A QUARTER CENTURY OF COASTAL CHANGE ON SAN SALVADOR ISLAND, BAHAMAS: 1988-2014

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CHRISTINA A. HEFRON

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Advisor: James L. Carew

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Christina Hefron[1], James L. Carew[1]

[1]*Department of Geology and Environmental Geosciences, College of Charleston, Charleston, SC*

ABSTRACT

In 1988, Daryl Clark completed a Masters thesis outlining the characteristics of modern beach sediment for 18 beaches on San Salvador Island, Bahamas. This study provides an assessment of 9 of the 18 beaches 25 years after Clark's study. Samples collected from the lower beachface, upper beachface, backbeach, and dune environments were processed to determine particle size, grain texture, sample sorting, sample skewness, and kurtosis. The results of this study, and a smaller study completed by a College of Charleston student in 2010, were compared to Clark's results to determine coastal changes on the island during the past quarter century. Clark concluded the major determinant of sediment texture and sorting on the island was platform geomorphology and antecedent topography. He also attributed coastal development to major storm events. Clark conducted his research during a relatively calm period in Bahamian hurricane history. From 1990 to 2013, multiple hurricanes have impacted the Bahamas, including San Salvador Island. Despite these storms, no conclusive results support Clark's conclusion that storm events are a major determinant of modern subaerial sedimentation. Therefore, antecedent topography and platform geomorphology appear to be the greatest factors in coastal development on San Salvador Island.

INTRODUCTION

This paper summarizes the textural analysis of modern Holocene carbonate beach sediment on San Salvador Island, Bahamas. Beaches are sedimentological systems that occur along coastlines. Wave energy dominates these systems composed of unconsolidated sediment (Inden and Moore, 1983). The relationship between sediment properties, including sorting and grain size, has been analyzed in regard to energy and physiographic features (Clark, 1988). Energy was defined as wind, wave, and storm activity. Physiographic features affecting sediment properties include platform morphology, beach slope, beach orientation, and antecedent topography. Because San Salvador is located on an isolated bank, it serves as a microcosm for larger, steep-sided Bahama banks, including the Great Bahama Bank (Mylroie, 2008). The results of this study were compared and contrasted to the results of Clark, creating a picture of coastal Bahamian change during the past twenty-five years.

GEOGRAPHICAL SETTING

The Bahama Archipelago is a series of shallow carbonate banks located in the southwestern North Atlantic Ocean. The Bahamas are attached to the subsiding eastern continental margin of the North American Plate (Clark, 1988). The archipelago, located southeast of Florida and northeast of Cuba, encompasses approximately 125,000 square kilometers (Meyerhoff and Hatten, 1974). Little Bahama Banks define the northwest extent of the Bahamas, and the Navidad Banks define the southeast border (Fig. 1). Puerto Rico, the Island of Hispaniola (includes the Dominican Republic and Haiti), and Turks and Caicos Islands are located southeast of The Bahamas. To the north of the archipelago lies the Blake Plateau and Blake Escarpment of the Atlantic Ocean.

The Bahamas are divided into the northern and southern islands. Large carbonate banks, the Great and Little Bahama Banks, comprise the shallow northern islands (Clark, 1988). Multiple cays can be found along the banks which are covered by less than 10 meters of water. Deep channels such as Tongue of the Ocean (TOTO), Northeast and Northwest Providence

Channels, and Exuma Sound cut through the banks and separate the islands. These channels can be as deep as 4,000 meters (Curran, 1985). The three channels intersect to form the largest canyon system, terrestrial or marine, in the world (Andrews et al., 1970).

The southern Bahamas comprises numerous small, shallow banks with emergent small islands and cays. U-shaped troughs and basins that exceed 2,000 meters depth separate the banks (Uchupi et al., 1971). The banks follow two northwest-southeast trending belts. San Salvador Island straddles the border between the northern and southern islands. Sitting on its own isolated bank, it represents a transition zone between the large banks located to the north and the smaller banks that characterize the south.

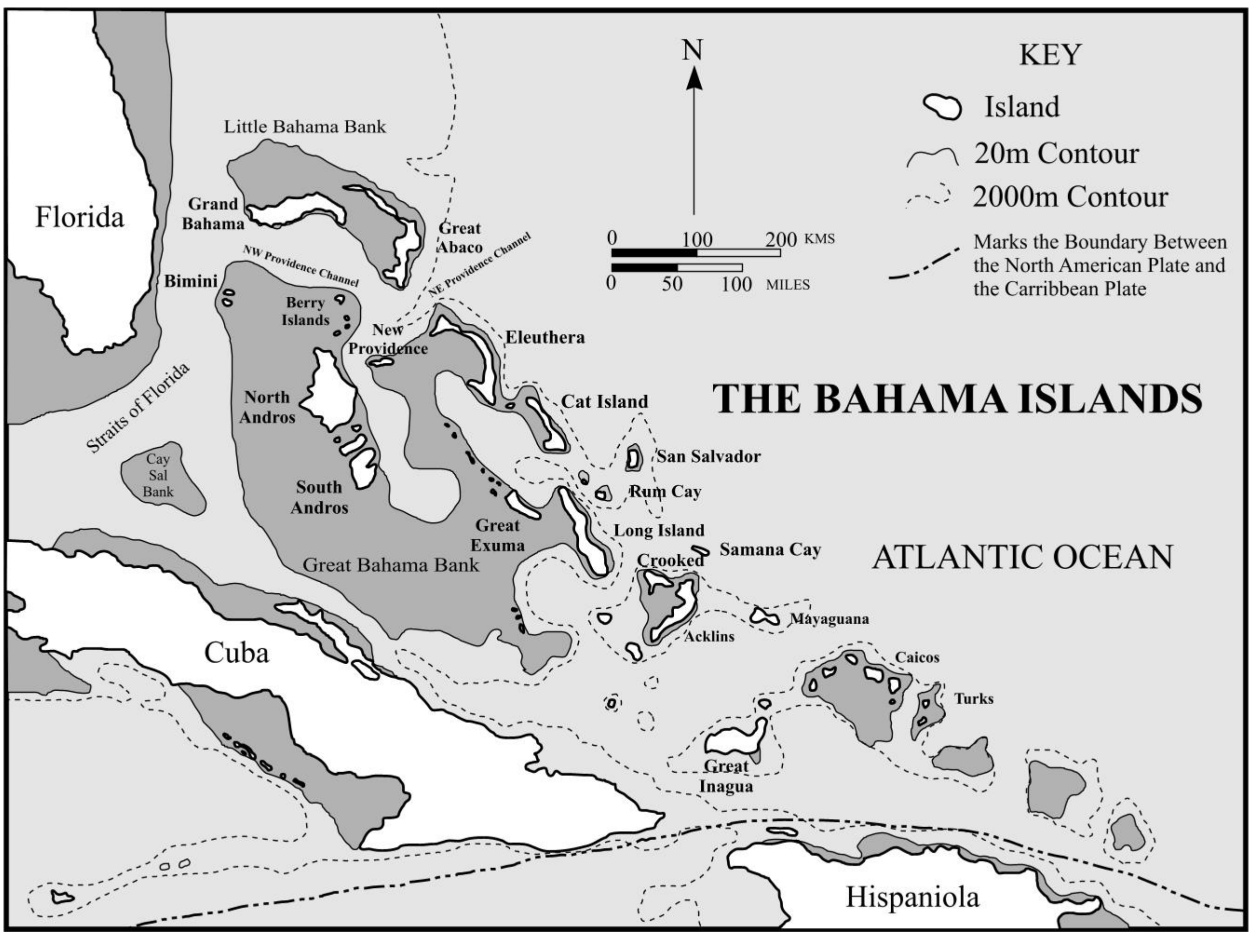

Figure 1. Geographic setting of San Salvador Island, Bahamas (modified from Mylroie and Carew, 2001, fig. 1).

GEOLOGIC HISTORY OF THE BAHAMAS

Thick deposits of carbonate rocks and sediment underlie the shallow banks of the Bahamas. These carbonate sequences are the result of carbonate production equal to platform subsidence (Mullins and Lynts, 1977). Although the platform is considered tectonically stable, the continental margin on which the islands are located is slowly subsiding. The rate of subsidence is disputed. Garrett and Gould (1984) proposed a rate of 3 meters per 125,000 years for Andros and the entire Bahamas. Subsidence rates range from 1.8 to 4.8 meters per 100,000 years during the Quaternary according to Myerhoff and Hatten (1974). Carew and Mylroie (1985) have estimated a subsidence rate of 1 to 2 meters per 100,000 years from data collected on San Salvador.

Sea level transgressions and regressions resulting from Pleistocene glaciations controlled the geologic development and stratigraphy of the Bahamas (Carew and Mylroie, 1985). Marine inundations of the bank tops during sea level highstands have resulted in reef development, and lagoon, beach, and dune deposits. During sea level lowstands paleosols and other erosional features formed.

Some controversy surrounds the formation of the Bahamian platform. Two hypotheses have received widespread support: Dietz and Holden's oceanic crust proposal (1973), and the continental crust hypothesis proposed by Myerhoff and Hatten (1974). According to the ocean crust hypothesis, during the Triassic, the North American and African plates rifted from upper mantle hot spot activity, creating a small basin in which volcanic rocks were deposited. Rotational movement of the North American plate created a sediment trap in which carbonates accumulated during a pause in plate movement, forming the Bahama Platform (Dietz and

Holden, 1973). When plate movement began again, the platform began to subside as an accreted portion of the North American plate. Ocean conditions favored coral formation and growth rate matched subsidence, thus keeping the platform near sea level despite isostatic subsidence.

Variations of the oceanic crust model continue to be developed, but the megabank model has gained the widest recognition (Meyerhoff and Hatten, 1974; Sheridan et al., 1981; Ladd and Sheridan, 1987). According to this hypothesis, rifting during the Triassic produced horsts that were eroded, and the resultant sediment settled in adjacent grabens. Jurassic evaporites accumulated atop the clastic material. Continued rifting and favorable climate throughout the Cretaceous allowed the formation of a large, single carbonate bank. The current shape of the Bahamas was caused by sea level rise during the Late Cretaceous combined with differential erosion and differential deposition. Leg 101 of the Ocean Drilling Program supported the megabank hypothesis (Austin and Schlager, 1987).

Meyerhoff and Hatten (1974) and Mullins and Lynts (1977) have been the main proponents of the continental crust basement model. During the rifting of North America from Africa and South America, a series of horsts and grabens were created by domal uplift, and mafic and ultramafic rocks intruded into the continental crust. These mafic intrusions increased the density of the banks, which had evolved into a transcurrent continental margin. The increase in density caused subsidence, while thick deposits of carbonates formed, keeping the platform in shallow water.

GEOLOGIC SETTING OF SAN SALVADOR

San Salvador Island is situated on an isolated bank that drops to deep ocean on the western and southern margins. The shelf is broader with a gentler slope to the deep ocean on the northern and eastern sides (Fig. 2). Fringing reefs and bank/barrier reefs surround the island on all sides. Numerous cays and of varying size are found along the northern and eastern bank margins.

The topography of San Salvador is determined by Pleistocene and Holocene arcurate eolian dune ridges (Curran, 1985). The ridges represent stages of eolian carbonate accretion (Adams, 1980). These ridges may reach heights of 40 meters. Many of them form headland cliffs which line the coastline of the island, allowing beaches to develop between them. These beaches are associated with a high energy, carbonate shelf environment in which the dominant geomorphology and sedimentation is controlled by wind, waves, and currents (Inden and Moore, 1983).

All rocks on the island formed during the Pleistocene and Holocene. Modern beachrock forms when cementation due to the geochemical mobility of calcium carbonate occurs near the sediment surface (Carew and Mylroie, 1997). Many of the modern beaches on the northern, southern, and western coasts of the island are characterized by the presence of beachrock.

The stratigraphy of San Salvador, first proposed by Titus (1982), was updated and revised by Carew and Mylroie (1985). Since then Carew and Mylroie have continued to develop the model for the geology of the island. The stratigraphic column (Fig. 3) is the focus of the following discussion (Carew and Mylroie, 1985; 1995; 1997).

The oldest exposed stratigraphic unit on San Salvador is the Owl's Hole Formation. This formation was deposited before the marine isotope substage 5e (MIS 5e) (Fig. 4). The steeply dipping crossbeds of the Owl's Hole Formation are mainly composed of bioclastic eolianites and

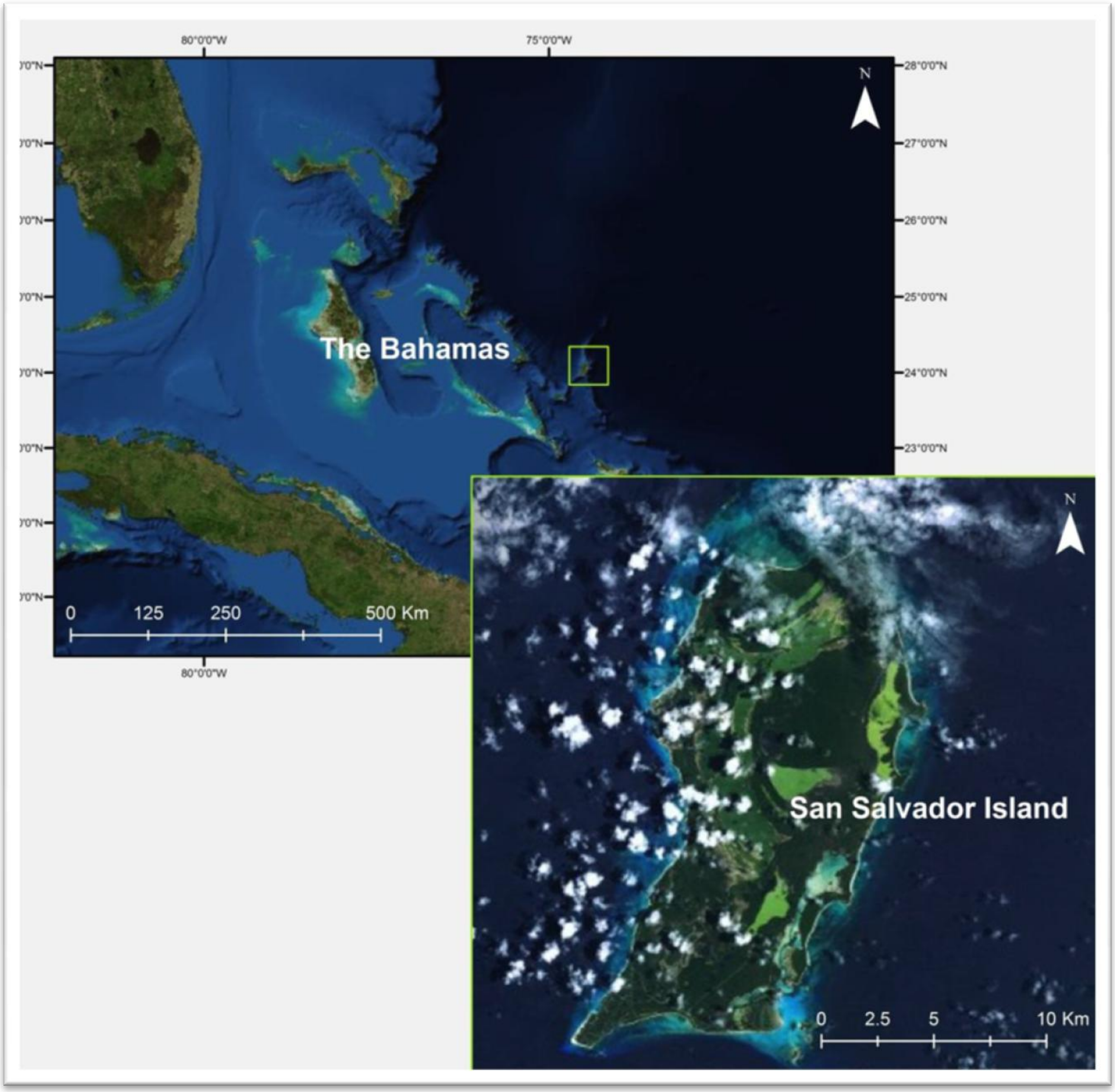

Figure 2. San Salvador Island, Bahamas created using ESRI high-resolution imagery in ArcGIS.

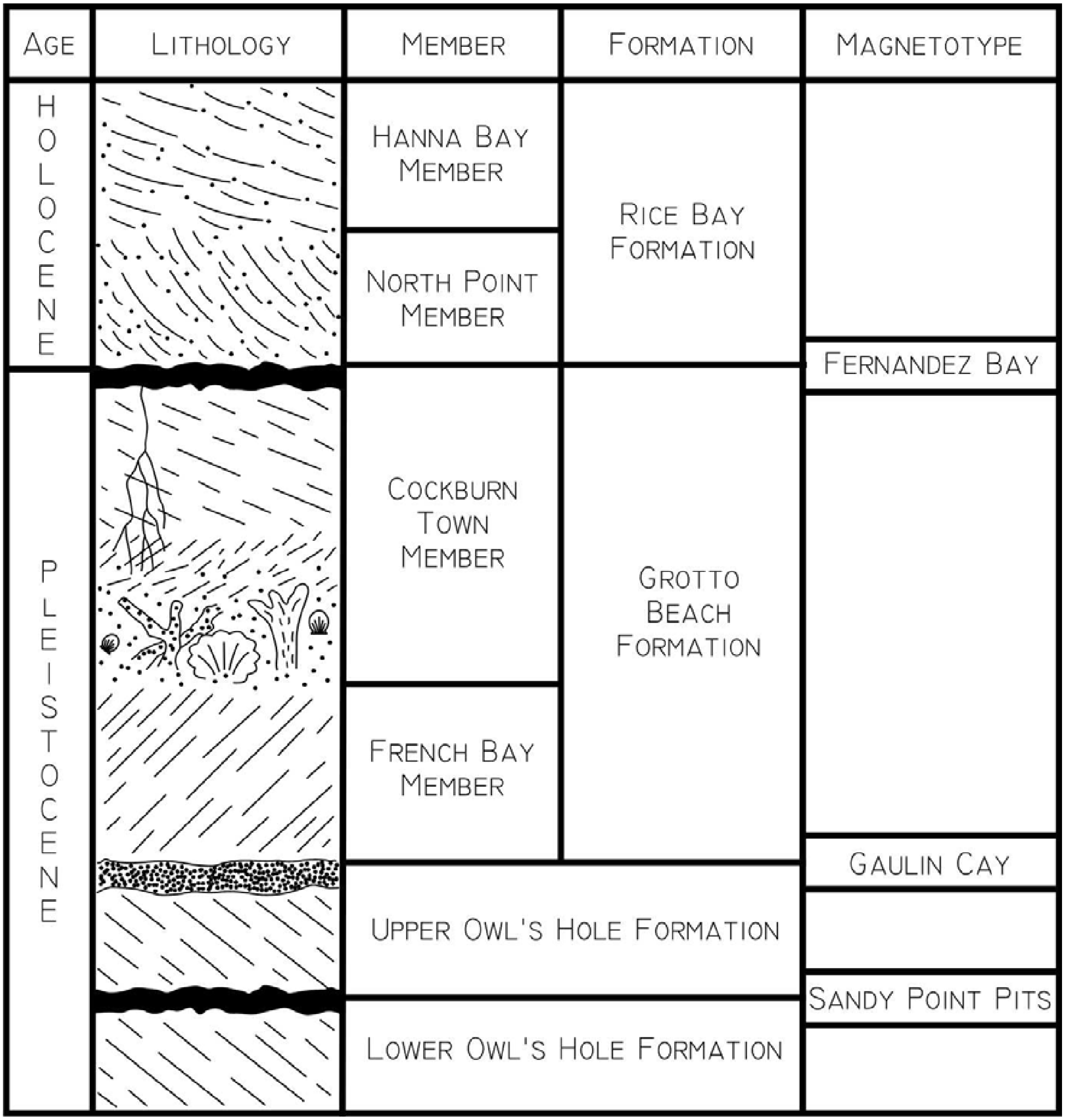

Figure 3. Stratigraphic column of San Salvador Island, Bahamas (from Mylroie et al., 2006, fig. 3).

is topped by a terra rossa paleosol (Carew and Mylroie, 1997). Terra rossa paleosols form when carbonate rocks are exposed to the atmosphere, undergo weathering and erosion, and accumulate Sahara dust during the long intervals of low sea level during glacial periods.

The Grotto Beach Formation is found above Owl's Hole and was deposited during MIS 5e. Two members, French Bay and Cockburn Town, represent the sea level oscillations during this period 131,000 to 115,000 years ago (Carew and Mylroie, 1985; Carew and Mylroie, 1997). The French Bay Member represents the transgressive phase of MIS 5. The sediment is beach to backbeach oosparite overlain by backbeach dune oosparite (Clark, 1988). The Cockburn Town Member comprises stillstand subtidal and intertidal facies topped by stillstand and regressive phase eolianites.

A terra rossa paleosol separates the Pleistocene and Holocene rocks. The youngest and topmost stratigraphic unit found on San Salvador is the Rice Bay Formation. This formation was divided into two members based on depositional differences in response to Holocene sea levels. The North Point Member is the older of the two and represents transgressive phase eolianities (Carew and Mylroie, 1997). This member extends below current sea level and has been whole rock ^{14}C dated to approximately 5,300 yBP (Carew and Mylroie, 1987). The youngest rocks are part of the Hanna Bay Member which is often found adjacent, though rarely overlying, the North Point Member. The intertidal facies and eolianites of this member are in equilibrium with modern sea level, indicating the member is part of a stillstand phase. Eolianite grains range in age from 3,300-400 yBP according to radiocarbon dating results (Carew and Mylroie, 1987; Boardman et al., 1989).

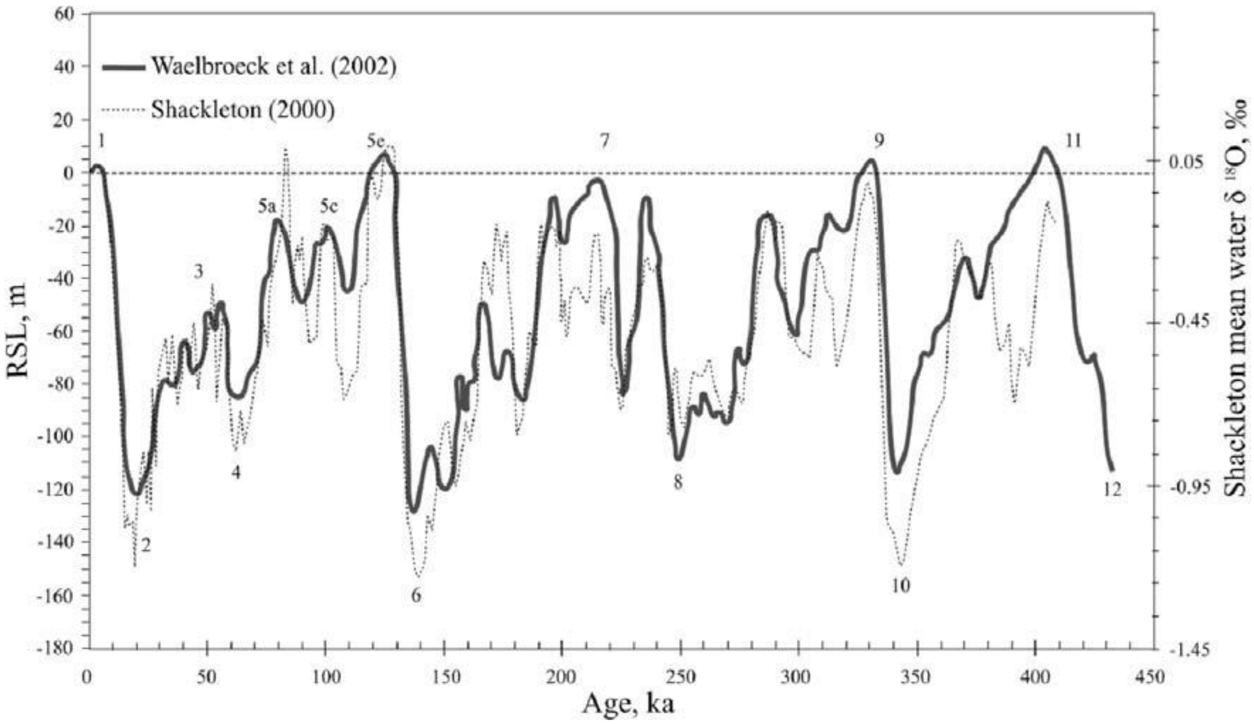

Figure 4. Quaternary sea level for the last 450 ka. Note modern sea level compared to past sea level highstands, specifically MIS 5e (from Lascu, 2005, fig. 6).

BEACH DESCRIPTIONS

This section describes the general coastal morphology of San Salvador Island. The coastline of this island varies greatly from one area to another. Variation in morphology influences the effect of energy events on beach development. The descriptions provided were recorded by Clark (1988) and updated when necessary from fieldwork completed during December 2013 and January 2014.

Northern Beaches

Rice Bay

Rice Bay beach is found opposite of the location of the old Coast Guard Loran Base, which is now the public high school on San Salvador Island. It is a relatively small curved beach nestled between two rocky outcrops. Beachrock formation is evident along the lower beachface. Some fringing reefs and two large cays are found offshore. Platform width (measured from shoreline to 1000 meters depth) is 4,700 meters. The distance from shoreline to the shallow bank edge (10 meters depth) is 1,400 meters. Clark recorded a beach transect of 24 meters, and this study recorded a similar transect length of 25.6 meters.

GRC (CCFL) Beach

Gerace Research Centre Beach (Fig. 5) is located directly north of the Gerace Research Center (GRC). When Clark collected data the upper beachface environment was missing; however, during this study that environment was present. The beach has coral rubble and exposed beachrock in the dune and backbeach. Numerous offshore reefs and cays are present. The platform off this beach is very broad, with a 7,000-meter width from the shoreline to 200 meters depth. The distance to the shallow bank edge (10 meters water depth) is 3,400 meters. The beach transect Clark measured was 9.75 meters, whereas the transect for this study was 10.8 meters.

Graham's Harbour

Formed between to headland ridges, Graham's Harbour beach (Fig. 6) is long narrow and curved. The beach is poorly developed, and beachrock and coral rubble are evident. Numerous cays and reefs are located offshore. The distance from shoreline to 1000 meters water depth is 10,800 meters. The distance from shoreline to 10 meters water depth is 6,800 meters. Clark recorded a beach transect 12 meters long, whereas the 2014 transect was slightly longer at 14.2 meters.

Southern Beaches

Sandy Hook

Sandy Hook beach is very broad and well developed. Located on the southeast tip of San Salvador, three large cays and numerous smaller ones are located offshore of this beach. Platform width is 7,700 meters (measured from shoreline to 1000 meters depth), whereas the distance from shoreline to shallow bank edge (10 meters depth) is 2,400 meters. Clark's beach transect was 44.8 meters, whereas the transect measured in 2014 was 32.3 meters.

French Bay

Beachrock is found along the entire beachface at French Bay. Reefs can be found offshore on bank margins. This beach is located between headland cliffs. Platform width measured from shoreline to 1000 meters depth is 3,000 meters. Distance to the shallow bank edge (10 meters depth) is 1,100 meters. Clark recorded a beach transect of 20.7 meters, whereas the transect measured in 2014 was 29.3 meters.

Figure 5. GRC (CCFL) Beach in 2014.

Figure 6. Graham's Harbour Beach in 2014.

Blackwood Bay

Pleistocene bedrock in the lower and upper beachface are characteristics of Blackwood Bay beach. Offshore on the bank edge there are east-west oriented reefs. The platform drops nearly vertical to abyssal ocean depths immediately seaward of the reef (Pace, 1987). From the shoreline to 1000 meters depth, the platform width measures 2,900 meters, and the distance to the shallow bank edge (10 meters water depth) is 1,050 meters. Clark's beach transect measured 18.6 meters, whereas the transect from this study measures 26.8 meters.

Sandy Point

Sandy Point beach is very broad and well developed. Multiple dune ridges – both vegetated and non-vegetated – dominate the coastal morphology in this location. Platform width from shoreline to 1000 meters water depth is 4,000 meters, and distance to the shallow bank edge (10 meters water depth) is 500 meters. Clark recorded a transect of 27 meters that encompassed all the beach environments. The beach transect measured in 2014 from the last vegetated dune to the water edge at low tide was 96.5 meters.

Eastern Beaches

Hanna Bay

Located on the northeastern edge of San Salvador, Hanna Bay is a small curved beach situated between two lithified dunes. Exposed beachrock located in the lower beachface noted by Clark was still present in 2014. Platform width measured from shoreline to 1000 meters depth is 8,550 meters. The distance from shoreline to the edge of the shallow bank (10 meters depth) is 2,500 meters. In 1988 the beach transect distance was 18.3 meters but in 2014 measured 21.3 meters.

East Beach

East Beach is separated from Hanna Bay to the north by a rocky outcrop. It is a long beach with offshore bank/barrier reefs. According to Clark the platform width from shoreline to deep water (1000 meters depth) is 8,400 meters while distance to shallow bank edge (10 meters) is 2,000 meters. Clark's beach transect measured 13.7 meters, and the transect of this study measures 36.8 meters.

Greens Bay

The following description of Greens Bay is taken solely from Clark. No geomorphologic observations were made in 2013-2014 as the beach was not visited due to time and logistical constraints. Greens Bay is a curved narrow beach situated in a cove on the east side of San Salvador. Two large headland cliffs mark the extent of the beach. Inland, the beach is separated from the rest of the island by Storr's Lake. Platform width measured from shoreline to 1000 meters depth is 6,800 meters, whereas the distance from shoreline to the shallow bank edge (10 meters depth) is 2,010 meters. Clark measured a beach transect of 10 meters.

Thumb Beach

Thumb Beach is a very broad and linear beach situated between two headland cliffs. Many coral reefs can be found offshore. Platform width from shore to deep water (1000 meters depth) is 6,600 meters. The distance from shoreline to the edge of the shallow bank measures 1,800 meters. Clark measured a beach transect distance of 51.2 meters, whereas the transect measured in this study is 40.1 meters.

Snow Bay

The following description was recorded by Clark. No updates have been made to his observations as fieldwork could not be done on Snow Bay during 2013-2014 due to logistical and time constraints. Located on the southeast edge of San Salvador, Snow Bay beach is a small, rocky, pocket beach between two headlands. Beachrock and coral rubble are found within each beach environment. Coral reefs and small cays are both situated offshore. Platform width from shoreline to 1000 meters depth is 4,200 meters, and distance to the shallow bank edge (10 meters depth) is 1,750 meters. Clark measured a beach transect 14 meters long.

Western Beaches

Palmetto Grove

Located between two rocky headland ridges, Palmetto Grove beach (Fig. 7) is broad and linear. Beachrock can be found in the lower beachface. There are no prominent reefs located offshore. Platform width (to 1000 meters depth) is 3,900 and the distance to the shallow bank edge (10 meters depth) is 2,000 meters. The beach transect recorded in 2014 measures 11.5 meters, whereas Clark's transect was 23 meters long.

High Reef Channel

This broad linear beach features exposed beachrock within the lower beachface (Fig. 8). Bank barrier reefs are located offshore. The platform width (measured from shoreline to 1000 meters water depth) is 4,100 meters and the distance to the shallow bank edge (10 meters depth) is 1,800 meters. Clark recorded a 28 meter beach transect, whereas the transect length measured in 2014 is 20.9 meters.

Bonefish Bay

Bonefish Bay beach (Fig. 9) is long narrow and curved. It formed in a cove between headland cliffs and is characterized by an offshore bank/barrier reef relatively close to the shoreline. 4,500 meters is the platform width measured from shoreline to 1000 meters water depth. The distance to the edge of the shallow bank (10 meters water depth) is 2,000 meters. The beach transect in 1988 measured 18 meters, whereas the 2014 transect is 21.6 meters long.

Fernandez Bay

The narrow, poorly-developed beach of Fernandez Bay has undergone significant geomorphologic change since Clark collected his data. No backbeach was recorded in 1988; however in 2014 a small backbeah was present. Despite this difference, the beach is still dominated by exposed beachrock and coral rubble along the shoreline. Reefs fringe the platform edge, and the platform width (measured from shoreline to 1000 meters depth) is 3,400 meters. The distance to the shallow bank edge (10 meters water depth) is approximately 800 meters. Clark's measured beach transect was 6.4 meters, whereas this study's transect is 12.9 meters.

Figure 7. Palmetto Grove beach in 2014.

Figure 8. High Reef Channel Beach in 2014.

Figure 9. Bonefish Bay in 2014.

Long Bay

As its name suggests, Long Bay is relatively long and has active beach rock formation in the lower and upper beachface. Fringing reefs can be found offshore. Platform width measured from shoreline to 1000 meters water depth is 5,000 meters. Distance to the shallow bank edge (10 meters depth) is 2,800 meters. Clark recorded a beach transect length of 22.5 meters. No beach width was measured during the most recent fieldwork due to lack of organization; however, transect length was measured using Google Earth imagery (Fig. 10) from 2012. The transect was 12.4 meters.

Grotto Beach

Grotto Beach (Fig. 11) is located in a small cove adjacent to Pleistocene headland cliffs, and beachrock is exposed in some portions of the lower and upper beachface. Multiple reefs are situated offshore. From shoreline to deep water (1000 meters depth), platform width is 3,150 meters. From shoreline to 10 meters depth is 800 meters. Clark's beach transect was 16.4 meters, whereas the transect measured in 2014 is 29.6 meters.

Figure 10. Long Beach transect measured in Google Earth from 2012 imagery.

Figure 11. Grotto Beach in 2014.

METHODS

Fieldwork

During the 2014 field season, samples were collected from 16 of the 18 beaches sampled by Clark. Only Greens Bay and Snow Bay were excluded from sampling due to time constraints and limited accessibility. Samples were collected from the lower beachface, upper beachface, backbeach, and dune environments during low tide (Fig. 12). Each sample was stored in a plastic sealable bag and labeled according to the collection date, beach, and environment. 64 samples were collected along the same transects determined by Clark (Fig. 13). Transects were measured from the ocean-side last vegetated dune to the swash zone to determine beach width.

Laboratory Analysis

Samples were dried in an oven to reduce particle clumping during grain-size analysis. Each sample was then weighed, dry sieved at -1.0 ϕ, and reweighed to determine the percent of sample that was larger than sand-sized according to the Udden-Wentworth scale (Table 1). Sand-sized grains were then analyzed using a laser particle size analyzer (CILAS 1800 and SizeExpert software). Samples were chosen for analysis at random (not grouped by beach) to ensure unbiased results. A sample from each environment was run three times to determine consistent results.

The grain sizes were then recorded at the following percentiles: 5, 16, 25, 50, 75, 84, and 95. These sizes were used to calculate sample sorting, average grain size of the sample, sample skewness, and kurtosis according to the modified Folk and Ward method (Table 2) developed by Blott and Pye (2001). Skewness and kurtosis are measures of grain distribution. Skewness is the spread of grains to one side of the average. Kurtosis is the degree of concentration of grains relative to the average (Blott and Pye, 2001). A visual analysis using a 10x hand lens also determined the sample sorting and grain roundness (Tucker, 1988).

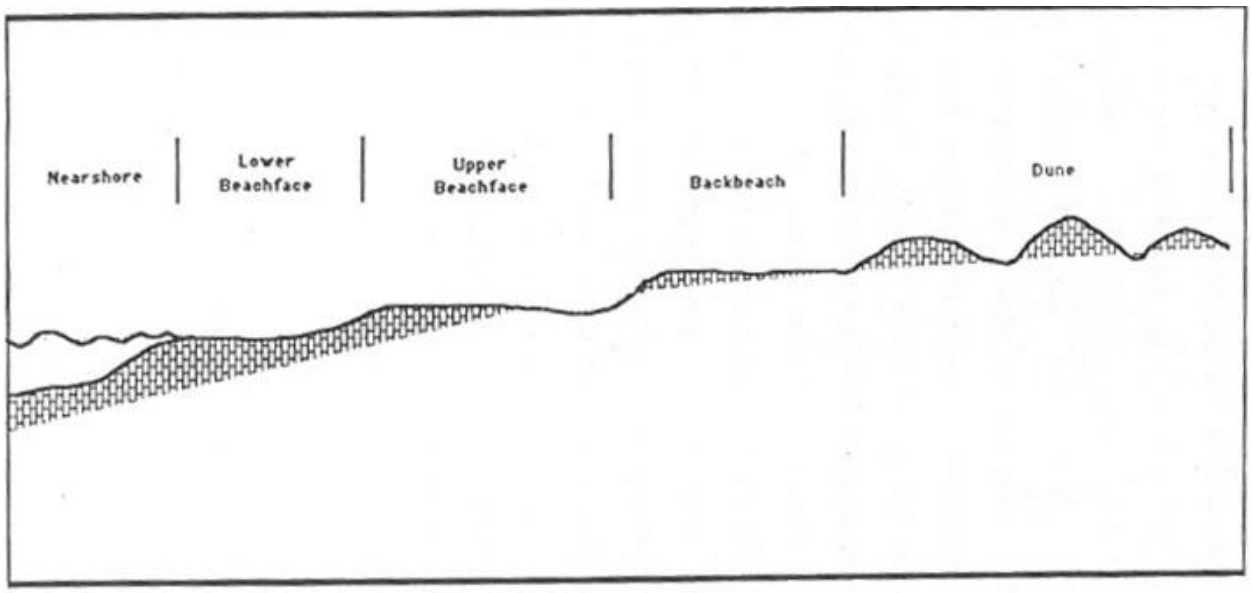

Figure 12. Profile of beach environments, including the lower beachface, upper beachface, backbeach, and dune (from Clark, 1988, fig. 9).

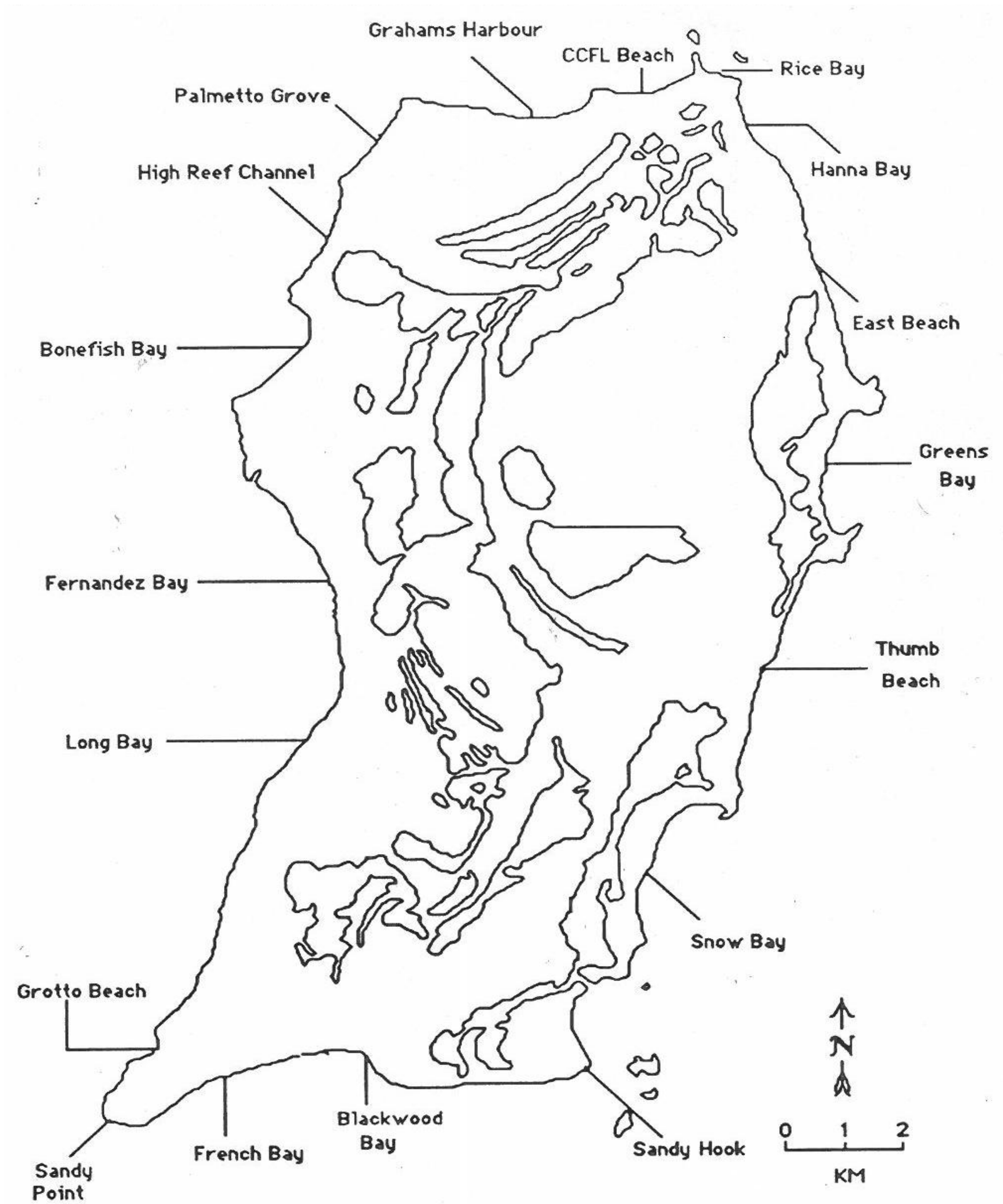

Figure 13. Location of transects on each beach (from Clark, 1988, fig. 8)

Table 1. Udden-Wentworth grain size scale (from Blott and Pye, 2001, Table 1).

Grain size		Descriptive terminology			
phi	mm/µm	Udden (1914) and Wentworth (1922)	Friedman and Sanders (1978)	GRADISTAT program	
			Very large boulders		
−11	2048 mm				
			Large boulders	Very large	
−10	1024				
			Medium boulders	Large	
−9	512	Cobbles			
			Small boulders	Medium	Boulders
−8	256				
			Large cobbles	Small	
−7	128				
			Small cobbles	Very small	
−6	64				
			Very coarse pebbles	Very coarse	
−5	32				
			Coarse pebbles	Coarse	
−4	16	Pebbles			
			Medium pebbles	Medium	Gravel
−3	8				
			Fine pebbles	Fine	
−2	4				
		Granules	Very fine pebbles	Very fine	
−1	2				
		Very coarse sand	Very coarse sand	Very coarse	
0	1				
		Coarse sand	Coarse sand	Coarse	
1	500 µm				
		Medium sand	Medium sand	Medium	Sand
2	250				
		Fine sand	Fine sand	Fine	
3	125				
		Very fine sand	Very fine sand	Very fine	
4	63				
			Very coarse silt	Very coarse	
5	31				
			Coarse silt	Coarse	
6	16	Silt			
			Medium silt	Medium	Silt
7	8				
			Fine silt	Fine	
8	4				
			Very fine silt	Very fine	
9	2	Clay			
			Clay	Clay	

Table 2. Folk and Ward (1957) graphical measures modified for geometric use. Used to determine the sorting, skewness, and kurtosis of beach sand samples. *Px* is the grain diameter in microns at the cumulative percentile value of *x* (modified from Blott and Pye, 2001, Table 2e)

Mean	Standard deviation
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\sigma_G = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6{\cdot}6}\right)$
Skewness	**Kurtosis**
$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$	$K_G = \frac{\ln P_5 - \ln P_{95}}{2{\cdot}44(\ln P_{25} - \ln P_{75})}$

Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
Very well sorted	<1·27	Very fine skewed	⁻0·3 to ⁻1·0	Very platykurtic	<0·67
Well sorted	1·27–1·41	Fine skewed	⁻0·1 to ⁻0·3	Platykurtic	0·67–0·90
Moderately well sorted	1·41–1·62	Symmetrical	⁻0·1 to ⁺0·1	Mesokurtic	0·90–1·11
Moderately sorted	1·62–2·00	Coarse skewed	⁺0·1 to ⁺0·3	Leptokurtic	1·11–1·50
Poorly sorted	2·00–4·00	Very coarse skewed	⁺0·3 to ⁺1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	4·00–16·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>16·00				

RESULTS

The following results are the compilation of Clark's results, that of an unpublished study in 2010, and this study. A former student at the College of Charleston, Miranda Murphy, completed an independent study in 2010 comparing modern sediments to those collected by Clark in 1988. Murphy's data only accounts for sediment collected from the dune and lower beachface of seven of the beaches on San Salvador Island. Murphy's data has been incorporated to the observations and analysis of this study.

The particle size analysis results are divided into groups based on the geographic location of the beaches: Northern Beaches (Appendix A), Southern Beaches (Appendix B), Eastern Beaches (Appendix C), and Western Beaches (Appendix D). Sections referenced by year (i.e., "1988," "2010," and "2014") should be attributed to Clark (1988), Murphy (2010), and this study (2014) respectively. Some sections have been assigned the designation of "not available." For 2010 data, this designation indicates that Murphy did not collect samples at the site. For 2014 data, “not available” indicates that sample results could not be determined due to software and analyzer malfunctions, unless otherwise specified. For all locations, refer to Figure 13.

Northern Beaches

The following results for the northern beaches include textural analysis (Table A1), sample sorting (Table A2), grain size (Table A3), sample skewness (Table A4), and kurtosis (Table A5) for each beach environment.

Of the northern beaches, only the results from Gerace Research Center (CCFL) Beach and Rice Bay can be compared. Clark’s analysis of sorting at GRC Beach ranged from well to poorly-sorted. The majority of samples from 2014 are well-sorted for this beach. Murphy studied Rice Bay in 2010, and classified the lower beachface and dune environments as moderately-sorted. Clark’s analysis for this beach yielded mostly well-sorted samples.

Fine sand was found at Rice Bay in both 1988 and 2010. GRC (CCFL) Beach consisted of significantly coarser sand now than it did in 1988. No significant pattern for skewness could be determined. The 2010 samples from Rice Bay matched the kurtosis determined for the lower beachface and upper beachface from 1988. 2014 samples are mostly classified as mesokurtic, whereas Clark’s samples were either platykurtic or leptokurtic.

Rice Bay

1988. The lower beachface of Rice Bay was composed of well-sorted fine sand. The grains were subangular. The sample was nearly symmetrical and mesokurtic. The upper beachface had well-sorted fine sand with subangular to subrounded grains. The sample was coarse skewed and leptokurtic. The backbeach had fine sand that was moderately well-sorted with grains ranging from subangular to subrounded. The leptokurtic sample was coarse skewed.

The dune sample contained well-sorted fine sand. Grains were subangular to subrounded, and the sample was nearly symmetrical and leptokurtic.

2010. The lower beachface of Rice Bay contained moderately-well-sorted fine sand. The sample was mesokurtic and symmetrical. The dune samples contained sediment of fine sand that was moderately well sorted. The samples were fine skewed and leptokurtic.

2014. Not available.

GRC (CCFL) Beach

1988. Moderately-well-sorted coarse sand is found on the lower beachface of GRC beach. The sample collected from the lower beachface was also fine skewed and platykurtic. No upper beachface was present in 1988. Clark's sample from the backbeach contained well-sorted medium sand. The leptokurtic sample was nearly symmetrical. The dune was composed of medium sand. The sample was poorly sorted, strongly coarse-skewed, and leptokurtic.

2010. Not available.

2014. The lower beachface of GRC Beach contained well-sorted rounded, coarse-grained sand. The sample was mesokurtic and was symmetrical. The coarsely-skewed mesokurtic sample from the upper beachface was well-sorted. This sample consisted of rounded coarse sand. Medium subrounded sand was collected from the backbeach. This sample was moderately sorted, leptokurtic and exhibited a very fine skew. The dune environment of this beach contained well-sorted rounded, coarse-grained sand. The mesokurtic sample was symmetrical.

Graham's Harbour

1988. Coarse sand was present in the lower beachface of Graham's Harbour. The sample was moderately-well-sorted and contained well-rounded grains. This nearly symmetrical sample was mesokurtic. The upper beachface consisted of subangular to subrounded medium sand. The sample was well sorted, coarse skewed, and leptokurtic. Moderately-well-sorted medium sand with subrounded to rounded grains was found in the backbeach environment. Backbeach sand was coarse skewed and mesokurtic. Subrounded to rounded medium sand was found in the dune environment. The mesokurtic sample was well-sorted and nearly symmetrical.

2010. Not available.

2014. Not available.

Southern Beaches

The following results for the southern beaches include textural analysis (Table B1), sample sorting (Table B2), grain size (Table B3), sample skewness (Table B4), and kurtosis (Table B5) for each beach environment.

No data was collected by Murphy from the southern beaches, and only data from Blackwood Bay was analyzed in 2014. Therefore no detailed comparison between beaches of coastal change over time can be made.

Sandy Point

1988. The lower beachface of Sandy Point contained well-sorted coarse sand with subangular to subrounded grains. The sample was nearly symmetrical and mesokurtic. The upper beachface also consisted of well-sorted coarse sand with subangular to subrounded grains. This sample was coarse skewed and mesokurtic. The sample collected from the backbeach environment had moderately-well-sorted coarse sand with subrounded grains. This sample was nearly symmetrical and mesokurtic. The nearly symmetrical, platykurtic sample collected at the dune environment was well-sorted. The coarse sand of this sample was composed of subrounded grains.

2010. Not available.

2014. Not available.

French Bay

1988. Moderately-well-sorted coarse sand composed of subangular grains was recorded in the lower beachface sample at French Bay. This sample was strongly fine skewed and very platykurtic. The upper beachface contained medium sand with subangular to subrounded grains. The sample was moderately sorted, coarse skewed, and mesokurtic. The medium sand found in the backbeach was moderately sorted and had subangular to subrounded grains, and was nearly symmetrical and platykurtic. A well-sorted sample of medium sand with subangular to subrounded grains was collected from the dune environment. This sample was nearly symmetrical and mesokurtic.

2010. Not available.

2014. Not available.

Blackwood Bay

1988. Moderately-well-sorted very-fine sand was recorded from the lower beachface environment. The grains of this sample were subangular to angular. Clark determined this sample to be strongly coarse skewed and mesokurtic. The coarse sand of the upper beachface was composed of subangular grains. The well-sorted sample was coarse skewed and mesokurtic. The backbeach environment of Blackwood Bay contained subangular medium sand. The sample was very-well-sorted and mesokurtic. The sample was also coarse skewed. Very-well-sorted medium sand was found in the dune environment. The grains were subangular to subrounded. The sample was nearly symmetrical and was mesokurtic.

2010. Not available.

2014. The lower beachface sample collected during the 2014 field season was moderately sorted consisting of subrounded, medium-sized sand. This sample was classified as very leptokurtic with a very-fine skew. The very leptokurtic upper beachface sample exhibited a very-fine skew and was found to be moderately sorted. The grains found in the upper beachface environment were medium sized and subrounded. Medium rounded grains were found in the backbeach. This moderately sorted sample was fine-skewed and mesokurtic. The sample collected from the dune environment was also mesokurtic and very-fine skewed. Grains in this environment were medium sized, rounded and well-sorted.

Sandy Hook

1988. The lower beachface environment contained coarse sand that was moderately sorted. The grains within the sample were subrounded, and the sample itself was strongly coarse skewed and platykurtic. Moderately-well-sorted fine sand with subrounded to rounded grains were found in the upper beachface. The sample from this environment was also strongly coarse skewed and mesokurtic. Well-sorted fine sand composed of subrounded to rounded grains were recorded in a sample taken from the backbeach. This sample exhibited a coarse skew and was classified as leptokurtic. The dune was also composed of well-sorted fine sand with subrounded to rounded grains. The sample was platykurtic and coarse skewed.

2010. Not available.

2014. Not available.

Eastern Beaches

The following results for the eastern beaches include textural analysis (Table C1), sample sorting (Table C2), grain size (Table C3), sample skewness (Table C4), and kurtosis (Table C5) for each beach environment.

The dominant grain texture recorded by Clark for eastern beaches was subangular to subrounded. Of the two beaches analyzed from the 2014 study, East Beach corresponds to Clark's results, whereas the majority of Thumb Beach environments are classified as angular as compared to subangular or subrounded. All 1988 samples were classified as well to moderately-well-sorted, except for the lower beachface environment of Snow Bay. The lower beachface and dune environments of Hanna Bay, East Beach, and Snow Bay were determined to be moderately sorted in 2010. Our analysis shows all beach environments analyzed to be very-well to well sorted, except for the backbeach of Thumb Beach which is moderately sorted.

Grain size of eastern beaches ranges from fine to medium for all years. Clark's samples ranged from symmetrically to coarsely skewed. Murphy's data ranged from fine to symmetrically skewness. Our samples range from a very fine skewness to symmetrical. Most of Clark's samples were mesokurtic, though some were platykurtic and leptokurtic as well. Murphy's data were mesokurtic and leptokurtic. The most recent data is platykurtic, mesokurtic, or leptokurtic with no dominant pattern.

Hanna Bay

1988. Textural analysis of Hanna Bay found the lower beachface was composed of well-sorted, subangular fine sand. The sample had a coarse skew and was mesokurtic. The upper beachface contained well-sorted, subangular to subrounded medium sand that was also coarse skewed and mesokurtic. The backbeach was well-sorted subangular to subrounded fine sand. The sample was nearly symmetrical and leptokurtic. Moderately-well-sorted subangular to subrounded fine sand characterized the dune sediment. This sand had a coarse skew and was leptokurtic.

2010. Textural analysis performed by Murphy in 2010 yielded moderately-well-sorted fine sand at the lower beachface. This sediment was symmetrical and leptokurtic. The dune sand was moderately-well-sorted and of medium grain size. It was fine skewed and mesokurtic.

2014. Not available

East Beach

1988. The lower beachface of East Beach was composed of subangular moderately-well-sorted fine sand. The sediment was nearly symmetrical and mesokurtic. Subangular to subrounded, well-sorted fine sand composed the upper beachface. The sediment was coarse skewed and mesokurtic. The backbeach of East Beach had medium sand that was moderately-well-sorted and subangular to subrounded. The sand had a coarse skew and was mesokurtic. The fine sand of the dune was moderately-well-sorted and subangular to subrounded. The sediment exhibited a strong coarse skew and mesokurtosis.

2010. Moderately-well-sorted fine sand composed the lower beachface of East Beach in 2010. The sand was fine skewed and leptokurtic. The dune sediment was moderately-well-sorted fine sand that was fine skewed and leptokurtic.

2014. Well-sorted fine subrounded sand was collected at the lower beachface in this study. This leptokurtic sample exhibited a fine skew. The platykurtic fine-skewed upper beachface sample was determined to be well-sorted by visual analysis. This environment contained subrounded fine sand. The backbeach encompassed subangular fine sand that was very-well-sorted. This sample was symmetrically skewed and platykurtic. The dune sample comprised mesokurtic well-sorted subangular medium sand with a symmetrical size distribution.

Greens Bay

1988. The lower beachface environment of this beach contained well-sorted subangular fine sand. The mesokurtic sample was nearly symmetrical. The upper beachface was also composed of well-sorted fine sand. Subangular to subrounded grains were contained in the coarse-skewed leptokurtic sample. Moderately-well-sorted medium sand was found in the backbeach. The coarse skewed, mesokurtic sample contained subangular to subrounded grains. Fine sand built the dune environment. The dune consisted of well-sorted fine sand that contained subangular to subrounded grains. The sample was nearly symmetrical and mesokurtic.

2010. Not available.

2014. Not available because inaccessible during field season.

Thumb Beach

1988. The lower beachface of Thumb Beach had medium sand that was moderately well sorted. The individual grains were subangular to subrounded, and the sample was coarse skewed and mesokurtic. The upper beachface was composed of well-sorted, subangular to subrounded fine to medium sand. The sample was coarse skewed and mesokurtic. The backbeach had medium sand that is well sorted and subangular to subrounded. It was coarse skewed and platykurtic. The dune had mostly fine sand that was well sorted. The grains were subangular to subrounded and exhibited a coarse skew. The sample was leptokurtic.

2010. Moderately-well-sorted fine sand dominated the lower beachface. The sample was nearly symmetrical and leptokurtic. The medium sized sand of the Thumb Beach dune system was moderately well sorted. The sample was fine skewed and leptokurtic.

2014. The lower beachface sample collected in 2014 contained very-well-sorted angular, fine-grained sand. This sample was very-fine skewed and mesokurtic. The upper beachface sample was also very-fine skewed and mesokurtic. It contained very-well-sorted fine-grained subangular sand. Angular fine sand that was moderately sorted was found at the backbeach. The sample exhibited a very-fine skew and was leptokurtic. The dune sample was also leptokurtic and very-fine skewed. The fine angular sand was very-well-sorted.

Snow Bay

1988. The lower beachface of Snow Bay contained moderately sorted subrounded medium sand. This sediment was coarse skewed and platykurtic. The grain size of upper beachface sediment was fine sand having subangular to subrounded grains. The sample was well-sorted, coarse skewed, and mesokurtic. Backbeach sediment was moderately-well-sorted medium sand with subrounded to rounded grains. The sample was nearly symmetrical and platykurtic. Well-sorted medium sand with subrounded to rounded grains dominated the dune sample. The sediment was nearly symmetrical and mesokurtic.

2010. Moderately-well-sorted fine sand was sampled from the lower beachface. The mesokurtic sample was symmetric. The dune samples were composed of medium sand grains. The sample was moderately well sorted, mesokurtic, and symmetrical.

2014. Not available due to inaccessibility during the field season.

Western Beaches

The following results for the western beaches include textural analysis (Table D1), sample sorting (Table D2), grain size (Table D3), sample skewness (Table D4), and kurtosis (Table D5) for each beach environment.

Grain texture of all the sediment found on the western beaches ranges from subangular to rounded in both Clark and our studies. The only exception is the lower beachface of Palmetto Grove, which consisted of angular sand in 2014. Many of Clark’s samples were determined to be moderately well sorted, whereas samples collected in 2010 and 2014 were either well sorted or moderately sorted. Grotto Beach was the exception to this rule, containing a very-well-sorted lower beachface sample and a poorly-sorted sample collected from the upper beachface in 2014.

Clark's grain sizes for the western beaches ranged from very fine to very coarse sand, with the majority of beach environments falling into the medium sand category. Data from 2010 and 2014 range from fine to very coarse sand, and the majority of environments are classified as coarse sand. Skewness ranges from very fine skewed to very coarse skewed from 1988-2014. The majority of sampled environments had symmetrical grain size distributions. Kurtosis calculated in Clark's study ranged from platykurtic to very leptokurtic, but the majority of environments were mesokurtic. The samples from 2010 and 2014 are predominantly mesokurtic, and platykurtic and leptokurtic samples are confined to Bonefish Bay and Long Bay.

Palmetto Grove

1988. No grain roundness was determined for any of the samples he collected at this beach. The lower beachface contained well-sorted medium sand. The sample exhibited a fine skew and was leptokurtic. Moderately-well-sorted medium sand was found in the upper beachface. The sample was nearly symmetrical and leptokurtic. Medium sand in a well-sorted sample was collected in the backbeach environment. This sample was nearly symmetrical and leptokurtic. The dune sample also contained medium sand that was moderately well sorted. The sample was nearly symmetrical and mesokurtic.

2010. Not available.

2014. The lower beachface sample was composed of angular coarse sand. Hand lens analysis determined the sample to be moderately sorted. The mesokurtic sample was symmetric. Rounded medium sand was well sorted. The sample was symmetrical and mesokurtic. The backbeach environment consisted of medium sand. The subangular grains were moderately sorted. The sample was symmetrical and mesokurtic, and composed of subangular well-sorted medium sand.

High Reef Channel

1988. Coarse sand with subangular grains was found in the well-sorted sample collected from the lower beachface of High Reef Channel. This sample was nearly symmetrical and leptokurtic. The upper beachface moderately-well sorted sample contained subangular coarse sand. Clark also determined the sample to be nearly symmetrical and leptokurtic. The fine-skewed mesokurtic sample collected from the backbeach was moderately-sorted coarse sand with subangular to subrounded grains. Very coarse sand in a moderately-well-sorted sample was collected from the dune environment. The sand grains exhibited a subangular to subrounded texture. The sample was nearly symmetrical and leptokurtic.

2010. Not available.

2014. Not available.

Bonefish Bay

1988. The lower beachface of Bonefish Bay contained moderately-well-sorted very-fine sand of subrounded to rounded grains. The sample was strongly coarse skewed and leptokurtic. Very-fine sand of subrounded to rounded grains was found in the upper beachface. This well-sorted sample was coarse skewed and mesokurtic. Well-sorted fine sand was recorded in the backbeach environment. The grains of this nearly-symmetrical, mesokurtic sample were rounded. Clark recorded fine sand of rounded grains in the dune environment. The sample was well-sorted, fine skewed, and leptokurtic.

2010. Not available.

2014. Subrounded fine sand was collected from the lower beachface. The sample was moderately-sorted, coarse skewed, and platykurtic. The moderately sorted upper beachface comprised subangular medium sand. The sample was very fine skewed and platykurtic. The backbeach sample was also platykurtic and very fine skewed. Medium subrounded sand was well-sorted according to visual analysis. Rounded coarse sand grains were also well sorted in the dune environment. The sample was coarse skewed and mesokurtic.

Fernandez Bay

1988. Coarse sand that was moderately well sorted was found at the lower beachface of Fernandez Bay. The grains were subangular to subrounded, and samples collected at the lower beachface were coarse skewed and platykurtic. The upper beachface of this beach contained well-sorted medium sand with subangular to subrounded grains. The sample was coarse skewed and leptokurtic. No samples from the backbeach were collected. The dune system contained medium sand that was moderately well sorted, and the grains were subangular to subrounded. The mesokurtic sample was nearly symmetrical.

2010. The lower beachface of Fernandez Bay contained well-sorted medium sand. The sample was skewed toward fine grains and exhibited mesokurtosis. No sediment samples were collected from the dunes.

2014. Subangular very-coarse sand was collected from the lower beachface. The sample was well-sorted according to visual analysis, and was symmetrical and mesokurtic. The mesokurtic coarse-skewed sample from the upper beachface also consisted of very coarse sand that was subangular and well sorted. The backbeach of Fernandez Bay contained rounded coarse sand that was moderately sorted. The sample was symmetrical and mesokurtic. The dune sample was also mesokurtic and symmetrical. Subangular coarse sand was collected at this site and determined to be moderately sorted.

Long Bay

1988. The lower beachface of Long Bay was composed of fine sand that had a subangular to subrounded texture. The sample was moderately well sorted, strongly coarse skewed, and mesokurtic. Moderately sorted subrounded to rounded fine sand was recorded in the upper beachface. The sample collected at this environment was strongly coarse skewed and very leptokurtic. The backbeach sample contained subrounded medium sand that was moderately well sorted. The nearly symmetrical sample was mesokurtic. Moderately-well-sorted medium sand with subrounded to rounded grains was found at the dune. This sample was nearly symmetrical and mesokurtic.

2010. Not available.

2014. The lower beachface environment contained rounded fine-grained sand. The sample was visually classified as well-sorted. It was also very-coarse skewed and platykurtic. The upper beachface sample was platykurtic and symmetrical. The moderately sorted sample consisted of rounded fine sand. Well-sorted rounded medium sand was collected at the backbeach environment. This sample had a very-fine skew and was leptokurtic. The dune sample was also determined to be leptokurtic and very-fine skewed. The dune contained medium sand with a subangular texture in a moderately-sorted sample.

Grotto Beach

1988. Moderately-sorted, subangular, coarse sand dominated the lower beachface of Grotto Beach. The sample was coarse skewed and leptokurtic. The upper beachface contained medium sand that was moderately well sorted. The grains were subangular to subrounded, and the sample exhibited a coarse skew and platy kurtosis. Backbeach samples contained well-sorted medium sand with subangular to subrounded grains. These samples were nearly symmetrical and platykurtic. The dune had well-sorted medium sand with subangular to subrounded grains. The sample was nearly symmetrical and mesokurtic.

2010. The lower beachface of Grotto Beach contained moderately well sorted coarse sand. The sample exhibited a fine skew and was mesokurtic. The dune in 2010 had coarse sand that was moderately well sorted, with a fine skew. The sample was also mesokurtic.

2014. The sample collected from the lower beachface of Grotto Beach contained rounded medium-sized sand grains. The sample was very-well-sorted, mesokurtic, and symmetrical. The upper beachface sample was also mesokurtic and symmetrical. The poorly-sorted sample contained subangular medium sand. Well-sorted rounded coarse sand was found in the backbeach environment. The sample was coarse skewed and mesokurtic. The mesokurtic, symmetrical dune sample contained coarse subrounded sand that was well sorted.

DISCUSSION

Distinct differences in grain size, grain-size sorting, and grain texture are evident among the many San Salvador beaches. No distinct pattern was determined for changes between 1988, 2010, and 2014 data. Clark (1988) attributed differences between beaches to the magnitude and frequency of wind and waves, beach orientation, platform width, antecedent topography, or a combination thereof. A discussion of these aspects follows.

Physical Energy Setting

San Salvador is mostly influenced by easterly trade winds. Wind observations in the San Salvador region (U.S. Naval Weather Service Command, 1974; National Oceanic and Atmospheric Administration, 2014) indicate that wind frequency and magnitude is greatest along the eastern margin (NE, E, SE), and lowest along the western margin. Wave direction and magnitude are also more dominant along the eastern margin due to dominant wind direction and orientation of the island (National Climatic Data Center, 2014) (Fig. 14). The eastern margin of San Salvador is bordered by the open Atlantic Ocean, as there are no outlying islands or cays to disrupt waves moving onto the platform. Thus there is a greater fetch on the eastern side than there is on the western side of the island. The intense wind and long fetch combine to create larger waves on the eastern margin (Clark, 1988).

Major storm events, including tropical events, play important roles in sediment transportation on San Salvador. The island's location on the eastern-most edge of the Bahamas Archipelago makes it more susceptible to hurricanes than the other islands. Although intense hurricanes are common for the island, from 1960 to 2010 only 9 hurricanes crossed the Bahamian islands (Park, 2012). In contrast, from 1980 to 2013, nine hurricanes made landfall on the islands of the Bahamas. Of those hurricanes, all occurred after 1992 and thus were not accounted for in Clark's thesis (HURDAT, 2014). High intensity storms, although short in duration, transport and deposit sediment farther onto the less protected beaches than during normal conditions (Clark, 1988).

Platform Width

The platform of the San Salvador bank is broad and gently sloped on the eastern and northern margins (Fig. 15). On the southern and western margins, the bank is narrow and ends in a near vertical slope into deep water. Currents generated in deep water lose energy as they flow onto the bank (Clark, 1988). Thus, waves and currents flowing onto broad banks lose more energy than those that flow onto narrow banks. Platform width therefore influences energy transferred to the beach environment, thus impacting grain size

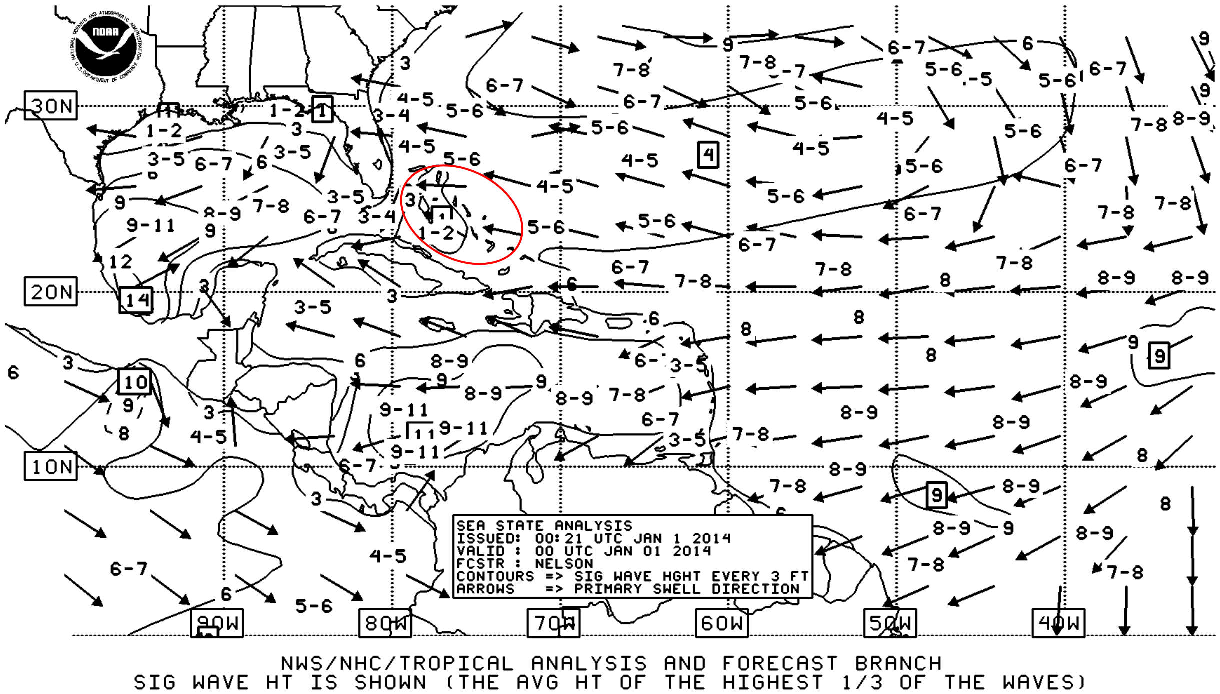

Figure 144. Dominant wave direction and average height during 2014. The Bahamas are circled in red (from the National Climatic Data Center, 2014).

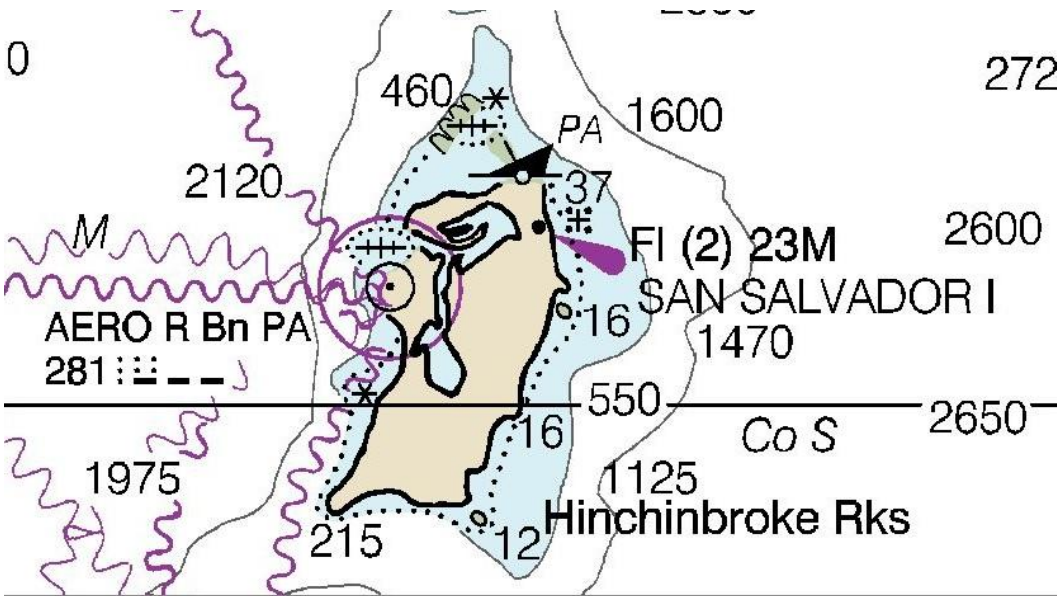

Figure 15. Bathymetry of San Salvador Bank. Note the narrow platform south and west of the island versus the wide, shallow platform to the north and east. Soundings are in fathoms (modified from NOAA Nautical Chart 11013, 2014).

Antecedent Topography

Cays, coral reefs, headland cliffs, and beachrock may diffract and dissipate wave energy. Prominent headland cliffs, offshore cays and reefs are common on the northern and eastern sides of the island. Pleistocene cliffs and fringing bank reefs protect southern beaches. Western beaches are the least protected by antecedent topography; however, reefs are common. Northern, southern, and western beaches commonly exhibit beachrock.

Grain Size Sorting

Clark noted that his sand samples exhibited a general uniformity in sorting, with 61 of the 70 samples ranging from moderately-well to very-well-sorted. This uniformity indicated that consistency of energy levels from wind, waves, currents, and storms in the depositional area yielded well sorted beaches around the island. Backbeach and dune sediments were especially well-sorted as the result of winnowing from consistent wind activity (Clark, 1988).

Exceptions to this rule were the lower beachface of Snow Bay, Sandy Hook, Grotto Beach, Graham's Harbour, and GRC Beach; the upper beachface of French Bay and Long Bay; the backbeach of High Reef Channel; and the dune environment of GRC Beach. All of these environments were moderately well sorted except the poorly-sorted GRC Beach dunes (Clark, 1988). The poorly-sorted sample collected from the dune environment at GRC Beach was surprising as dunes are generally the best sorted. Clark attributes these differences to local disruptions in energy processes such as erosion and reworking of existing rock, and the disruption of waves and currents from subaerial or bottom topography.

Murphy did not determine sample sorting for the data collected in 2010.

Samples from this study were classified exclusively as very-well-sorted using the modified Folk and Ward method from data obtained using the laser particle size analyzer (Blott and Pye, 2001). This may have been the result of the small sample size necessary for use by the laser sediment analyzer; however, the overall results mimic the general trend found by Clark. Visual analysis of the samples also indicated a well-sorted trend, again confirming Clark's analysis. Exceptions to this rule were the backbeach of GRC Beach; the lower beachface, upper beachface, and backbeach of Blackwood Bay; the backbeach of Thumb Beach; the lower and upper beachfaces of Bonefish Bay; the backbeach and dune of Fernandez Bay; the upper beachface and dune of Long Bay; and the upper beachface of Grotto Beach. All of these samples were determined to be moderately-sorted by visual analysis, except the upper beachface of Grotto Beach which was classified as poorly-sorted.

Grain Size

The magnitude of physical energy in the depositional environment is the dominant factor that determines average grain size. Antecedent topography and platform slope may also be contributing factors. Nearly all the sediment on the eastern beaches was classified as fine sand in 1988. This trend is consistent with the 2014 results. A high degree of grain size variation from beach to beach is evident on the western margin in both the 1988 and 2014 data as well. Northern and southern beaches consist of predominantly medium and coarse sand in both studies.

Clark attributes grain size variation to differing platform morphology and antecedent topography. The eastern beaches receive more intense wind and wave energy and therefore should consist of coarse-grained sand. However, fine sand is found on the eastern beaches in all studies. In contrast, northern, southern, and western beaches receive less wave and wind energy, therefore one would expect finer sands to occur on these beaches. However, coarser grained sands were recorded in all studies from these beaches. Therefore, Clark (1988) suggested that platform morphology and antecedent topography are important factors in determining grain size, outweighing the influence of average physical energy.

Clark (1988) also noted that major storm events may override the influence of average physical energy. However, in the years before Clark completed his fieldwork, the Bahamas experienced relatively calm hurricane seasons (HURDAT, 2014). In contrast, from 1990 to 2013, nine hurricanes made landfall in the Bahamas, including Hurricane Lily in October 1996, Hurricane Floyd in September 1999, and Frances in September 2004; all of which directly impacted San Salvador (Dick and Cartright, 2011). Despite these storm events, sediment sorting and grain size results remain generally consistent among all three studies.

Beach Width Changes

Beach transect length is the most notable difference between the data collected in 1988 and 2014. The majority of transects measured in 2014 are longer than those in 1988. All of the northern beaches are wider than in 1988 (Fig. 16), and each southern beach is wider than in 1988 except for Sandy Hook (Fig. 17). Sandy Hook was also the most susceptible to storm surge damages from Hurricane Frances (Dick and Cartright, 2011), possibly contributing to this deviation from the overall trend. Sandy Point had a significantly longer transect during 2014 than was measured in 1988. It is possible that dominant currents and wave direction transported the sediment from Sandy Hook to Sandy Point after the storm.

Eastern beaches also show an increase in transect length, except for Thumb Beach (Fig. 18). Thumb Beach is exposed to the dominant physical energy direction without protection from offshore cays. However, it is relatively protected by offshore reefs and two headland cliffs. Western beaches do not show an overall pattern of increase in beach width compared to that in 1988 (Fig. 19). Bonefish Bay, Fernandez Bay, and Grotto Beach are wider than when Clark measured transects at the sites; whereas, Palmetto Grove, High Reef Channel, and Long Bay all have shorter transects than measured by Clark. However, it should be noted that the beach transect at Long Bay was not ground-truthed as discussed in the "Beach Description" section of this paper.

Particle Size Analysis Remarks

This study was originally intended to be a comprehensive comparison of beach sedimentation from 1988 to present day. The 64 samples collected during the 2014 field season would provide a beach-by-beach comparison to Clark's analysis in his 1988 thesis. However, upon return to the College of Charleston, the laser particle size analyzer (CILAS 1180) experienced multiple problems; such as the introduction of bubbles to the system, and the breaking pipes within the analyzer. The root of the problem was later discovered to be from the piping installed in the new marine and sedimentation laboratory. Although the analyzer was temporarily fixed multiple times during Spring 2014, it eventually became permanently inoperable and thus sample analysis was terminated. In addition, no data was available for some samples that had been analyzed due to software malfunctions associated with the analyzer. Hopefully this study will be concluded next year by an underclassman that was trained during this project.

CONCLUSIONS

The most significant changes observed in coastal development from 1988 to present was changes in beach width. Although major storm events may have contributed to some of these changes, the results of this study and the one conducted in 2010 generally match Clark's results. The majority of samples from all studies are moderately to very-well-sorted. Eastern beaches consisted of finer sand than northern, southern, or western beaches despite dominant easterly wind and wave direction. The results from this study support Clark's arguments that antecedent topography and platform width were the major contributions to sediment sorting and grain size.

Very few hurricanes impacted San Salvador prior to Clark's study; however, nine hurricanes made landfall on the island from 1992 to 2013. This increase in storm activity was expected to greatly change the grain size and sample sorting of the beach environments. However, only limited change was observed. Therefore, Clark's assumption that major storm events are a major contributing factor to coastal change on San Salvador remains unsupported. Further studies will hopefully be completed in the next year to analyze the remaining samples collected on San Salvador during the 2014 field season.

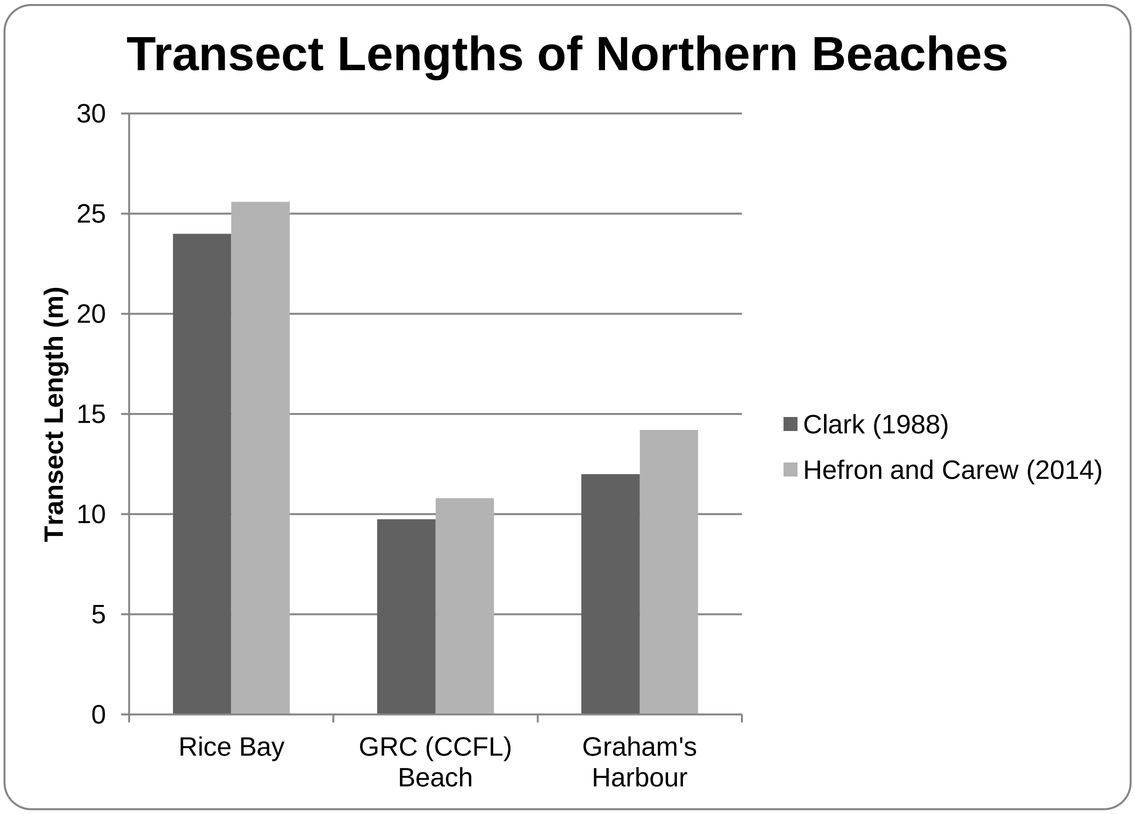

Figure 16. Comparison of transect lengths for northern beaches between Clark (1988) and the current study.

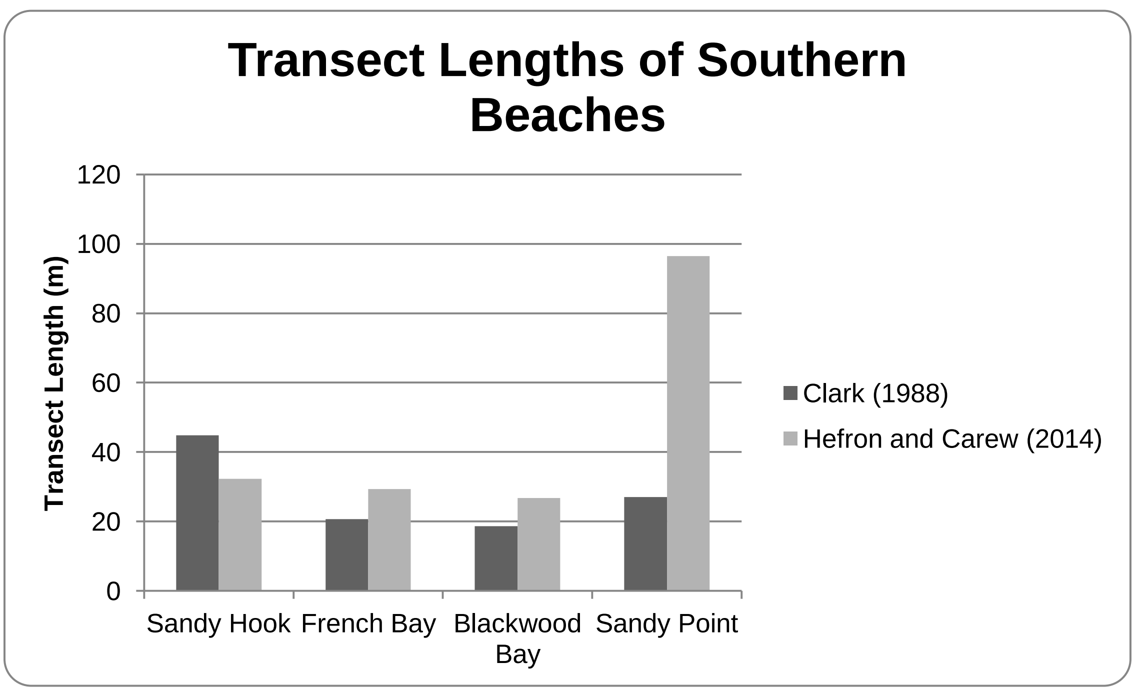

Figure 17. Comparison of transect lengths for southern beaches between Clark (1988) and the current study.

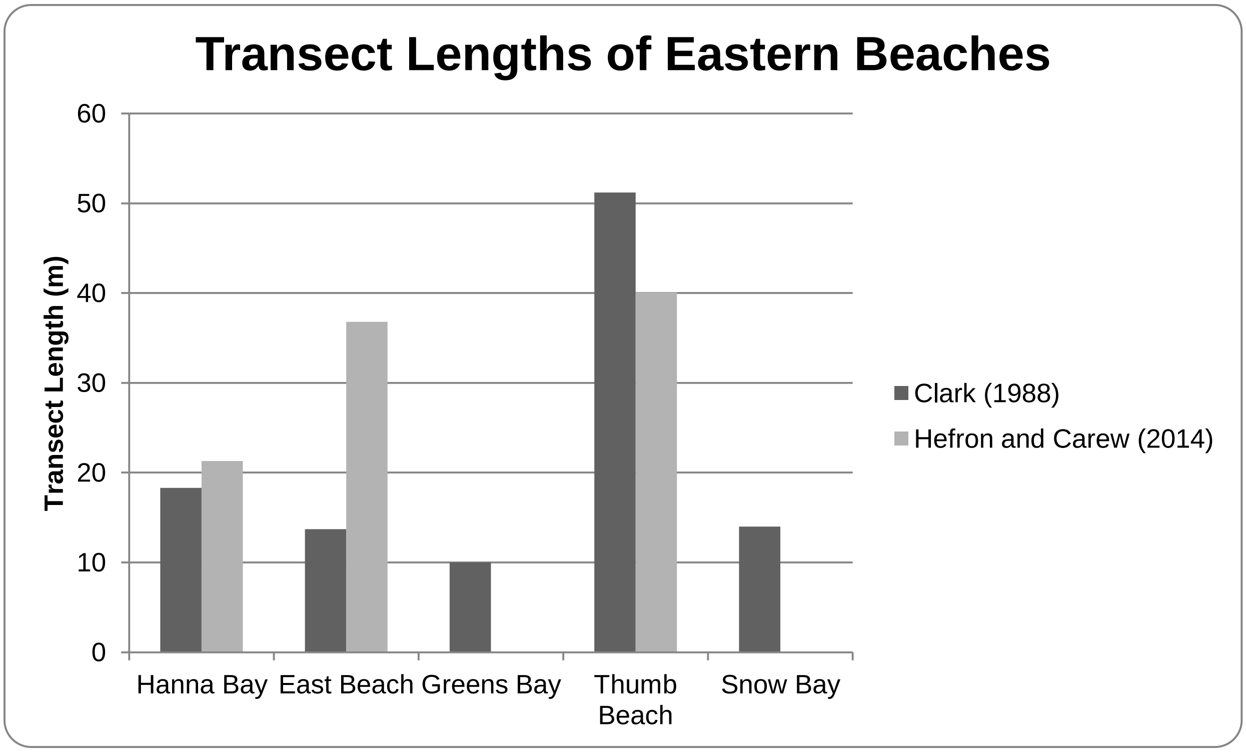

Figure 18. Comparison of transect lengths for eastern beaches between Clark (1988) and the current study. Where there is no data from 2014, no transects were measured.

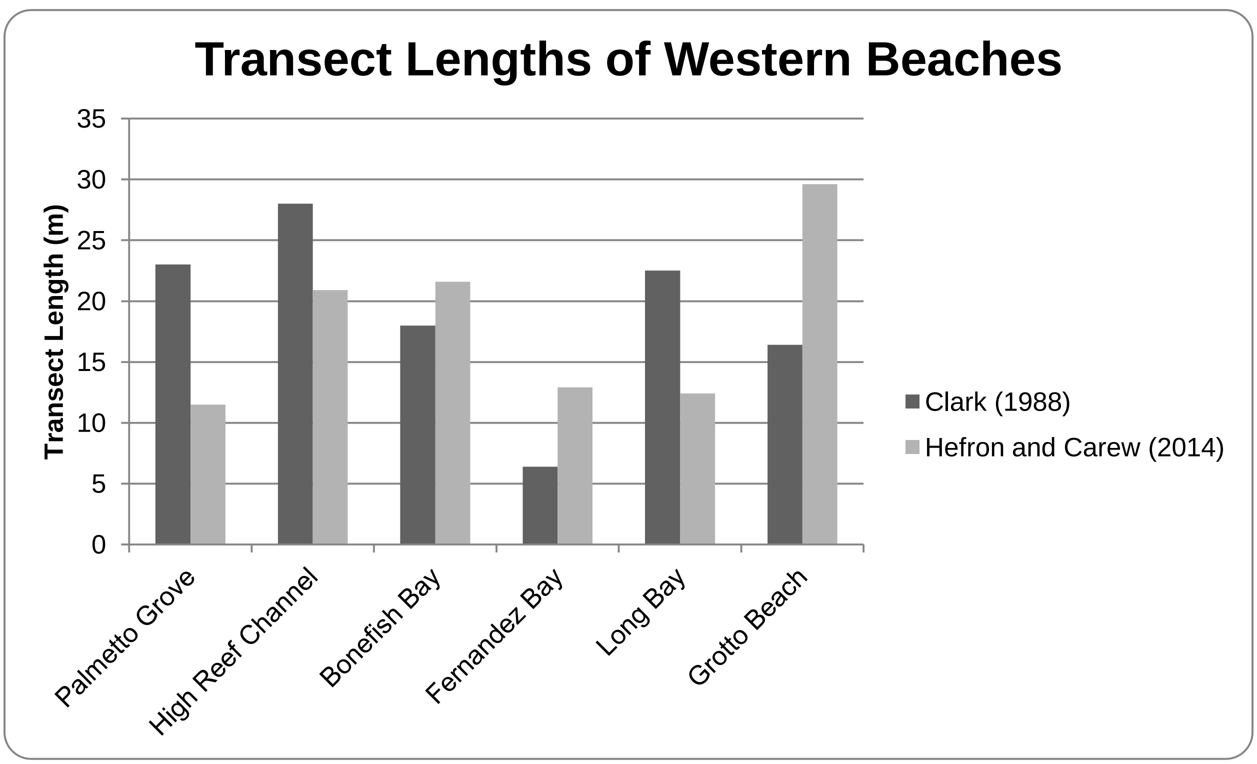

Figure 19. Comparison of transect lengths for western beaches between Clark (1988) and the current study.

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APPENDIX A: PSA RESULTS FROM NORTHERN BEACHES

Table A1. Grain texture of northern beaches. X = Clark (1988), X = Hefron & Carew (2014).

Beach	Angular	Subangular	Subrounded	Rounded
Rice Bay				
Lower Beachface		X		
Upper Beachface		X	X	
Backbeach		X	X	
Dune		X	X	
Gerace Research Center (CCFL)				
Lower Beachface				X
Upper Beachface				X
Backbeach			X	
Dune				X
Graham's Harbour				
Lower Beachface			X	
Upper Beachface		X	X	
Backbeach			X	X
Dune			X	X

Table A2. Sample sorting of northern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014), X = Hefron & Carew visual analysis (2014).

Beach	Very Well	Well	Moderately Well	Moderate	Poor
Rice Bay					
Lower Beachface		X		X	
Upper Beachface		X			
Backbeach			X		
Dune		X		X	
Gerace Research Center (CCFL)					
Lower Beachface	X	X	X		
Upper Beachface	X	X			
Backbeach	X	X		X	
Dune	X	X			X
Graham's Harbour					
Lower Beachface				X	
Upper Beachface		X			
Backbeach			X		
Dune		X			

Table A3. Grain size of sand from northern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Medium	Coarse	Very Coarse
Rice Bay					
Lower Beachface		XX			
Upper Beachface		X			
Backbeach		X			
Dune		XX			
Gerace Research Center (CCFL)					
Lower Beachface				XX	
Upper Beachface				X	
Backbeach			XX		
Dune			X	X	
Graham's Harbour					
Lower Beachface				X	
Upper Beachface			X		
Backbeach			X		
Dune			X		

Table A4. Sample skewness from northern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Symmetrical	Coarse	Very Coarse
Rice Bay					
Lower Beachface			XX		
Upper Beachface				X	
Backbeach				X	
Dune		X	X		
Gerace Research Center (CCFL)					
Lower Beachface		X	X		
Upper Beachface				X	
Backbeach	X		X		
Dune			X		X
Graham's Harbour					
Lower Beachface			X		
Upper Beachface				X	
Backbeach				X	
Dune			X		

Table A5. Sample kurtosis from northern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Platykurtic	Mesokurtic	Leptokurtic	Very Leptokurtic
Rice Bay				
Lower Beachface		XX		
Upper Beachface		X		
Backbeach			X	
Dune			XX	
Gerace Research Center (CCFL)				
Lower Beachface	X	X		
Upper Beachface		X		
Backbeach			XX	
Dune		X	X	
Graham's Harbour				
Lower Beachface		X		
Upper Beachface			X	
Backbeach		X		
Dune		X		

APPENDIX B: PSA RESULTS FROM SOUTHERN BEACHES

Table B1. Grain texture of southern beaches. X = Clark (1988), X = Hefron & Carew (2014).

Beach	Angular	Subangular	Subrounded	Rounded
Sandy Hook				
Lower Beachface			X	
Upper Beachface			X	X
Backbeach			X	X
Dune			X	X
Blackwood Bay				
Lower Beachface	X	X	X	
Upper Beachface		X	X	
Backbeach		X		X
Dune		X		X
French Bay				
Lower Beachface		X		
Upper Beachface		X	X	
Backbeach		X	X	
Dune		X	X	
Sandy Point				
Lower Beachface		X	X	
Upper Beachface		X	X	
Backbeach			X	
Dune			X	

Table B2. Sample sorting of southern beaches. X = Clark (1988), X = Hefron & Carew (2014), X = Hefron & Carew visual analysis (2014).

Beach	Very Well	Well	Moderately Well	Moderate	Poor
Sandy Hook					
Lower Beachface				X	
Upper Beachface			X		
Backbeach		X			
Dune		X			
Blackwood Bay					
Lower Beachface	X			XX	
Upper Beachface	X	X		X	
Backbeach	XX			X	
Dune	XX	X			
French Bay					
Lower Beachface			X		
Upper Beachface				X	
Backbeach		X			
Dune		X			
Sandy Point					
Lower Beachface		X			
Upper Beachface		X			
Backbeach			X		
Dune		X			

Table B3: Grain size of sand from southern beaches. X = Clark (1988), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Medium	Coarse	Very Coarse
Sandy Hook					
Lower Beachface				X	
Upper Beachface		X			
Backbeach		X			
Dune		X			
Blackwood Bay					
Lower Beachface	X		X		
Upper Beachface			X	X	
Backbeach			XX		
Dune			XX		
French Bay					
Lower Beachface				X	
Upper Beachface			X		
Backbeach				X	
Dune			X		
Sandy Point					
Lower Beachface				X	
Upper Beachface				X	
Backbeach				X	
Dune				X	

Table B4: Skewness of samples from southern beaches. X = Clark (1988), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Symmetrical	Coarse	Very Coarse
Sandy Hook					
Lower Beachface					X
Upper Beachface					X
Backbeach				X	
Dune				X	
Blackwood Bay					
Lower Beachface	X				X
Upper Beachface	X			X	
Backbeach		X		X	
Dune	X			X	
French Bay					
Lower Beachface	X				
Upper Beachface				X	
Backbeach			X		
Dune			X		
Sandy Point					
Lower Beachface			X		
Upper Beachface				X	
Backbeach			X		
Dune			X		

Table B5: Kurtosis of samples from southern beaches. X = Clark (1988), X = Hefron & Carew (2014).

Beach	Very Platykurtic	Platykurtic	Mesokurtic	Leptokurtic	Very Leptokurtic
Sandy Hook					
Lower Beachface		X			
Upper Beachface			X		
Backbeach				X	
Dune		X			
Blackwood Bay					
Lower Beachface			X		X
Upper Beachface			X		X
Backbeach			XX		
Dune			XX		
French Bay					
Lower Beachface	X				
Upper Beachface			X		
Backbeach		X			
Dune			X		
Sandy Point					
Lower Beachface			X		
Upper Beachface			X		
Backbeach			X		
Dune		X			

APPENDIX C: PSA RESULTS FROM EASTERN BEACHES

Table C1. Grain texture of samples from eastern beaches. X = Clark (1988), X = Hefron & Carew (2014).

Beach	Angular	Subangular	Subrounded	Rounded
Hanna Bay				
Lower Beachface		X		
Upper Beachface		X	X	
Backbeach		X	X	
Dune		X	X	
East Beach				
Lower Beachface		X	X	
Upper Beachface		X	XX	
Backbeach		XX	X	
Dune		XX	X	
Greens Bay				
Lower Beachface		X		
Upper Beachface		X	X	
Backbeach		X	X	
Dune		X	X	
Thumb Beach				
Lower Beachface	X	X	X	
Upper Beachface		XX	X	
Backbeach	X	X	X	
Dune	X	X	X	
Snow Bay				
Lower Beachface			X	
Upper Beachface		X	X	
Backbeach			X	X
Dune			X	X

Table C2. Sample sorting from eastern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014), X = Hefron & Carew visual analysis (2014).

Beach	Very Well	Well	Moderately Well	Moderate	Poor
Hanna Bay					
Lower Beachface		X		X	
Upper Beachface		X			
Backbeach		X			
Dune			X	X	
East Beach					
Lower Beachface	X	X	X	X	
Upper Beachface	X	XX			
Backbeach	XX		X		
Dune	X	X	X	X	
Greens Bay					
Lower Beachface		X			
Upper Beachface		X			
Backbeach			X		
Dune		X			
Thumb Beach					
Lower Beachface	XX		X		
Upper Beachface	XX	X			
Backbeach	X	X		X	
Dune	XX	X			
Snow Bay					
Lower Beachface				XX	
Upper Beachface		X			
Backbeach			X		
Dune		X		X	

Table C3. Grain size of sand from eastern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Medium	Coarse	Very Coarse
Hanna Bay					
Lower Beachface		XX			
Upper Beachface			X		
Backbeach		X			
Dune		X	X		
East Beach					
Lower Beachface		XXX			
Upper Beachface		XX			
Backbeach		X	X		
Dune		XX	X		
Greens Bay					
Lower Beachface		X			
Upper Beachface		X			
Backbeach			X		
Dune		X			
Thumb Beach					
Lower Beachface		X	X		
Upper Beachface		XX	X		
Backbeach		X	X		
Dune		XX			
Snow Bay					
Lower Beachface		X	X		
Upper Beachface		X			
Backbeach			X		
Dune			XX		

Table C4. Skewness of samples from eastern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Symmetrical	Coarse	Very Coarse
Hanna Bay					
Lower Beachface			X	X	
Upper Beachface				X	
Backbeach			X		
Dune		X		X	
East Beach					
Lower Beachface		XX	X		
Upper Beachface		X		X	
Backbeach			X	X	
Dune	X		X	X	
Greens Bay					
Lower Beachface			X		
Upper Beachface				X	
Backbeach				X	
Dune			X		
Thumb Beach					
Lower Beachface	X			X	
Upper Beachface	X			X	
Backbeach	X			X	
Dune	X			X	
Snow Bay					
Lower Beachface			X	X	
Upper Beachface				X	
Backbeach			X		
Dune		X	X		

Table C5. Kurtosis of samples from eastern beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Platykurtic	Mesokurtic	Leptokurtic	Very Leptokurtic
Hanna Bay				
Lower Beachface		X	X	
Upper Beachface		X		
Backbeach			X	
Dune		X	X	
East Beach				
Lower Beachface		X	XX	
Upper Beachface	X	X		
Backbeach	X	X		
Dune		XX	X	
Greens Bay				
Lower Beachface		X		
Upper Beachface			X	
Backbeach		X		
Dune		X		
Thumb Beach				
Lower Beachface		XX		
Upper Beachface		XX		
Backbeach	X		X	
Dune			XX	
Snow Bay				
Lower Beachface	X	X		
Upper Beachface		X		
Backbeach	X			
Dune		XX		

APPENDIX D: PSA RESULTS FROM WESTERN BEACHES

Table D1. Grain texture of western beaches. . X = Clark (1988), X = Hefron & Carew (2014).

Beach	Angular	Subangular	Subrounded	Rounded
Palmetto Grove				
Lower Beachface	X			
Upper Beachface				X
Backbeach		X		
Dune		X		
High Reef Channel				
Lower Beachface		X		
Upper Beachface		X		
Backbeach		X	X	
Dune		X	X	
Bonefish Bay				
Lower Beachface			XX	X
Upper Beachface		X	X	X
Backbeach			X	X
Dune				XX
Fernandez Bay				
Lower Beachface		XX	X	
Upper Beachface		XX	X	
Backbeach				X
Dune		XX	X	
Long Bay				
Lower Beachface		X	X	X
Upper Beachface			XX	X
Backbeach			X	X
Dune		X	X	X
Grotto Beach				
Lower Beachface		X		X
Upper Beachface		XX	X	
Backbeach		X	X	X
Dune		X	XX	

Table D2. Sample sorting from western beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014), X = Hefron & Carew visual analysis (2014).

Beach	Very Well	Well	Moderately Well	Moderate	Poor
Palmetto Grove					
Lower Beachface	X	X		X	
Upper Beachface	X	X	X		
Backbeach	X	X		X	
Dune	X	X	X		
High Reef Channel					
Lower Beachface	X	X			
Upper Beachface	X	X			
Backbeach	X			X	
Dune	X		X		
Bonefish Bay					
Lower Beachface	X		X	X	
Upper Beachface	X	X		X	
Backbeach	X	XX			
Dune	X	XX			
Fernandez Bay					
Lower Beachface	X	XX	X		
Upper Beachface	X	XX			
Backbeach	X			X	
Dune	X		X	X	
Long Bay					
Lower Beachface	X	X	X		
Upper Beachface	X			XX	
Backbeach	X	X	X		
Dune	X		X	X	
Grotto Beach					
Lower Beachface	XX			XX	
Upper Beachface	X		X		X
Backbeach	X	XX			
Dune	X	XX		X	

Table D3. Grain size of sand samples collected from western beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Medium	Coarse	Very Coarse
Palmetto Grove					
Lower Beachface			X	X	
Upper Beachface			XX		
Backbeach			XX		
Dune			XX		
High Reef Channel					
Lower Beachface				X	
Upper Beachface				X	
Backbeach				X	
Dune					X
Bonefish Bay					
Lower Beachface	X	X			
Upper Beachface	X		X		
Backbeach		X	X		
Dune		X		X	
Fernandez Bay					
Lower Beachface			X	X	X
Upper Beachface			X		X
Backbeach				X	
Dune			X	X	
Long Bay					
Lower Beachface		XX			
Upper Beachface		XX			
Backbeach			XX		
Dune			XX		
Grotto Beach					
Lower Beachface			X	XX	
Upper Beachface			XX		
Backbeach			X	X	
Dune			X	XX	

Table D4. Skewness of samples from western beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Very Fine	Fine	Symmetrical	Coarse	Very Coarse
Palmetto Grove					
Lower Beachface		X	X		
Upper Beachface			XX		
Backbeach			XX		
Dune			XX		
High Reef Channel					
Lower Beachface		X			
Upper Beachface			X		
Backbeach		X			
Dune			X		
Bonefish Bay					
Lower Beachface				X	X
Upper Beachface	X			X	
Backbeach	X		X		
Dune		X		X	
Fernandez Bay					
Lower Beachface		X	X	X	
Upper Beachface				XX	
Backbeach			X		
Dune			XX		
Long Bay					
Lower Beachface					XX
Upper Beachface			X		X
Backbeach	X		X		
Dune	X		X		
Grotto Beach					
Lower Beachface		X	X	X	
Upper Beachface			X	X	
Backbeach			X	X	
Dune		X	XX		

Table D5. Kurtosis of samples from western beaches. X = Clark (1988), X = Murphy (2010), X = Hefron & Carew (2014).

Beach	Platykurtic	Mesokurtic	Leptokurtic	Very Leptokurtic
Palmetto Grove				
Lower Beachface		X	X	
Upper Beachface		X	X	
Backbeach		X	X	
Dune		XX		
High Reef Channel				
Lower Beachface			X	
Upper Beachface			X	
Backbeach		X		
Dune			X	
Bonefish Bay				
Lower Beachface	X		X	
Upper Beachface	X	X		
Backbeach	X	X		
Dune		X	X	
Fernandez Bay				
Lower Beachface	X	XX		
Upper Beachface		X	X	
Backbeach		X		
Dune		XX		
Long Bay				
Lower Beachface	X	X		
Upper Beachface	X			X
Backbeach		X	X	
Dune		X	X	
Grotto Beach				
Lower Beachface		XX	X	
Upper Beachface	X	X		
Backbeach	X	X		
Dune		XXX		

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