence of a mobile shoreface influences the potential for morphological change to the beachface and backbeach in response to changing wave conditions. A classification of BVI beaches based on shoreface/nearshore morphology (Figure 7) identifies an initial split between beaches with sandy shorefaces and those without. Those that lack a shoreface further divide into those fronted by one of three types of fringing reef or those fronted by seagrass beds.

Coral reef foreshores

The majority of reefs around the high volcanic islands of the BVI are fringing reefs that have developed close to shore on a narrow shelf between the low tide shoreline and the 20m bathymetric contour. Anegada's Horseshoe Reef covers approximately 133km^2 and is composed of two distinctive facies, a high-energy reef front on the north-north-eastern windward side of the island, and a series of systematically distributed patch reefs along the island's southern leeward side (Brown and Dunne, 1980). The fringing reef on the north side of Anegada extends beyond the eastern end of the island to the southeast for ~14km. This entire reef system is the largest contiguous reef in the BVI and is a major source of the carbonate sediments found on the Anegada Bank between Anegada and Tortola. Many of the fringing reefs in the high volcanic islands of the BVI lack an identifiable reef crest.

Fringing reefs fronting beaches are common throughout the BVI and our study shows that there is further variability in form of fringing reefs backed by beaches. Three types of fronting reef exist in conjunction with BVI beaches: headland-attached reefs, terrace flats and graded reefs.

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

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

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

Seagrass meadow foreshores

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

Sandy shorefaces

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

BEACH COMPOSITION

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

Coral rubble beaches

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

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

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

Sand beaches

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

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

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

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

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

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

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

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

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

DISCUSSION

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

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

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

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

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

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

Conclusions

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

Beaches are composed of sand or coral rubble. Coral rubble beaches dominate the modally low energy Caribbean-facing shorelines while sand dominates those facing the high-energy Atlantic-facing shores. This paradoxical primary textural division (sand and rubble associated with modally high and low energy, respectively) is explained by the varying reef morphology and the ability of hurricanes to break large clasts from modally low energy environments whose energy-attenuating ability is minimal. Modally high-energy reefs in contrast have greater wave energy dissipation.

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

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

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

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Figure Captions

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

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

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

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

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

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

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

Figure 8. Classification of beach planforms in the BVI.

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

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

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

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

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

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

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