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Cover image - Patch reef near the wall off Grotto Beach (photo by Lee Florea).

Large boulders on Green Cay, San Salvador Island, The Bahamas

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1. Abstract

In this study, we document the extent and location of large boulders on Green Cay, a small island located along the northwest side of Graham's Harbour on San Salvador island in the Bahamas. During the observation period (2012-2016), very large boulders (> 1 m^3) did not move. Smaller boulders (< 0.1 m^3) did move during storm events in this period. Analyses of Google Earth satellite imagery back to 2003 suggests that the largest boulder (8.5 m^3) that weighs approximately 16 metric tons and appears unweathered was likely moved by the storm surge during the 2004 Hurricane Frances. Boulders appear to be staged and ready to move up the cliff along narrow, wave-cut coves on the northwestern side of the cay. Some boulders are imbricated, show evidence of percussion, rotation, and rounding, and are positioned at the cliff base. Other boulders in the staging ground are cemented to the bedrock, suggesting that the events that transport large boulders to higher elevations may be episodic and separated by enough time for carbonate cementation to permanently cement boulders in the wave-focused coves.

2. Introduction

Anomalously large boulders located inland and above cliffs along coastlines worldwide have been the subject of recent investigations because of the uncertainty in their mode of emplacement (e.g. Jones and Hunter 1992; Hearty 1997; Barbano et al. 2011; Cox et al. 2012). High wave energy is clearly needed to transport megaboulders, boulder ridges, and boulder fields from rocky coastlines to higher inland elevations, but these can be produced by large tropical storms and also by a tsunami (e.g. Nott 2003a, 2003b; Scheffer 2004; Scheffer and Scheffer 2007; Morton et al. 2008, Atwater et al. 2014; Spiske and Halley 2014).

In the Bahamas, the most noted anomalously large boulders are found on the northern part of Eleuthera island (Hearty 1997). Two very large boulders, measuring up to 1000 m^3 and colloquially called the "cow" and the "bull", are found about 20 m above present sea level (Hearty 1997). Kelletat et al. (2004) interpret these and other boulder fields on Eleuthera and Long Island as possible tsunami deposits.

On San Salvador, previous studies have documented the movement of boulders in hurricanes. Walker et al. (2001) and Curran et al. (2001) document movement of boulders at coastal locations along the west side of San Salvador in Hurricane Floyd in 1999. Niemi et al. (2008) documented movement of boulders along the south and southeast side of San Salvador at the Gulf and at Ocean House (see Figure 1 for locations) in Hurricane Frances in 2004. In this paper, we document the boulder field on Green Cay from field surveys conducted between 2012-2016 and analyses of satellite imagery from 2003, 2007, 2014, and 2015.

3. Methods

3.1. Study area

The small offshore island of Green Cay is located approximately 2.5 km northwest of Barker's Point on San Salvador (Figure 1). It measures approximately 600 m long from tip to tip, has a maximum width of 85 m, and covers an area of approximately 39,000 m^2. Satellite imagery (Figure 2) clearly show that Green Cay is part of a series of islands and shoals that form a fringe reef, separating the deeper water of the Atlantic Ocean from the shallow water of Graham's Harbour. The rocks along

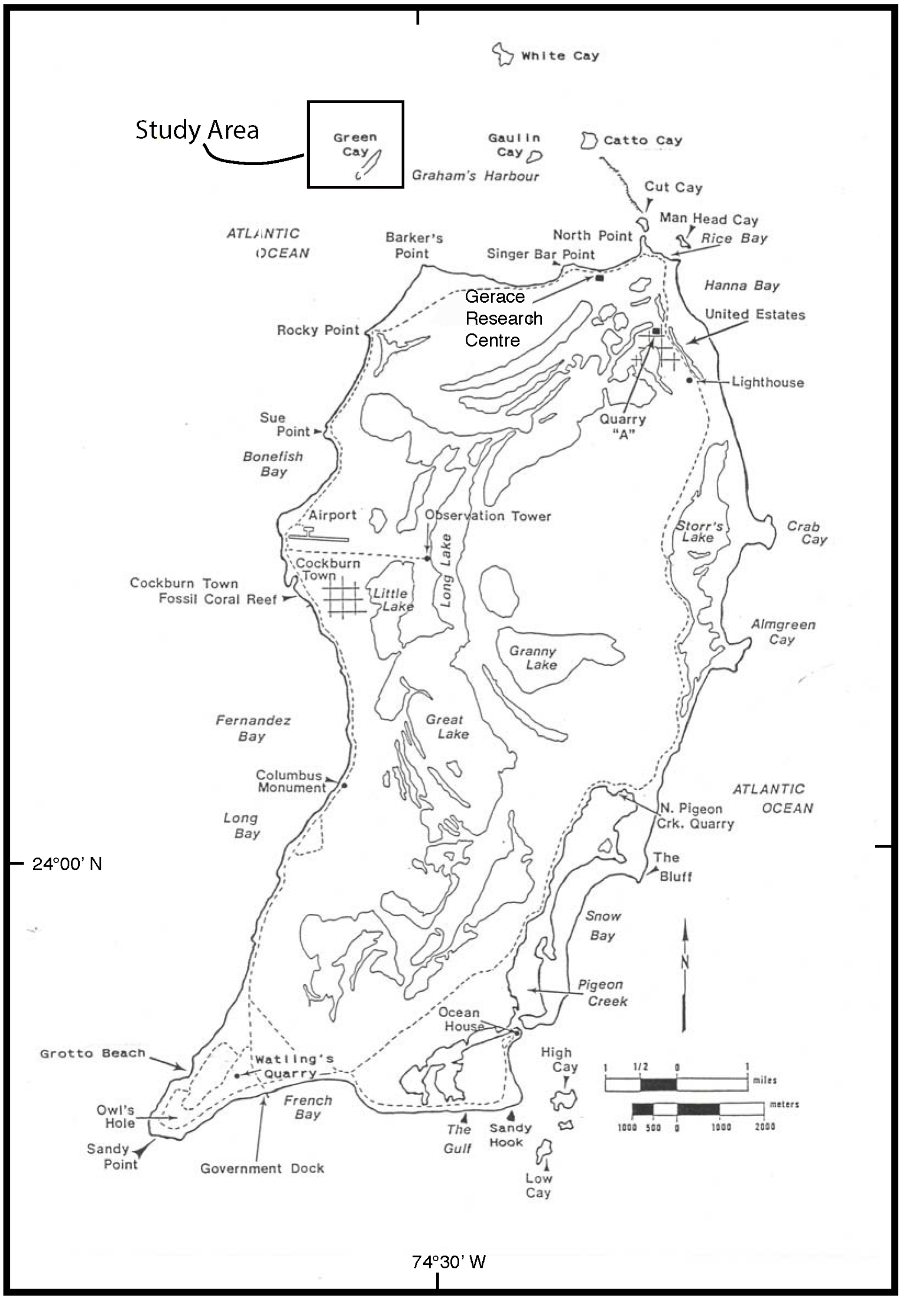

Figure 1: Map of San Salvador island in the Bahamas showing the location of the Green Cay study area (After Mylroie and Carew 2010).

the northeastern side of Graham's Harbour are weakly cemented, Holocene carbonate sand dune ridges of the North Point Member of the Rice Bay formation, whereas the rocks of Green Cay are mapped as undifferentiated Pleistocene (Carew and Mylorie 1995).

The bedrock stratigraphy of Green Cay is exposed along the cliffs that face toward the northwest (Figure 3) and can be divided into two units. The lower rock section is comprised of a cross-bedded, carbonate sandstone (calcarenite). The upper section is a heavily bioturbated calcarenite with plant trace fossils, including root casts and tree trunk molds that are locally called vegemorph (e.g. Carew and Mylorie 2010). Capping the vegemorph unit is either a calcrete crust or remnants of a terra rossa paleosol. Geologically, the rocks are interpreted as a fossilized Pleistocene sand dune (eolianite) that was heavily vegetated and rapidly lithified.

The morphology of Green Cay preserves some of the original Pleistocene sand dune topography. The island has a gentle slope toward the southeast and a northeast-trending ridge that marks the crest of the dune. The northwestern margin of Green Cay is steeper and marked by active cliff retreat erosion. Areas of extensive mass wasting are evident where arcuate-shaped headwall scarps punctuate the ocean-facing island margin. The highly weathered, pitted, and jagged surface of the bedrock is a product of karst weathering.

3.2. Data collection and analysis

We discovered large boulders on Green Cay (Figure 4) during a class trip to the island in 2012, which initiated a program to document the size and monitor the location of the boulders during annual trips to San Salvador in March. Four topographic profiles were measured using the Emery method that records the difference between the horizontal distance and vertical elevation between two points, using poles marked every 2 cm and a line level (Emery 1961). Topographic transects were conducted

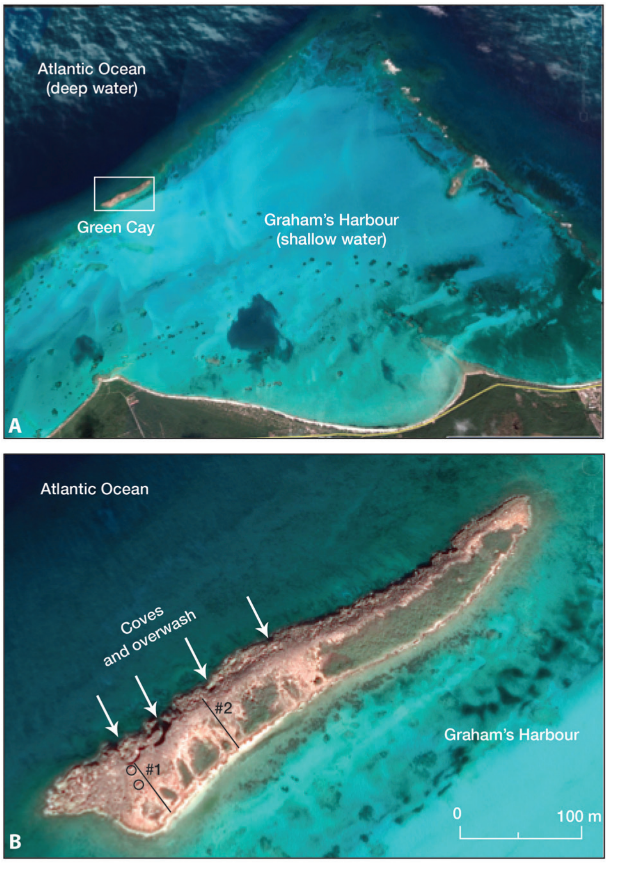

Figure 2: Satellite images of Graham's Harbour and Green Cay from December 30, 2014 (Google Earth 2016, Digital Globe map source). A) Green Cay is part of a line of Pleistocene bedrock ridges that separate the deep water of the Atlantic Ocean from the shallow water of Graham's Harbour along the north side of San Salvador island. B) Image of Green Cay showing the location of two topographic profile transects labeled #1 and #2. Two small circles along profile #1 mark the location of large boulders. Arrows mark the locations of erosional coves, area of focused wave energy, and overwash from storm events.

from sea level on the southeast side of Green Cay to its highest point. Two of these profiles are shown in Figure 5. These data show that the maximum height of Green Cay is 6 m above present sea level on the southwest side of the cay.

The source of the boulders is the erosion of the Pleistocene eolinate bedrock that comprises the island. The northwest ocean side of the island is marked by an irregular shoreline that is

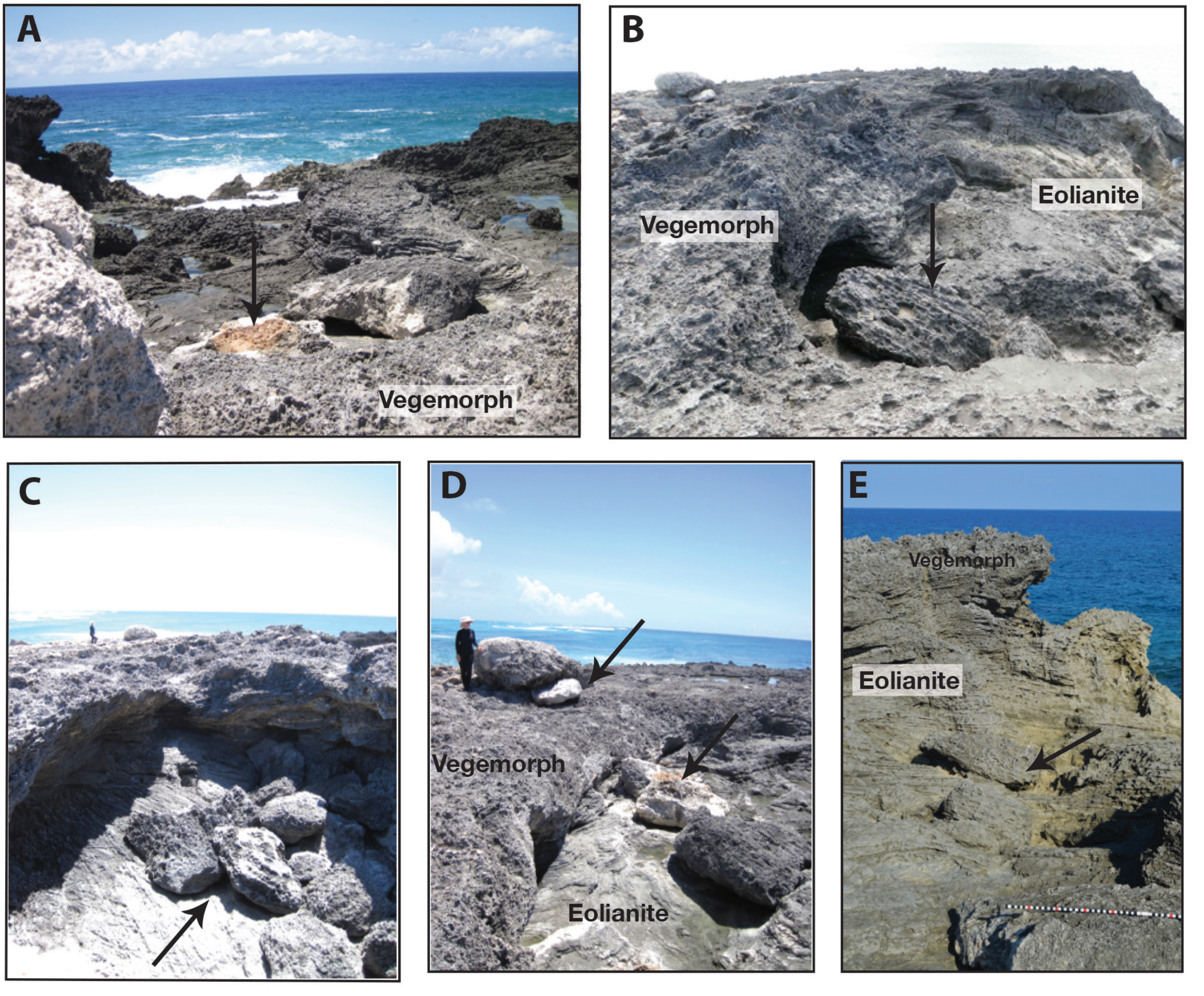

Figure 3: Photographs of the northwestern margin of Green Cay in 2012. The bedrock consists of cross-bedded calcarenite interpreted as a fossil sand dune (eolianite). The upper portion of the bedrock is heavily bioturbated with plant root casts (vegemorph). A) Cliff retreat and erosion along the northwest margin of Green Cay. View toward the northwest and the deep water of the Atlantic Ocean. Arrow points to a location where wave action has eroded a portion of the cliff. B) Some boulders within the erosional cove are cemented in place (arrow). C) Arrow points to imbricated boulders at the base of the cliff. View toward the southeast. D) Newly transported boulders have fresh unweathered surfaces. Locations where rocks have been plucked or percussed are also unweathered. E) The eolinate bedrock is capped by plant root clasts (vegemorph). Boulders of the eolinate are cemented to the bedrock (arrow).

indented with a few pronounced coves (Figure 2B). The two southernmost coves have arcuate headwall scarps of approximately 2 m in height, while a third cove has a scarp that extends the ~5-6 m height of the island and plummets to a deep (>5 m) ocean cove that is a popular cliff jumping location. The shoreline below the crest of the ridge is generally characterized by an approximately 20 m-wide zone of cliff erosion at different elevations. It is unclear at this point whether a distinct wave-cut platform above present sea level is found along this coastland as we have not topographically surveyed this side of the island. As the bedrock is eroded and the cliff collapses, boulders become available for transport. Along the southern cove, where the largest boulders originated, boulders are imbricated beneath the uppermost 2 m high cliff base and appear percussed, rounded, and ready for upward transport (Figure 3). Lower,

Figure 4: Photographs of boulders on the southwestern portion of Green Cay. A) Boulders at the top of the cliff do not have a weathering patina and rest directly on the karst and paleosol surface of the eolinate bedrock. Arrow points to inverted boulder (B14) measuring 3.2 m x 1.9 m x 1.4 m (8.5 m^3) located at the top of the cliff. B) View from the distal portion of the boulder field to the northwest and the cliff edge. Note the line of boulders along this trend. Arrow point to the B14 Boulder. C) Large boulder (B10) transported ~20 m from the cliff edge. Note the two small unweathered rocks that are wedged onto the larger boulder. This area is vegetated with some growth on boulders. D) Wave-cut platform with boulders that have advance to the lower southeastern edge. Also seen is flotsam and jetsam brought onshore from the direction of Graham's Harbour. Remnants of a terra rossa paleosol are evident. Note on scale: The pole is 2 m in length and marked with 2 cm increments. GSA photoscale in figure D.

at a level that is approximately 2-4 m above present sea level, large boulders are cemented to the bedrock. This suggests that the events that transport large boulders to higher elevations may be episodic and separated by enough time for carbonate cementation to permanently cement boulders in the wave-focused coves. Alternatively, they may be the remnants of cliff retreat erosion of a higher wave-cut platform in the Holocene.

The dimensions of boulders located on the southeast, leeward side of Green Cay were measured along two transects where the boulders are the largest during field work in 2012 (Figure 2). The dimensions of these boulders are given in Table 1. Some very large boulders were discovered a significant distance from the cliff face. Profile #1 (Figure 5) documents large boulders at 25 m and 35 m from the cliff front. Boulders on these distal lower slopes have a darker weathering patina, and some have vegetation growing on them. Neither of these pieces of evidence denote a long period of exposure because in

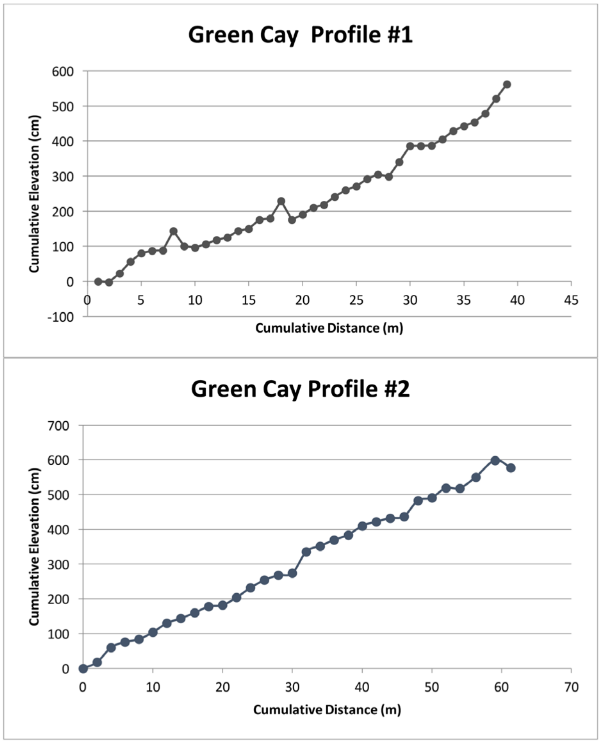

Figure 5: Topographic profiles of Green Cay measured using the Emery method. See Figure 2 for location of transects.

this subtropical environment, vegetation and bedrock weathering occur very rapidly. It was also noted that sand was deposited on the surface near the large boulders and along all of the storm washover locations.

One large boulder (B10; Figure 4C) that measures 4 m x 1.5 m x 1.0 m (6 m^3) has been transported ~20 m down the slope from the cliff edge. This boulder is weathered gray. If we assume a density of limestone in the range of 1.9-2.3 g/cm^3, then the boulder (B10) weighs about 11,400 to 13,800 kg, or about 11 to 14 metric tons. Two smaller, unweathered boulders (Figure 4C) are seen at the base of the B10 boulder in the photograph from 2015. Photographs of the same location in 2012 show only one of these boulders. The largest boulder (B14) measures 3.2 m x 1.9 m x 1.4 m (8.5 m^3). Using the same density as describe above, this boulder weights between 16 and 20 metric tons. The boulder is clearly inverted with the weathered karst surface facing downward and an un-weathered surface on top (Figure 4 A, B).

Comparison between the satellite images of Green Cay from 2003 and 2007 (Figure 6) clearly shows that boulder B14 appears to have been transported during this time period. Boulder B10 is seen in both images. This is corroborated by the observation that B10 is gray with a weathering patina. Additionally, the June 4, 2007 image shows multiple bright white sand that was washed over onto Green Cay in a hurricane (Figure 6).

4. Results and Discussion

The most likely storm to have caused transport of the large boulder B14 on Green Cay, is the 2004 Hurricane Frances. The eye of Hurricane Frances made landfall on the island of San Salvador on September 2, 2004, at 3:00 p.m. (EDT) as a Category 4 hurricane on the Saffir-Simpson Hurricane Scale, with sustained maximum winds of 233 kph (145 mph) (Parnell et al. 2004). Niemi et al. (2008) report a storm surge height of 4.8 to 5.5 along the southeast side of the island based on the elevation of the upper limit of storm flotsam and jetsam. These values are higher than the storm surge of 3.11 m measured along the east side, and 2.65 m on the west side of the island, respectively, by Parnell et al. (2004). Hurricane Frances passed over the island of San Salvador from the southeast toward the northwest, and thus the forward motion of the storm along with the onshore directed winds helped to elevate the storm surge height along the southeast side of the island (e.g. Liu 2004). Here, boulders with a maximum length of 1 m were imbricated and some transported 50 m inland along the rocky coast (Niemi et al. 2008). As the storm moved off San Salvador in the north, winds were from the northeast and caused significant damage to structures in the United Estates town (Figure 1) located on the northeast side of the island (Parnell et al. 2004). Eyewitness accounts (V. Voegeli, pers. comm., 2005) indicate that the storm surge submerged portions of Green Cay. It is likely that these NE winds and storm surge caused the boulder movement. If this

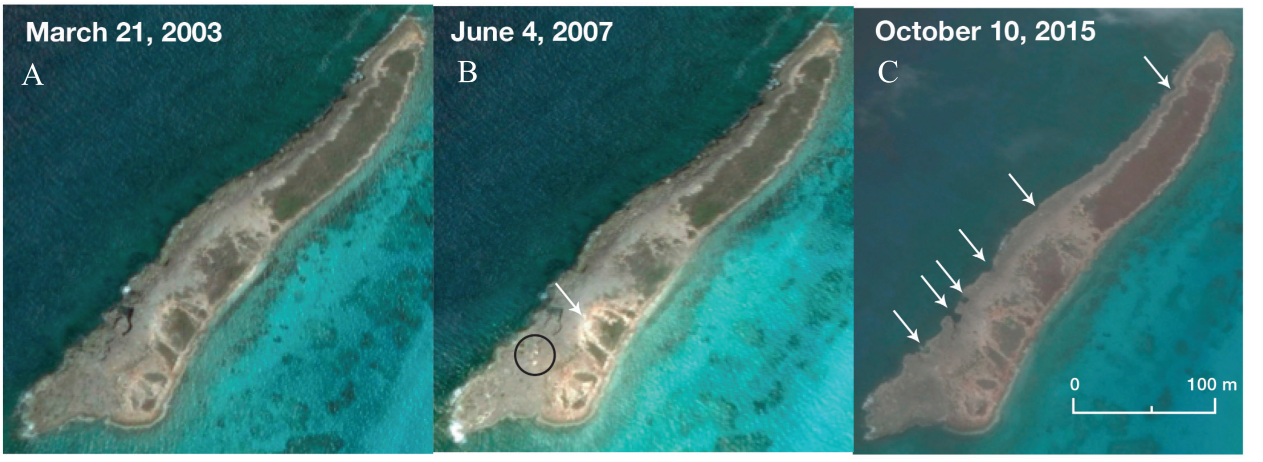

Figure 6: Satellite images of Green Cay in 2003, 2007, and 2015 (Google Earth 2016, Digital Globe map source). A) The image on the left shows the island before the 2004 Hurricane Frances. B) The middle image clearly shows that boulders moved (circle) and sand overwash occurred between 2003 and 2007. The most likely storm to cause these changes is the 2004 Hurricane Frances. C) The image on the right shows Green Cay after the 2015 Hurricane Joaquin. No noticeable large areas of sedimentation seen as bright areas can be discerned. The arrows point to coves where wave action likely focuses energy during storms and is the location of overwash sedimentation and boulder movement.

interpretation is correct, then our profile leveling data suggest that the Hurricane Frances storm surge height was at least 6 m on Green Cay.

Reentrants or coves along the northwestern margin of Green Cay appear to be locations where wave energy is likely focused during storms. Boulders derived from erosion of the shoreline cliff are staged at various levels of the collapsed margin. Some boulders are imbricated below the uppermost, 2 m high cliff (Figure 3). Movement of these boulders in the coves helps accelerate erosion by undercutting the cliff thus ultimately causing bedrock collapse and cliff retreat. The coves must create wave surges that help to lift boulders and transport them to the top of the island. As the northeast side of Green Cay has few of these coves, it explains why this area is still vegetated and has little evidence of storm washover.

We have made field observations of the Green Cay boulder field between 2012-2016 and have noted that the large boulders did not move. Smaller boulders are clearly documented to have moved in storms.

Large boulders have been documented to move in hurricanes at other locations. Scheffers and Scheffers (2006) reported the transport of boulders in the 2004 Hurricane Ivan on Bonaire Island in the Caribbean. Wave swells of the storm surge in this hurricane are reported to have reached a peak high of 12 m with water fountains shooting to 30 m high. Boulders as large as 4 to 6 tons were transported more than 50 m inland to an elevation of 6 m (Scheffers and Scheffers 2006). The largest boulder which weighed about 25 tons was moved only several meters. These authors note that the slab-shaped boulders moved without rolling and either slid or glided landward in sheet flow. Other slabs as long as 6 m were ripped up from the 5 m high reef terrace and found inverted some 10s of meters inland.

Satellite images of Green Cay after the 2015 Hurricane Joaquin show no noticeable overwash sedimentation or boulder movement (Figure 6). This is surprising given the unprecedented movement of a boulder field that occurred on the south side of San Salvador in 2015 with the landfall of Hurricane Joaquin as documented, for example, in Preisberga et al. (2016). It is likely that the specific barometric pressure, wind speed, direction, and duration, and the path of the eyewall of a hurricane plays a major role in the nature of the storm surge and its ability to transport boulders.

Table 1: Measurement of the dimensions of boulders found on Green Cay in 2012.

Boulder No.	Position	Length (m)	Width (m)	Height (m)	Volume (m^2)
A1	distal	0.8	0.5	0.3	0.1
A2	distal	0.7	0.45	0.35	0.1
A3	top of cove cliff	1.05	0.95	0.6	0.6
A4	top of cove cliff	1.3	0.9	0.4	0.5
A5	boulder in cove	1.6	1.4	0.65	1.5
B1	35 m from cliff	1.2	1.1	0.6	0.8
B2	35 m from cliff	0.9	0.65	0.3	0.2
B3	35 m from cliff	1.9	1.7	0.6	1.9
B4	35 m from cliff	1.8	0.85	0.8	1.2
B5	35 m from cliff	0.9	0.6	0.4	0.2
B6	35 m from cliff	1.3	0.7	0.3	0.3
B7	35 m from cliff	0.2	0.2	0.2	0.01
B8	35 m from cliff	0.4	0.3	0.2	0.02
B9	35 m from cliff	0.6	0.5	0.2	0.1
B10	20 m from cliff	4.0	1.5	1.0	6.0
B11	20 m from cliff	0.2	0.2	0.2	0.01
B12	20 m from cliff	1.9	1.1	0.9	1.9
B13	20 m from cliff	1.2	0.6	0.2	0.1
B14	top of cove cliff	3.2	1.9	1.4	8.5
B15	boulder in cove	1.5	0.85	0.4	0.5
B16	boulder in cove	1.9	0.65	0.6	0.8
B17	boulder in cove	2.2	1.5	0.95	3.1
B18	boulder in cove	2.0	1.7	0.85	2.9

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