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AERIAL PHOTOGRAPHY OF COASTAL EROSION AND LARGE BOULDER TRANSPORT FROM HURRICANE MATTHEW (2016) ALONG CLIFTON BEACH, NEW PROVIDENCE ISLAND, THE BAHAMAS

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ABSTRACT

In October 2016, Hurricane Matthew passed as a Category 4 storm across western New Providence island in The Bahamas. A comparison of satellite and high-resolution aerial imagery along with field observations and boulder measurements allowed for damage analysis of Clifton Heritage Park and surrounding areas. At Flipper Beach in the Park, storm surge deposited significant amounts of large debris well inland in an area previously cleared of vegetation. Nearby locations not cleared of vegetation arrested inland inundation of storm surge debris. Loyalist period drystone walls also were unexpectedly resistant to storm surge damage. At the nearby Pirate Stairs, evidence of storm surge overwash included moved boulders and sea wrack deposited atop an approximately 6-m-high cliff. This is in stark contrast to the reported storm surge of 2.5 m. The measurements and locations of transported boulders, including a 6 m^3 boulder and the large block which had formerly formed the lintel over the Pirate Stairs, suggest that the method of movement was sliding and/or hydroplaning. Local focusing of wave energy is likely the mechanism for high storm surge and boulder movement.

INTRODUCTION

In the Caribbean and The Bahamas, hurricanes have been a threat with occasional devastating results during the past five centuries (e.g. Neuman et al., 1987; Shaklee, 1997). Hurricanes have also been an important factor in shaping the environment, geography, and even the physical shape of the islands (Shaklee, 1997; Sealey, 2006). As the islands do not have large amounts of topographic relief, they are particularly vulnerable to storm surge. Furthermore, due to their generally thin soils, the islands are vulnerable to wind damage to vegetation, as evidenced by our own observations of uprooted trees.

In March 2017, we had the opportunity to conduct field research on New Providence Island. The damage to the island from Hurricane Matthew was quite evident. We examined two areas along the western coast of New Providence Island–Flipper Beach at Clifton Heritage Park, and the famous Pirate Stairs near Clifton Pier (Figure 1). Clifton Pier is a small port built on the west side of New Providence island. Deep oceanic water close to the island margin allows tankers to offload fuel for the nearby Clifton Pier oil power plant. In this study we collected high-resolution aerial images with a photographic drone to document the damage caused by Hurricane Matthew along this section of the coastline. We photographed and measured boulders that had moved as a result of the hurricane; in most cases their original position was discernable. This study of the movement of boulders by hurricane storm surge is important because identifying these shoreline boulder deposits and characterizing them is critical to modeling the potential energy of storms, as well as understanding the processes forming coastal topography in The Bahamas. Drone aerial imagery provides high-resolution imaging of hurricane damage fields and

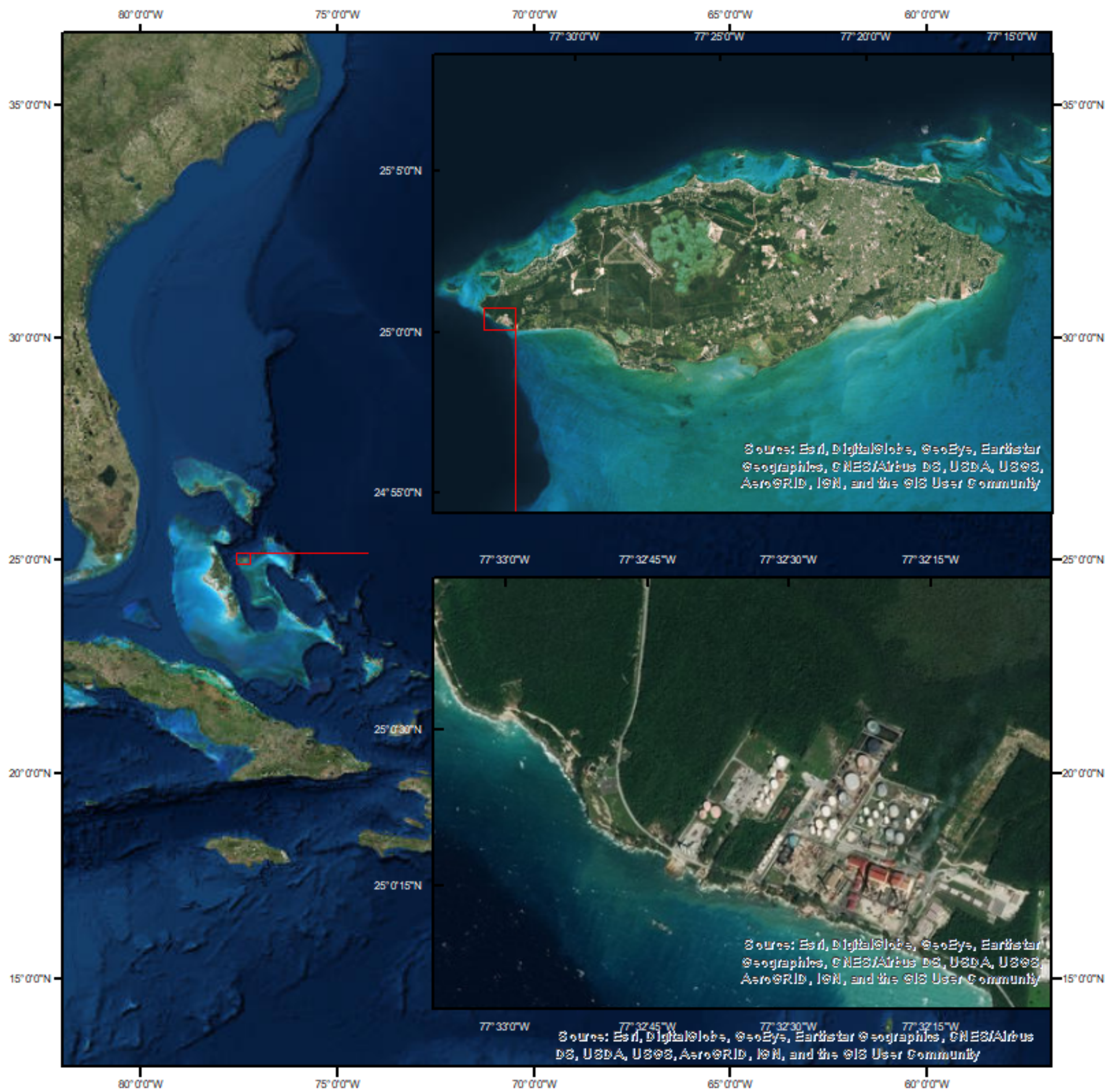

Figure 1: Location of the study area on the west side of New Providence Island in The Bahamas.

potentially provides a baseline for future monitoring of the coastal environment and identification of sites of inundation vulnerability.

HURRICANE MATTHEW

Hurricane Matthew began as a tropical storm that formed about 28 km north-northwest of Barbados on September 28, 2016 (Figure 2). The storm intensified and developed into a tropical cyclone, reaching a peak intensity of Saffir-Simpson Category 5 on October 1. This occurred when the storm was located less than 150 km north of Punta Gallinas, Colombia. This makes Matthew the southernmost Category 5 hurricane recorded in the Atlantic Basin (Stewart, 2017). Hurricane Matthew began to weaken as it tracked slightly west of north. It crossed the western end of Haiti as a Category 4 hurricane and weakened to Category 3 as it crossed the eastern end of Cuba. Matthews's track continued through the middle of the Bahamian archipelago, re-strengthening to Category 4 as it moved along the deep water of the Tongue of the Ocean between the islands of Andros and New Providence causing severe flooding on New

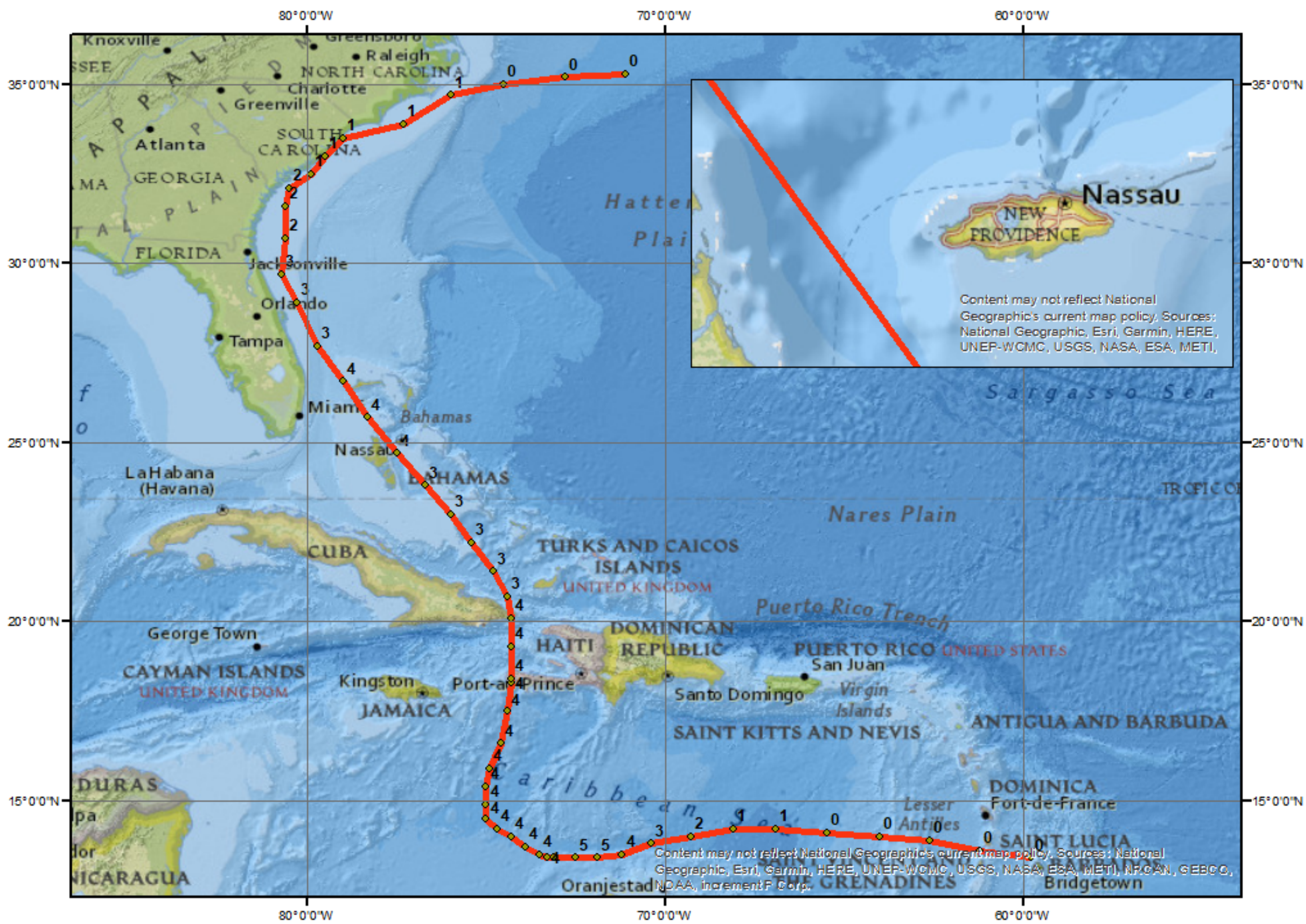

Figure 2: Hurricane Matthew storm track between September 29, 2016 to October 9, 2016. Numbers indicate the intensity of the storm on the Saffir-Simpson scale.

Providence Island (Stewart, 2017). It then weakened again as it moved north, passing over Grand Bahama Island as a Category 3 hurricane on October 7. It then followed the east coast of the United States, as for north as South Carolina, before turning east and gradually dissipating on October 9.

On October 6, 2016, Matthews's eyewall passed directly over the far western end of New Providence Island, the location of Clifton Heritage Park. At that time, Matthew was a Category 4 hurricane with wind speeds measured at ca. 230 kph. According to the US National Oceanic and Atmospheric Administration (NOAA) Hurricane Matthew report (Stewart, 2017), Matthew had a recorded storm surge of 2.5 m along the southern coast of New Providence. The rainfall from this hurricane varied sharply from as little as 75 mm to as much as 500 mm, eastern to western archipelago, respectively (Stewart, 2017).

CULTURAL HISTORY

The Bahamas has a long cultural history. From the Lucayans who arrived between 500 and 800 CE (Craton and Saunders, 1999), serving as a haven for pirates through the 17th century, to the settlement of American Loyalists in the late 18th century (Caviedes, 1991), and today's citizens, all have had to and continue to contend with hurricanes.

Today's Bahamians also seek to record and display the long history of settlement and the unique culture created here. In terms of public policy, this included a number of different legislative acts, beginning with the National Trust Act of 1959, and including the Abandoned Wreck Act of 1965, the Public Records Act of 1971 (which led to the Department of Archives being designated as the agency responsible for cultural resources) and the Antiquities, Monuments and Museums Act of 1998 (Siegel and Righter, 2011). Archaeologically, first steps in this direction were of the classificatory-descriptive paradigm of archaeology, and in general, Bahamian archaeology has followed the succession of theoretical models common to North American archaeology (Berman, 2015). Today, however, a trend towards not only scientific exploration but also explication to the public at large is becoming more prominent (Siegel and Righter, 2011). A centerpiece of this historic preservation and education effort is the Clifton Heritage Park on New Providence Island. The park, which opened in 2009 after a lengthy and controversial battle between real estate developers and historic preservationists (Siegel and Righter, 2011), serves as an important monument both in itself, and as a symbol for success of cultural resource management in The Bahamas (Siegel and Righter, 2011).

The Park today occupies the area of the former Whylly and Johnston plantations, located on the western point of New Providence Island, and features the ruins of the plantations, as well as reconstructions of the slave quarters (Siegel and Righter, 2011).

Not as obtrusive, but more important to our study, are the many drystone field walls in the area. These walls, built both as markers of the edges of agricultural fields and of property boundaries, are ubiquitous throughout those Islands of the Bahamas settled by British Loyalists that fled the new United States after the American War of Independence. In addition to their obvious functional role, they are also the almost inevitable result of the need to clear rocks from the fields for agriculture.

Approximately 400 m southeast of Flipper Beach and just north of the Clifton Pier lie the Pirate Stairs. This is a relatively well-known tourist attraction on New Providence and is a stop in the New Providence Island field trip guide (Mylroie et al., 2012). It consists of a narrow (<1 m in places) stairway cut into the Pleistocene bedrock of the island, leading from the top of an approximately 6.5 m cliff to a wave-cut platform at sea level. Prior to Hurricane Matthew, a large boulder cut into a rough rectangle formed a lintel over the stairs. While known as the Pirate Stairs, and with local legend having nefarious buccaneers carrying chests laden with doubloons up and down this hidden stairway, it is much more likely it is associated with the Loyalist period, and served as a landing point for passengers or small cargo (the stairway is narrow) for the nearby plantations. It is possible that it does predate the loyalist plantations, but due to the low population of the island during the 17th century, it is unlikely that pirates would have found it necessary to create such an architectural feature so far from the main settlement of the island. After all, when Woodes Rogers sailed into Nassau in 1718 as the first Royal Governor of the Bahamas, and proclaimed a general amnesty for pirates who would reform, he only encountered 500-600 inhabitants on the island (not counting 'about 4 score who made their escape') (Cash et al., 1991). On the other hand, the earliest map available of New Providence Island (Figure 3), *An exact draught of the island of New Providence one of the Bahama Islands in the West Indies,* (dated around 1750) contains the somewhat mysterious notation "Rogers" not far from the location of the Pirate Stairs, which does suggest some human activity of some kind there.

DATA ACQUISITION

This study required two separate methods. First, pedestrian survey and direct observation and measurement of dislodged and moved boulders. Second, collection and analysis of aerial and satellite imagery of the two locations using a DJI Phantom 3 Quadcopter mounted with 12 Megapixel, 4K video camera with geo-referencing to produce orthophoto mosiacs. For this project, a programmed flight path obtained photos at 50 m of elevation with 60% overlapping. Agisoft Photoscan Professional produced orthophoto mosaics for this project; software versions 1.2.4 build 2399. Using Google Earth historic

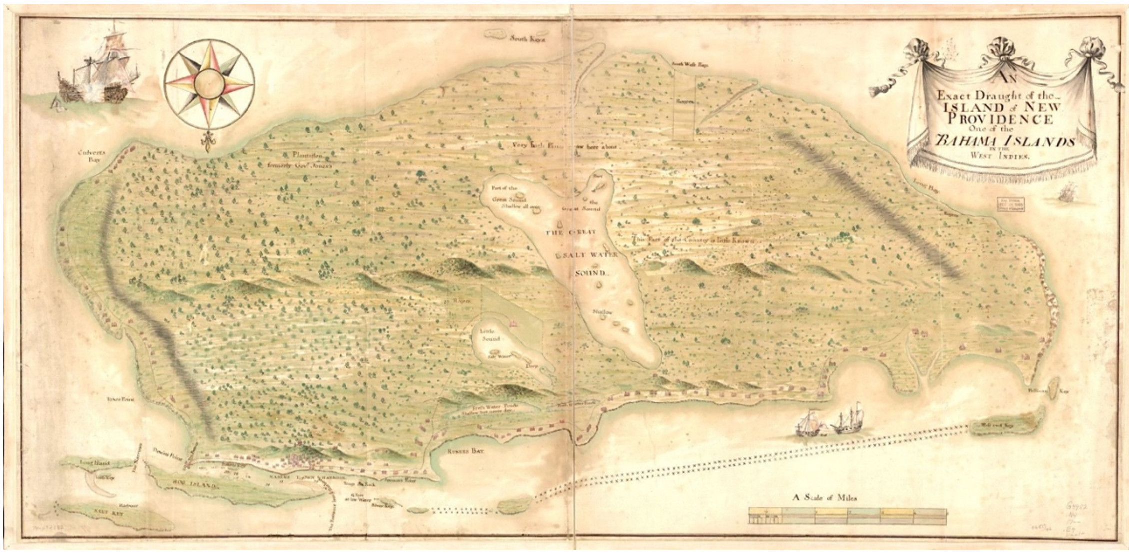

Figure 3: An Exact Draught of the Island of New Providence One of the Bahama Islands. Variously dated between 1700-1750. Note inverted orientation (North is down).

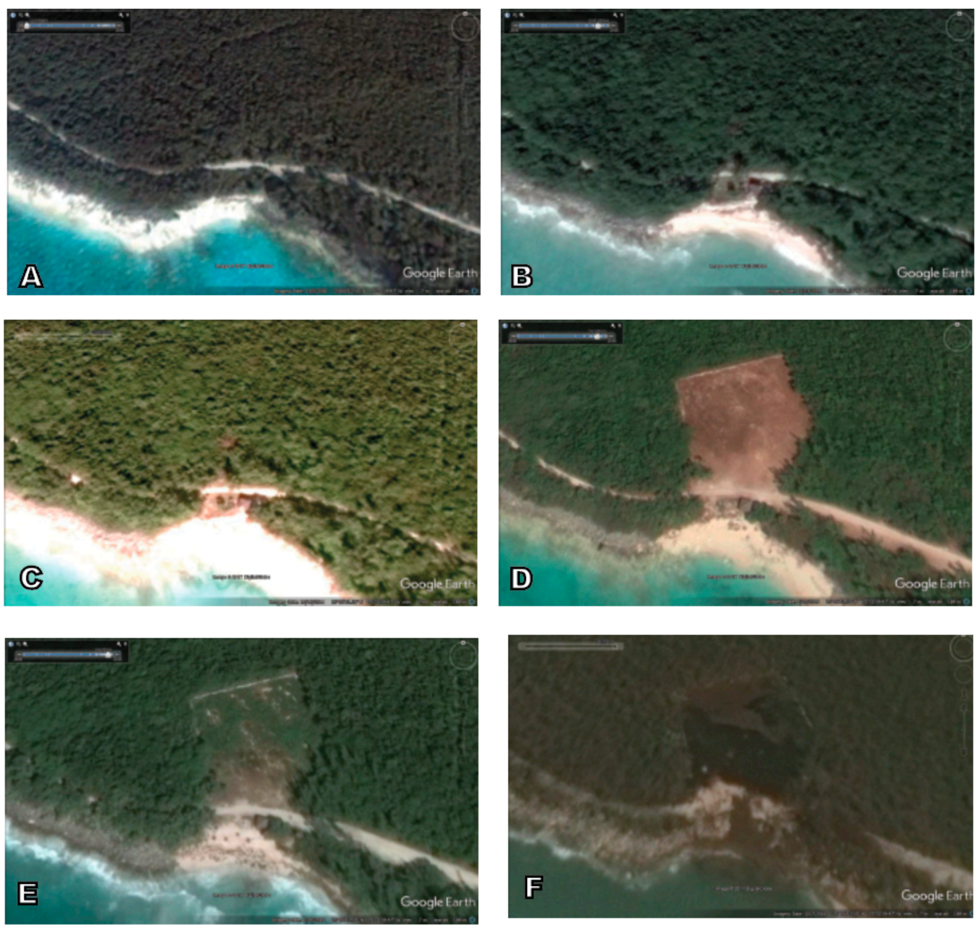

Figure 4: Google Earth images of the Flipper beach area, and the cleared area inland, bounded by Loyalist drystone walls. Dates: A) 11/5/2000, B) 10/31/2014, C) 12/16/2014, D) 2/13/2015, E) 1/16/2016 F) 10/7/2016. It is possible to see the clearance, regrowth, and, in image F standing water, as the image was taken the day after Hurricane Matthew passed.

vegetation to post-Matthew vegetation loss, pre-existing boulders and inundation related transport, and changes in coastal morphology.

OBSERVED HURRICANE DAMAGE

Flipper Beach, a popular snorkeling location for tourists, is located within Clifton Heritage Park on the western end of New Providence. In addition to a small beach with an approximately 25-m-long sandy shoreline, there was a small cabana or shelter just above the crest of the beach dune before Hurricane Matthew. The topography of Flipper Beach is very flat, with only a few meters rise in elevation from the beach to the northern end of the cleared square north of shore. Our analysis of the Google Earth archived images for this area from 2014 to 2016 showed (Figure 4) that an area to the north of the beach approximately 55 m^2 cleared of vegetation between December 2014 and February 2015. The fresh soil visible in the 2015 image suggests that it was a recent clearing at that time. A fortuitous satellite image taken October 7, 2016, a day after the hurricane, reveals this area succumbed to storm surge inundation and ocean water remained standing in this area.

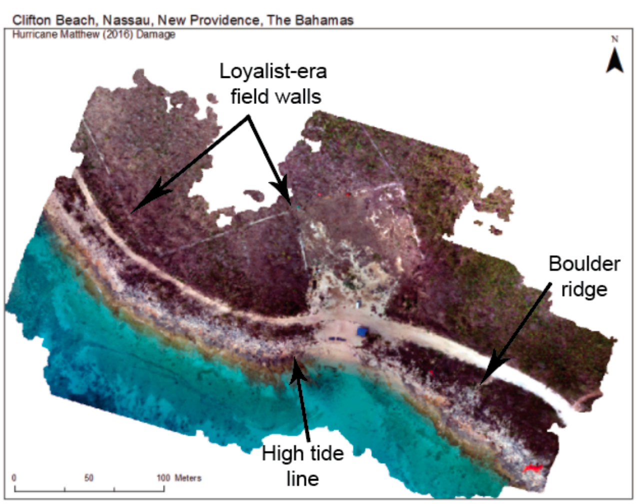

Figure 5: Drone image of Flipper Beach showing the area inundated by storm surge in Hurricane Matthew and Loyalist-era field walls. Beachrock present along the coast has broken into boulders that have been transported above the high tide line.

From field acquired orthophoto mosaics (Figure 5), field walls are visible. These walls, normally covered with vegetation such that only faint hints can be seen on aerial imagery now lay exposed clearly in imagery. Debris is piled against these field walls and surrounding trees (Figure 6). The cabana/beach shelter was deposited in the northwestern corner in a pile of debris. In many places the soil washed away, leaving large patches of bare bedrock. Interestingly, along the shoreline, to either side of the sand beach (which had also suffered severe erosion), imbricated boulders lined the edges of the vegetated edge of the beach dune. Aerial imagery (Figure 5) shows the boulder ridge extends along the coast.

At the nearby Pirate Stairs location (Figure 7), the topography has changed to a steep cliff exposure. Hand cut from bedrock, The Pirate Stairs create a path from a wave-cut platform at sea level about 6 m from the low tide level up to the top of the cliff (Figure 8). This cliff exposes the late Pleistocene rocks of the Cockburn Town Member of the Grotto Beach Formation topped by a *terra rossa* paleosol (Mylroie et al., 2012). The bedrock is a calcarenite with herringbone cross stratification and tabular and planar cross-beds which deposited in a subtidal to intertidal environment. Iron-rich red caliche line the vertical and horizontal fractures in the bedrock (Figure 8). These fractures form weaknesses in the bedrock that facilitate collapse and cliff retreat in storms.

When we visited this site, it was immediately clear that storm surge had affected this area along the cliff front and at the top of the cliff. Based on the exposed white unweathered color of the cliff face, one section of the cliff had clearly collapsed to the shallow water below. The erosional retreat of the cliff left smaller boulders dislodged at the top of the section. Analysis of the high-resolution drone imagery also shows numerous very large blocks submerged near the cliff edge (Figure 7).

Along the top of the cliff, Australian pine trees (*Casuarinas* sp.*)* lay uprooted and large boulders (up to 6 m^3) moved inland. Sea wrack, mostly brown seaweed (*Sargassum* sp.) became trapped in a fence toppled by boulders that subsequently rest on top of it (Figure 9 and 10). Boulders transported

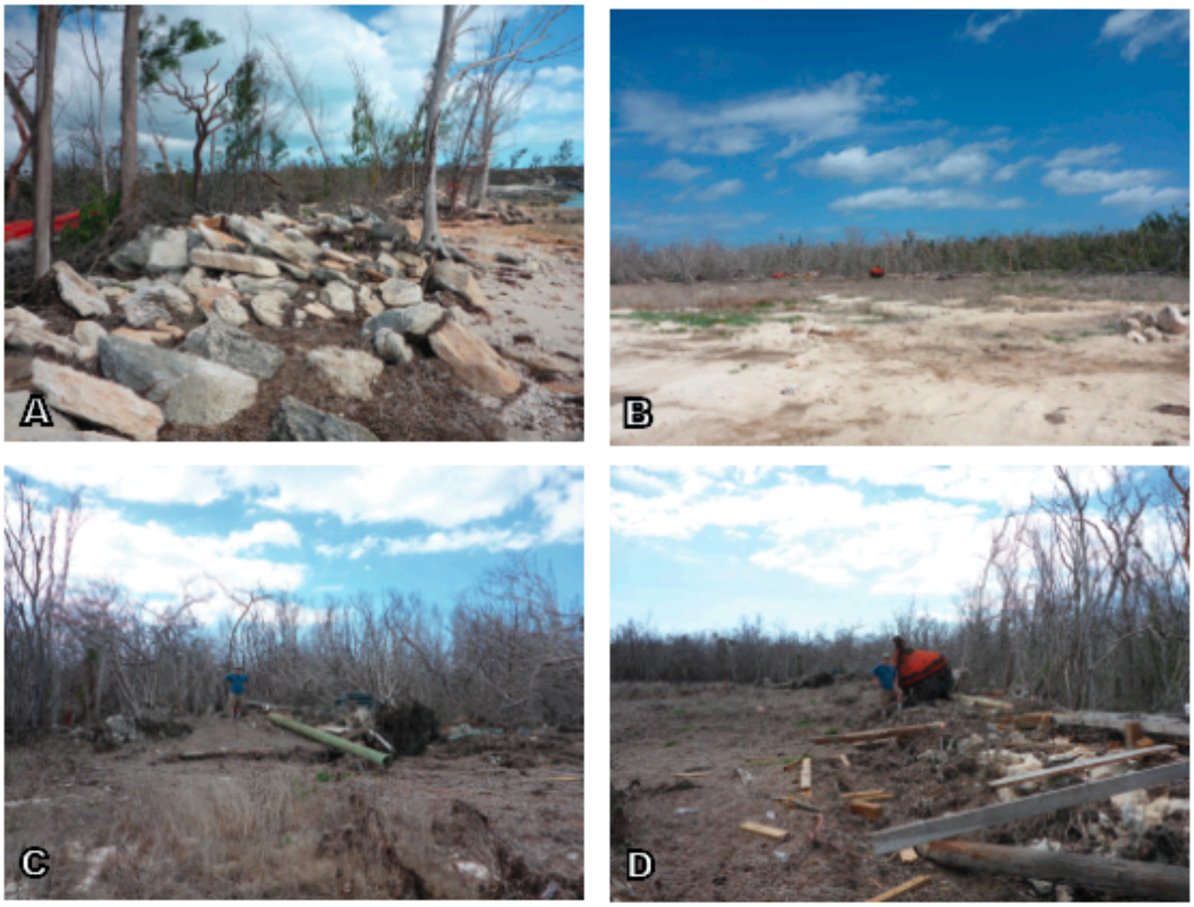

Figure 6: A) Imbricated boulders just east of Flipper Beach. B) Cleared area inland of the beach, post hurricane Matthew, showing bare bedrock patches. C) Remains of beach house/cabana in western corner of the cleared quadrangle (author for scale). D) Large navigation buoy against drystone wall on northern edge of cleared quadrangle (author for scale) (buoy also visible in Figures 6 and 7 B).

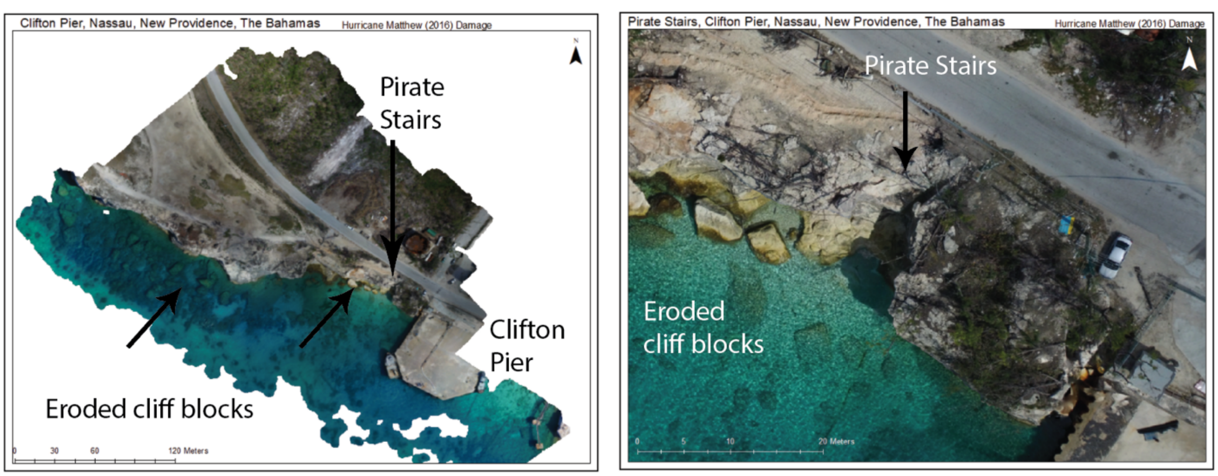

Figure 7: Drone imagery of the area around Clifton Pier and the Pirate Stairs showing large blocks of bedrock that have been eroded from the cliff. Hurricane Matthew storm surge transported debris to the top of the 6.5-m-high cliff.

Figure 8: The Pirate Stairs near Clifton Pier showing damage from Hurricane Matthew. A) Photograph from June 2012, and B) Photograph from March 2017. Note the fence that once stood at the edge of the cliff and around the stairs in the 2012 image and the broken and transported lintel block.

by storm surge is evidenced by *Sargassum* found under boulders themselves. This is a strong argument against its arrival by some other means than storm surge. At this site, we recorded dimensions and orientation of several large boulders that showed clear evidence of recent movement. Table 1 provides measurements of some of the largest boulders. While there are many large boulders that moved inland by water at this site, there are two that stand out. First, the boulder that previously served as a lintel over the narrow stairway has broken off and shifted over on top of the broken base of the steel post that previously held the fence along the edge of the cliff. Other boulders are now sitting on other parts of this fence as well. Second is a large slab of concrete. We hypothesize that it was excess concrete out of a cement truck, possibly during construction of the fence. In any case this concrete formed a rough lens shape about 2 m by 3 m, but only about 20-30 cm thick (~1.8 m^3). It originally formed in a slight depression in the bare bedrock. Based on marks in the bedrock, this slab slid about 2 m inland requiring very high wave energy.

Boulder	**Long axis**	**Short axis**	**Thickness**	**Notes**
A	190	110	65	
B	120	85	35	
C	120	105	30	on top of fence
D	105	90	25	
E	310	230	85	upside down
F	320	130	60	
G	130	110	60	
H	185	165	55	
I	190	130	30	

Table 1: Boulders transported by storm surge

Figure 9: A) Cliff showing bedrock exposure immediately to the west of the Pirate Stairs. B) Very large boulder dislodged form top edge of approximately 6-m-high cliff, west of the Pirate Stairs (researcher for scale). Note the red caliche that lines the vertical and horizontal fracture surfaces. The unweathered surface of the cliff and boulders indicates recent collapse and movement. C) Boulder deposited on top of flattened fence. Also note uprooted Casuarinas Sp. D) Boulder moved inland and uprooted Casuarinas sp. E) Boulder deposited on top of remains of fence with uprooted tree and sea wrack. F) Waste concrete slab apparently lifted and slide inland. It's original location in approximately where the "F" is located on the image.

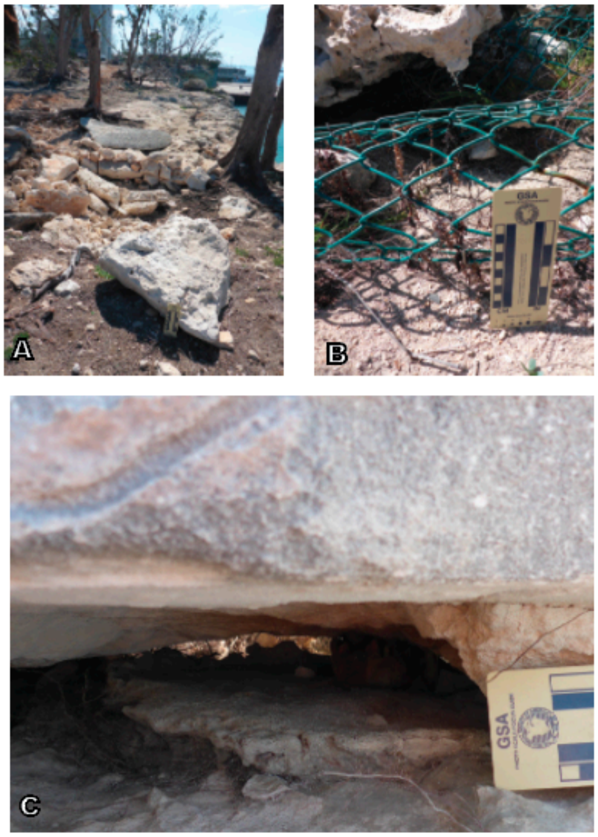

Figure 10: A) Small boulder apparently moved by rolling. B) Sea wrack entangled in the fallen fence. One of the boulders now resting atop the fence is visible at top of image. C) This is the very large slab of rock that previously formed the lintel over the Pirate Stairs. It has been shifted up, inland, and slightly to the west, and now rests directly atop the sheared off base of one of the metal fence posts (visible in the crevice). This slab is visible in Figure 8 A, as it originally rested, and the corner of it is visible on the right edge of Figure 8 B, in its post Hurricane Matthew location.

DISCUSSION AND CONCLUSIONS

Our observations of the damage from Hurricane Matthew at these two sites located along the western shore of New Providence island provide evidence for three conclusions. First, it is not possible to overstate the power of vegetation in resisting storm surge inundation. Even when that vegetation is later killed by the saltwater contamination, it holds soil, and resists even the battering of large boulders, shown by the difference in the effects on the cleared area at Flipper Beach and the surrounding vegetated areas. It is likely that the very common high peaked ridge of imbricated boulders has its origin in boulders coming to rest against even a relatively small area of vegetation. It is also curious that the drystone field walls resisted the inundation so well. It may well be the presence of the overgrowing vegetation, and its ingrowing roots that supports the field walls against the water's erosion. However, we hypothesize that in both cases–the shoreline vegetation and the field walls, it is only necessary that they stop the first few boulders or bits of flotsam and jetsam. As boulders imbricate, and debris accumulates, they are effectively armoring themselves against further erosion.

Second, at the Pirate Stairs, the boulders did not roll. In general, they are flattish slabs of bedrock, similar to an airfoil, that have been plucked loose and slid along. We hypothesize that the mechanism for this is that water is \forced under them and lifts them on a cushion of water as they slide. This is particularly evident for the concrete described above. Also, the NOAA report on Hurricane Matthew records a 2.5 m storm surge on New Providence (Stewart, 2017). At the Pirate Stairs, we have clear evidence of boulder movement and flotsam and jetsam at the top of an approximately 6-m-high cliff. The reason for this discrepancy is likely an offshore storm surge focusing mechanism, probably the deep water immediately offshore.

Third, even lacking prior data, it was possible to determine direction, and distance of movement of the boulders at the Pirate Stairs through observation (and application of the law of superposition). This direct observation and measurement has proven very effective, even lacking clear pre- and post-event images. However, the combination of historic satellite images with our high resolution aerial photomosaic has also provided a powerful tool for quantifying the effects of events such as hurricanes.

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