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Front Cover: Rice Bay Formation, looking southwest along Grotto Beach. Photograph by Sandy Voegeli.

Back Cover: Dr. John Milliman, The College of William and Mary. Keynote Speaker for the 13th Symposium. Photograph by Sandy Voegeli.

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IMPACT OF THE SEPTEMBER 2, 2004 HURRICANE FRANCES ON THE COASTAL ENVIRONMENT OF SAN SALVADOR ISLAND, THE BAHAMAS

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ABSTRACT

The impact of Hurricane Frances that directly hit San Salvador, Bahamas as a Category 3 hurricane on September 2, 2004 was investigated from satellite imagery and field mapping in March 2005. Landsat 7 Enhanced Thematic Mapper images of San Salvador from before and after the storm were analyzed to determine the storm surge impact and identify areas for field research. Our main focus was documenting storm surge deposits and beach accretion and erosion processes on the southeastern coast of the island from Dim Bay to Sandy Hook. These areas clearly show a significant reworking of sand and loss of vegetation. Other areas of the island also showed significant changes in beaches, but were not studied at this time. The storm surge from Hurricane Frances ripped up large slabs of beachrock (up to 1 m^2) along the southeast beaches, Sandy Hook, and the Gulf, transported them inland, and deposited them in seaward-dipping, imbricated piles. The mangrove vegetation line retreat on Sandy Hook was measured as approximately 40 m. The adjacent beach to the south showed signs of a 30 m accretion. A maximum height of the storm surge of 4.8 m, 4.9 m, and 5.5 m was measured by leveling to the upward limit of flotsam and jetsam deposited by Hurricane Frances at three localities—the south end of Storr's Lake and two sites near the tombolo called 'The Thumb'—along the eastern shore of San Salvador. Evidence of Frances and other storms were also found in stratified trash deposits south of and around The Thumb. A 1.7-m-thick section was measured that showed 80 cm of aeolian sand burying a 40 cm thick horizon of stratified trash. At this location Hurricane Frances deposits were found at higher elevations and further inland. These data indicate that the Hurricane Frances storm surge was likely more intense than the previous hurricanes that hit the island during the 1990's. The storm surge washed over the coastal barrier, defoliated a large tract of land, and deposited a blanket of sand and other debris into Salt Pond and Storr's Lake from the east and Pigeon Creek from the south. Based on a line of organic debris and defoliated vegetation marking a high water mark, either high winds or the storm surge from Hurricane Frances caused Pigeon Creek tidal estuary to overwash its northwest and north shore. The damage data and storm surge height measurements for Hurricane Frances correspond to a Category 4 hurricane. The enhanced storm surge height measured along the southeast side of San Salvador is likely the combination of the onshore-directed winds with the forward movement of the storm center as the hurricane eyewall made landfall on the island.

INTRODUCTION

The 2004 Atlantic hurricane season was one of the most active on record. Five hurricanes made landfall in the United States with an unprecedented four hurricanes (Charley, Frances, Ivan, Jeanne) hitting Florida (NCDC, 2004). This was the first time since 1886 that a state had been struck by four hurricanes in one season (NCDC, 2004). By its end the 2004 hurricane season was the most costly U.S. hurricane season on record. This record was eclipsed by the devastating and

record-breaking 2005 hurricane season. The 2005 Atlantic hurricane season is noted for the most named storms and the most hurricanes recorded in a single season (NCDC, 2006). Four hurricanes (Emily, Katrina, Rita, and Wilma) were classified as Category 5 hurricanes (NCDC, 2006).

Of the storms that developed in the 2004 and 2005 hurricane seasons, Hurricane Frances was the only storm to make landfall on San Salvador and to cause significant damage (Figure 1). San Salvador is a small outer island of the Bahamas Archipelago located about 640 km southeast of Florida at 24° N, 74.5°W. 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 (Table 1) with sustained maximum winds of 233 kilometers per hour (kmph; 126 knots, kts; 145 miles per hour, mph) (Parnell et al., 2004).

The following information about Hurricane Frances is summarized from the National Hurricane Center's Tropical Cyclone Report (Beven, 2004). Hurricane Frances began as a tropical wave off the coast of Africa on August 21, 2004, and quickly developed on August 24 to a tropical storm status. By August 26, 2004, the storm was named a hurricane. On August 31, 2004, Hurricane Frances reached peak intensity of a Category 4 less 36 hours before making landfall on San Salvador. The air pressure low and wind speed maximum for the storm reached a double peak (Figs. 1C and 1D). The first peak intensity period was during the night of August 31st to September 1st when the lowest central air pressure was estimated by research flights at 934 millibars (mb). The second peak intensity period with low pressure and high winds occurred on September 2nd. Graphs of the best track for the storm's pressure and wind speed show that the hurricane was close to its maximum by midday on September 2, 2004, and then began to lose intensity.

The Gerace Research Centre on the north side of the island at Graham's Harbor recorded the lowest pressure value from a land station of 954 mb before the instrument malfunctioned (Parnell *et al.*, 2004). Rainfall from Hurricane Frances on San Salvador was recorded as 5.47 inches (139 mm; Beven, 2004).

The post-Hurricane Frances survey of Parnell et al. (2004) conducted between six and ten days after the storm showed that the heaviest damage to structures was reported in the United Estates settlement on the northeast side of the island. Structures on the west side of the island in the town of Cockburn and near the airport were also damaged (Parnell et al., 2004). Hurricane Frances storm surge heights were reported to be 3.11 m along the east shore, 2.65 m at the seawall in Fernandez Bay, and 3.75 to 5 m at Sandy Point (Parnell et al., 2004).

Most of the rain from Hurricane Frances fell on the mainland of the United States. Hurricane Frances's destruction potential passed almost as quickly as it formed, the storm became a tropical depression in the northeastern United States on September 7, 2004. Hurricane Frances was indirectly related to 42 deaths, and directly related to 7 others (Beven, 2004).

San Salvador has been hit by several hurricanes in the past decade. During the period from 1899-1994, thirteen hurricanes directly tracked over the island (Shaklee, 1996). During the same period, September was the month when the most hurricanes made landfall in the Bahamas (Shaklee, 1996).

Most recently during the summer of 1996, San Salvador was directly hit by two storms, Tropical Storm Bertha and Hurricane Lili (Lawrence, 1996a,b). Coastal damage caused by the 1996 hurricanes was concentrated mainly on the southwestern side of the island of San Salvador. Damage to homes and other buildings was extensive. Damage surveyed by Garver (1996) consisted mainly of scattered coral damage, trash deposition, and major overwash sediment fans around French Bay and the Gulf.

Hurricane Floyd indirectly hit San Salvador in 1999. Floyd passed 30-56 km to the northeast to north of San Salvador (Pasch et al., 1999). Gamble et al. (2000) report that the eye of Hurricane Floyd passed 24 km north of San Salvador. Damage from Hurricane Floyd was most intense on the northern and western shores of San Salvador but less intense than the 1996 Hurricane Lili (Gamble et al. 2000). Significant erosion occurred on Fernandez Bay with significant washout of the

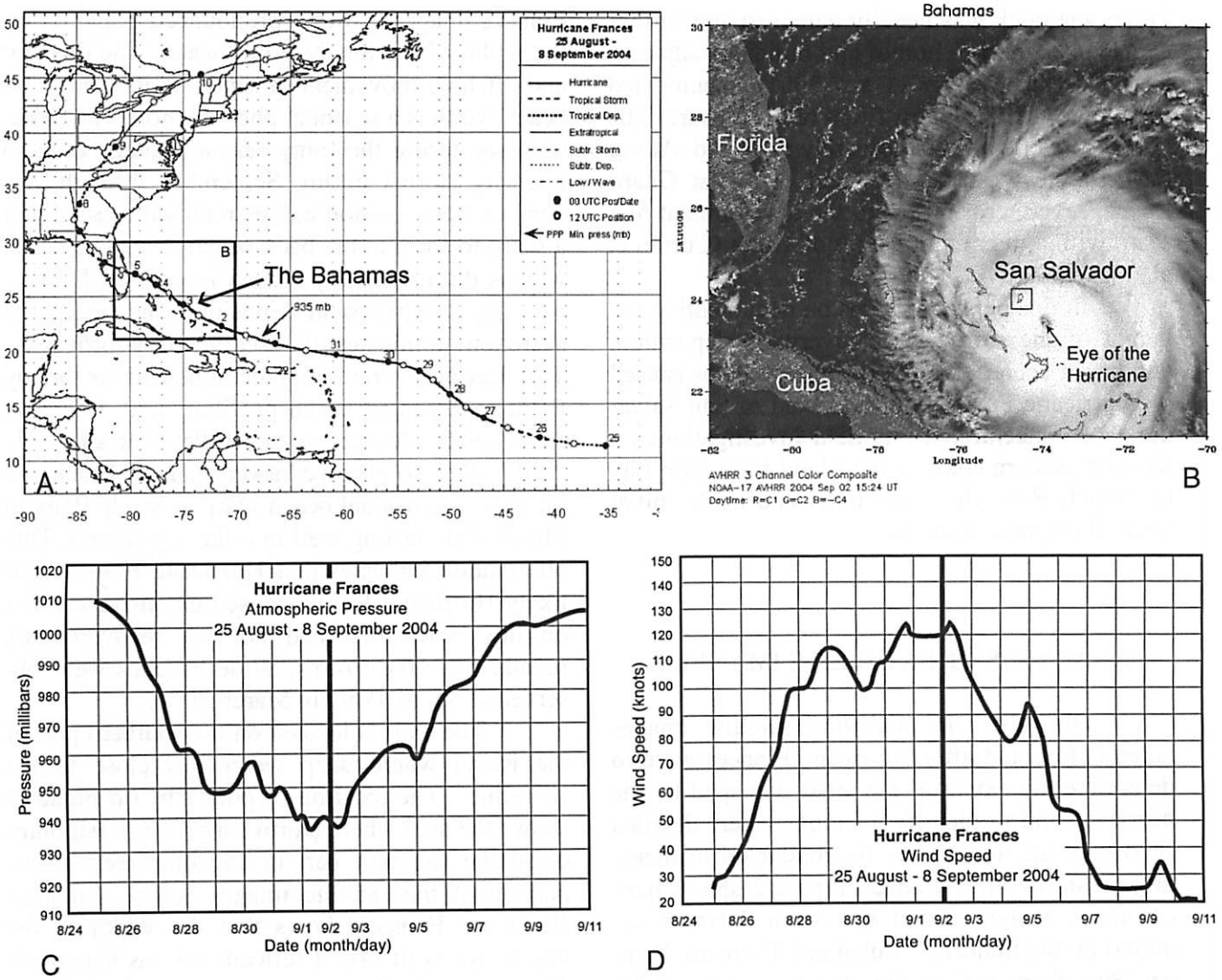

Figure 1. A) Storm track of Hurricane Frances from 25 August to 8 September, 2004. The numbers along the track mark the days. The storm reached its lowest barometric pressure and Category 4 hurricane status on September 1, 2004. Hurricane Frances struck most of the Bahamian Islands as a Category 3 hurricane and Florida as a Category 2 hurricane. The location of Figure 1B is outlined. (Source of image: Beven, 2004). B) NOAA-17 satellite Advanced Very High Resolution Radiometer (AVHRR) three channel color composite daytime image of Hurricane Frances as it approached San Salvador on 2 September 2004 at 15:24 UT. Image used by permission and courtesy of Dr. Steven Babin and Ray Sterner of The Johns Hopkins University Applied Physics Laboratory (http://fermi.jhuapl.edu/hurr/04/frances/index.html). C) The National Weater Service's National Hurricane Center published its best track of the barometric air pressure changes of Hurricane Frances (Beven, 2004). Hurricane Frances struck the island of San Salvador on 2 September 2004 when the storm was near its barometric lowest pressure. D) The National Hurricane Center's best track for the maximum wind speed of Hurricane Frances (Beven, 2004).

road in places (Curran et al., 2001). In Cockburn Town, the dock was heavily damaged and further damage occurred to homes and buildings adjacent to the beach. Walker et al. (2001) documented damage to the Cockburn fossil reef exposure. The town cemetery was also severely damaged. Along most of the western shore and on Coast Guard Beach, severe erosion led to the development of a scarp with a maximum height of 1.8 m (Curran et al., 2001).

In this paper we focus on documenting the height of the storm surge, overwash deposition, and beach accretion and erosion processes caused by Hurricane Frances on the island of San Salvador. We concentrated our field investigations on the southeastern coast of the island from Dim Bay to French Bay where the hurricane made initial landfall (Figures 2 and 3).

ANALYSES OF SATELLITE IMAGERY

Our goals in analyzing satellite images taken before and after Hurricane Frances were to determine the extent of the areas damaged by the hurricane and to identify locations where detailed field investigations could be conducted to measure the storm surge impact. Figure 2 shows panchromatic images (Band 8) of San Salvador acquired by the Landsat 7 Enhanced Thematic Mapper Plus from before the storm on August 30, 2004 and after the storm on October 1, 2004. The spatial resolution of the images is 15 m. Black lines are a result of an instrument failure of the satellite's Scan Line Corrector that occurred on July 14, 2003 and extends to all images acquired to the present date. The lines show the original data gaps which gradually diminish in width toward the center of the scene. The GeoTIFF image files were radiometrically and geometrically corrected by the provider. The scene was plotted using Leica Geosystems' ERDAS Imagine and ESRI's ArcView products. Points for discussion are labeled on Figure 2.

Sandy Point (labeled point "a") is the southwesternmost extension of the island. A visual comparison of the pre- and post-Hurricane Frances images shows a pronounced reduction in the width of the Sandy Point beach. The onshore and offshore movement of sand and its control on beach width is a seasonal phenomenon. The beach narrows during the rainy season months of high intensity storms during September through November when erosion causes removal of sand and a scarp to form in the back beach area. The beach widens during the dry season months of December-August when sand deposition and beach bar accretion dominates the sedimentary processes. This has been previously documented for Sandy Point by repeated beach profiling (*e.g.* Loizeaux et al. 1993; Beavers et al., 1995; Curran et al., 2001). We also observed a very narrow beach and ~2-m-high erosional beach scarp at Sandy Point in March 2005 lasting well into the dry season. This observation indicates that Hurricane Frances and likely Hurricane Jeanne caused extensive erosion on this beach that had not yet recovered six months after the storms. Wide beaches were observed at Sandy Point in March 2007.

The Gulf is located on the southern part of the island where deep water lies close to the shoreline. The location of point "b" on Figure 2 shows the area where storm surge overwash inundated the southern part of Pigeon Creek. Comparison of the satellite images before and after Hurricane Frances shows that the width of the beach (zones of bright reflections) has narrowed. This is largely due to the massive movement of blocks and boulders of bedrock landward caused by the storm surge.

Low Cay is marked as point "c". Comparison of the images in Figure 2 show that the vegetated area of the island was sharply reduced by the hurricane. Large areas of defoliated vegetation and re-deposited sand are noted on the eastern side of the island.

The Pigeon Creek tidal inlet is labeled as point "d". The beach south of the inlet down to the southeastern point is known as Sandy Hook. The satellite data confirm that the east face of Sandy Hook was significantly altered by the Hurricane Frances storm surge. The beach has narrowed by processes of vegetation and removal at

Table 1: Saffir-Simpson Hurricane Scale

Category	Wind Speed	Barometric Pressure	Storm Surge	Damage Potential
Tropical Depression	< 39 mph < 34 kts			Minimal
Tropical Storm	39 - 73 mph 34 - 63 kts			Minimal
Hurricane 1 (Weak)	74 - 95 mph 64 - 82 kts	28.94" or more 980.02 mb or more	4.0' - 5.0' 1.2 m - 1.5 m	Minimal damage to vegetation
Hurricane 2 (Moderate)	96 - 110 mph 83 - 95 kts	28.50" - 28.93" 965.12 mb - 979.68 mb	6.0' - 8.0' 1.8 m - 2.4 m	Moderate damage to houses
Hurricane 3 (Strong)	111 - 130 mph 96 - 112 kts	27.91" - 28.49" 945.14 mb - 964.78 mb	9.0' - 12.0' 2.7 m - 3.7 m	Extensive damage to small buildings
Hurricane 4 (Very strong)	131 - 155 mph 113 - 135 kts	27.17" - 27.90" 920.08 mb - 944.80 mb	13.0' - 18.0' 3.9 m - 5.5 m	Extreme structural damage
Hurricane 5 (Devastating)	> 155 mph > 135 kts	< 27.17" < 920.08 mb	> 18.0' > 5.5m	Catastrophic building failures possible

The Saffir-Simpson Hurricane Scale defining the category of hurricanes based on wind speed in miles per hour (mph) and knots (Kts), barometric pressure in inches (") and millibars (mb), the resultant storm surge height in feet (') and meters (m) and description of damage potential. Source of Table: http://meta1.srcc.lsu.edu/OEP/hurr_scale.html.

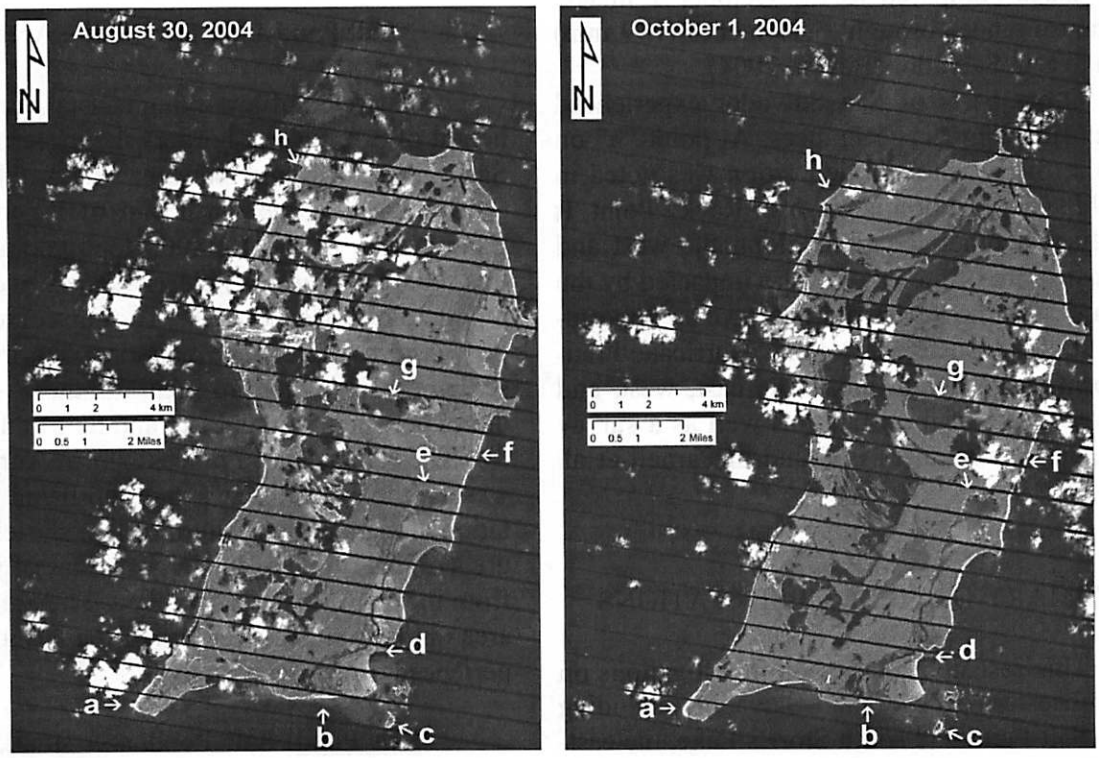

Figure 2. Panchromatic images (Band 8) of San Salvador acquired by the Landsat 7 Enhanced Thematic Mapper Plus from before Hurricane Frances (left; August 30, 2004) and after (right image; October 1, 2004). Cloud cover shown as white spots. Image is annotated for special sites of interest: a=Sandy Point; b= The Gulf; c=Low Cay; d=Pigeon Creek inlet; e=north Pigeon Creek; f=Salt Pond; g=inland lake area; h=north Rocky Point. See text for discussion.

its northern end and slightly widened by sand deposition along the southern end.

The northern end of the Pigeon Creek estuary is marked with the letter "e". The storm caused water to overtop the banks of this water body. The overwash deposition is shown as areas of bright reflections on the October 1, 2004 image (Figure 2).

Point "f" on Figure 2 is the location of Salt Pond. Like the other inland lakes, the levels of Salt Pond rose after the hurricane. The width of the de-vegetated beach also widened north of point "f".

One of the most pronounced differences between the August 30th and October 1st images is in the water level of the interior lakes. Point "g" on Figure 2 highlights only one of the many lakes. This lake is called Granny Lake. On the August image, the bright outlines around the lake mark the lowstand shoreline exposing the un-vegetated lake margins. Lake levels are markedly lower in all the lakes compared to the October 1 image. Hurricane Frances brought 5.47 inches (139 mm) of rain to San Salvador (Beven, 2004).

Other parts of San Salvador experienced impacts from Hurricane Frances. At point "h" on Figure 2, overwash sand deposition was noted in the field. This location is north of Rocky Point. It is likely that other locations along the west and northeast shore of the island were impacted by the hurricane. We, however, did not have an opportunity to study those areas. Data for Hurricane Frances storm surge height along the east, west, and southwest parts of the island, as well as a survey of damage to structures is found in Parnell et al. (2004).

SUMMARY OF FIELD OBSERVATIONS

This research focuses on investigations on the southeastern side of San Salvador, including sites at Salt Pond and south Storr's Lake, the eastern beach area around and south of The Thumb, the north Pigeon Creek area, the Pigeon Creek inlet, Sandy Hook, and the Gulf (Figure 3). These locales were chosen based on analyses of satellite imagery and discussions with Vincent Voegeli who was at the Gerace Research Station at the north end of the island at the time of the hurricane.

Field study of the sites was conducted during March 4-11, 2005. We measured beach profiles at points where the maximum storm surge washover height could be determined using the Emery method (Emery, 1961; Kraus, 2004) with a hand level and a 1.5 m high stadia rod divided into 10 cm and 2 cm increments. The Storr's Lake site profile was measured in March 2005 with the horizontal distance recorded at each major inflection points rather than at every 2 m. The beach profiles at the 'Thumb' and the stratified trash locations were measured in January 2008. The distance from high tide to areas of interest of beach erosion and accretion were measured using the pace method and by tape measure. The following discussion summarizes our observations at each of the field sites.

Salt Pond and Storr's Lake Area

A stretch of low-lying coastal dunes with a height of 3 m or less borders the eastern shore of San Salvador island between the south end of Storr's Lake to the north end of Pigeon Creek. Examination of the 1:10,000 topographic map of this region (Figure 4B) clearly shows two areas of topography lower than the 10-foot contour along this eastern shore. The abandoned Fortune Hill settlement area lies adjacent to these low sand dunes between Storr's Lake and Salt Pond (Figure 3). The Hurricane Frances storm surge overwashed the coastal dunes and defoliated the vegetation along a 300 m length of this shoreline (Figure 4). This is one of the largest areas of washover from the storm that we surveyed. The Sandy Hook area on the southeast section of the island also experienced extensive washover.

Salt Pond. Salt Pond is a small, shallow coastal lake with a highly variable salinity. In general during the rainy months in the Bahamas between May and October (Shaklee, 1996), freshwater input causes the lake level to rise and

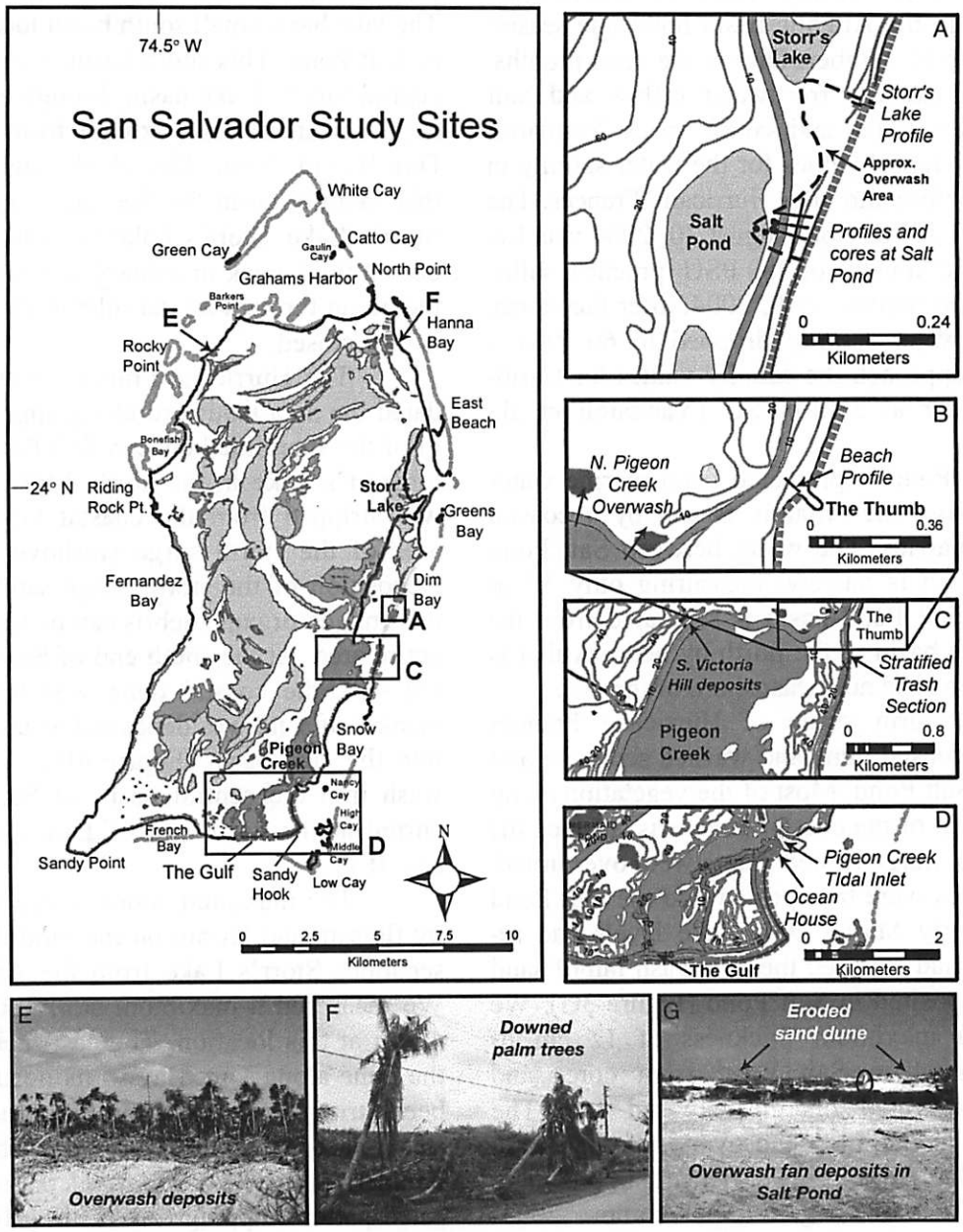

Figure 3: Map showing sites on the island of San Salvador, The Bahamas where damage from Hurricane Frances was documented in this study. Images are plotted from the GIS database of R. Laurence Davis and Matthew C. Robinson (1999, University of New Haven). A) Location of the overwash fan in Salt Pond and Storr's Lake and storm surge profiles and cores. B) Detailed map of 'The Thumb' showing location of beach profile. The overwash from north Pigeon Creek is also labeled. C) Map showing the location of storm surge height profiles at The Thumb and stratified trash section. D) Detail of the southeast section of San Salvador showing the location of Ocean House at the Pigeon Creek tidal inlet and overwash deposits at 'The Gulf'. E) Hurricane Frances also caused overwash deposition along the northwest part of the island. View toward the southeast. F) Four palm trees were blown down onshore of Hanna Bay. View toward the southeast. G) Photograph of the overwash fan deposits in Salt Pond viewed toward the east. The beach barrier sand dune was stripped of vegetation and eroded. Oval outlines a person for scale.

reduces the water salinity. These months roughly correspond to the Atlantic basin hurricane season from June to November. During the drier months, evaporation exceeds freshwater inflow and Salt Pond lake levels fall and salinity rises. Yannarell et al. (2007) report values for the water salinity in Salt Pond before and after Hurricane Frances. The salinity of Salt Pond on August 30, 2004 was hypersaline with a value of 280 PSU (practical salinity units). On September 9, 2004, after the storm, Salt Pond water salinity dropped to 60 PSU—levels that approach the salinity values for Caribbean seawater at 35-40 PSU (Yannarell et al., 2007).

Salt Pond is protected from marine water incursion from the Atlantic Ocean by a coastal sand-dune barrier. The width between Salt Pond and the ocean is narrow; measuring only 50 m wide. The Salt Pond basin is separated from the Storr's Lake basin to the north by bedrock that is exposed along the northeast shore of the lake.

The storm surge of Hurricane Frances eroded the coastal dune and washed sediment and water into Salt Pond. Most of the vegetation along a 70 m length of the coastal dune was stripped off (Figure 3G). Large rooted plants were overturned. Whole shrubs were transported into the Salt Pond basin. In early March 2005, lake levels had retreated and had exposed the overwash fan of sand that was deposited in Salt Pond (Figure 3G). We measured a maximum thickness of 12 cm of overwash sand in Salt Pond from cores and trenches excavated on the exposed fan. The maximum thickness of sand overwash deposition is likely to have been thicker depending on where sampled. Vincent Voegeli (pers. comm., 2005) reported that at least 8 inches (20 cm) of sand was deposited over the road adjacent to Salt Pond. Description of the Hurricane Frances overwash deposits in Salt Pond is the subject of a companion paper in this volume (McCabe and Niemi, 2008). Also in this volume, a paper by Park et al. (2008) presents a longer record of hurricane deposition and faunal changes in Salt Pond based on analyses of sediment cores from the center of the lake.

Storr's Lake. Paralleling nearly 7 km of the eastern shore of San Salvador, Storr's Lake can be divided into three sub-basins (Figure 3). The lake has a small south basin located just north of Salt Pond. This south basin is connected to the central Storr's Lake basin through a narrow channel. The central basin extends from the latitude of Dim Bay to Greens Bay. A channel also connects this central basin to the large north basin of Storr's Lake. Storr's Lake is likely to have once been a tidal creek or estuary directly connected to the ocean through a tidal inlet at its south end that is now closed.

The Hurricane Frances storm surge inundated the area landward along approximately 300 m of the shoreline between Salt Pond in the south to Storr's Lake in the north. Most of the foliage was stripped from the coastal vegetation in the area of the storm surge washover (Figure 4A). Deposition of the storm surge sand, flotsam and jetsam, and organic debris can be traced along this entire area. At the south end of Storr's Lake (Figure 4C), the coastal dune was breached and a blanket of sand was deposited as an overwash fan into the lake basin (Figure 4D). A second overwash into the central basin of Storr's Lake occurred at the north end of Dim Bay (Figure 4E and 4F).

The maximum storm surge was identified by flotsam and jetsam on the sand dune crest that separates Storr's Lake from the Atlantic Ocean. We measured a maximum storm surge height of 4.8 m at this location. The east-facing portion of the dune along Dim Bay to its northern limit has been stripped of vegetation and eroded leaving a steep east-facing scarp. The storm transported boulders inland and deposited them in an imbricated pattern dipping east (seaward). These large imbricated slabs line the base of the sand dunes along this eastern shore (Figure 4F) and likely represent an accumulation of numerous storms in addition to Hurricane Frances.

The Thumb Area

Along the east coast of San Salvador just north of Pigeon Creek there is a southeast-trending tombolo locally known as 'The Thumb' (GPS coordinates: 2655774N, 555390E). The

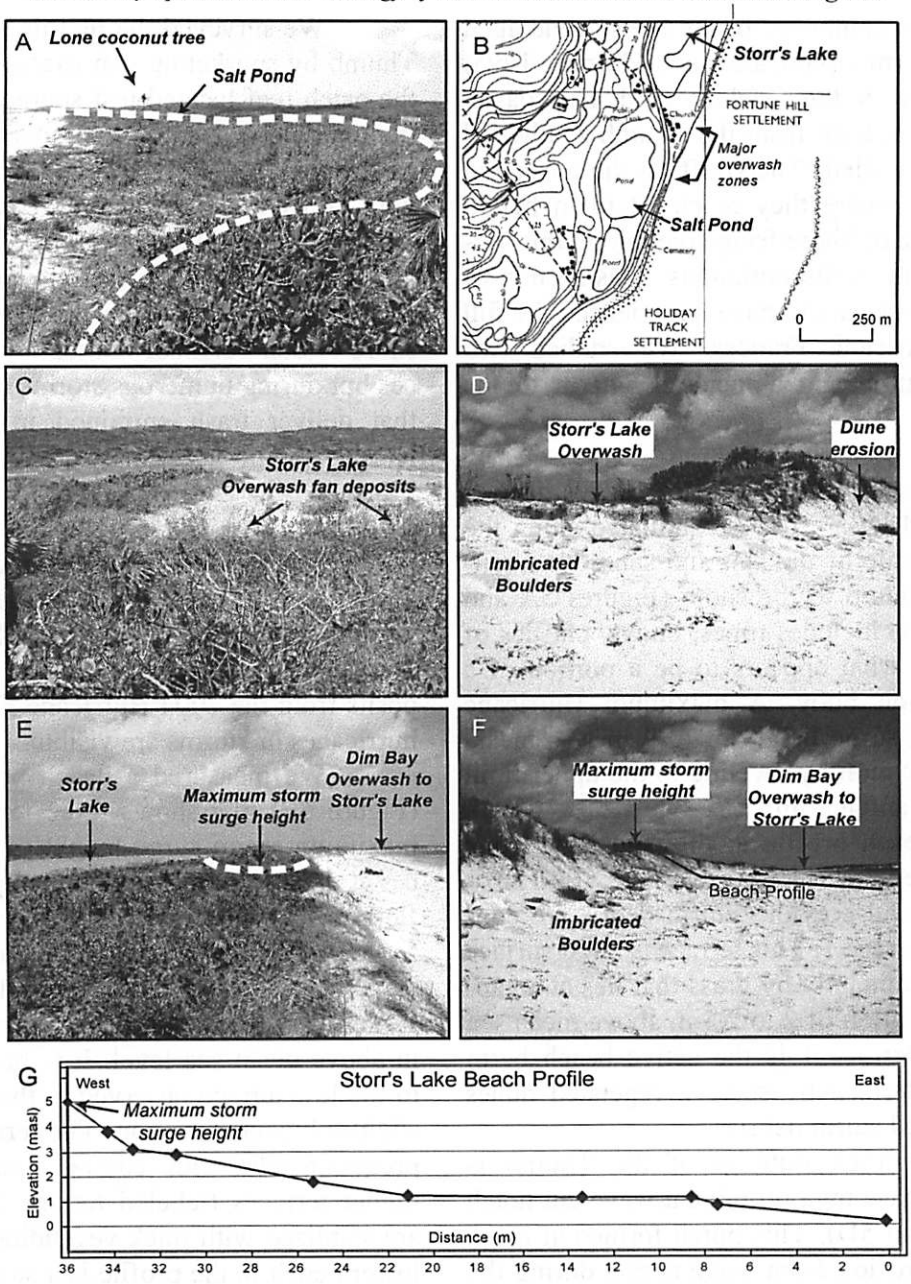

Figure 4:Photographs of Hurricane Frances storm surge damage in the Fortune Hill Settlement area between Storr's Lake and Salt Pond. A) View south from Storr's Lake showing area of extensive washover and defoliated vegetation. B) A portion of the 1:10,000-scale topographic map showing the area around Salt Pond. C) The south end of Storr's Lake showing the overwash fan deposits. Vegetation in the foreground is defoliated. (View west). D) View northwest toward Storr's Lake showing the overwash breach, eroded dunes, and storm deposited imbricated boulders at the base of the sand dune. E) View north along the sand dune crest that separates Storr's Lake from the Atlantic Ocean. The location of the maximum storm surge height is marked. F) The eroded eastern side of the coastal sand dunes viewed north along Dim Bay. The maximum storm surge was identified by the upper limit of flotsam and jettsam deposited on the sand dune. G) Beach profile showing maximum storm surge height (4.8 m). Location of profile in F.

rock outcrop is composed of the Pleistocene-aged Owl's Hole Formation (Carew and Mylroie, 1995) and is connected to the beach by sand. The coastal bluffs are 7-8 m high from the Thumb southward until the point called 'The Bluff' at the north end of Snow Bay where they reach 12 m in height (Figure 3). The offshore fringe reef along this section of coastline is discontinuous. This section of San Salvador appears to have experienced the full force of Hurricane Frances. We studied two sites—the Thumb and a location 540 m to the south.

The Thumb. An areally expansive deposit of flotsam and jetsam has accumulated along the southwestern side of the spit and sand dune connecting the Thumb to the shore (Figures 5A and 5B). The debris includes ropes, buoys, plastics of all types, and what appears to be a portion of a large navigation buoy. A maximum Hurricane Frances storm surge height of 4. 9 m was measured at this location by leveling to the upper limit of the flotsam and jetsam.

The beach profile at this site shows one distinct terrace level (terrace 1; Figure 5F). Hurricane Frances and previous storm debris are concentrated on terrace 1. This terrace is a flat surface covered predominantly by grass that lies at an approximate elevation of 2 to 2.5 m above mean sea level. Below terrace 1 is the active beach berm that is characterized by sparely vegetated dunes and remobilized storm debris.

The bedrock outcrop of the Thumb is marked at its base by a prominent wave-cut notch (Figures 5C and 5D). This notch formed at mean sea level by erosion from wave action during the normal high and low tidal range. The weathered craggy outcrop above the notch is strewn with nets and ropes across the entire exposure indicating complete submergence of the bedrock knob during the hurricane storm surge and in previous storms. Two recognizable terrace levels can be seen in the bedrock profile (Figure 5D). The lower terrace A is a zone of bare rock outcrop formed about 1-2 meters above the notch. The upper flat terrace B is vegetated. This vegetation has been defoliated by the storm surge.

We surveyed the reef in the vicinity of the Thumb by snorkeling. An example of the state of the patch reef located just southeast of the end of the tombolo is seen in the underwater photograph of Figure 5E. The reef shows signs of damage with broken and overturned blocks. There are numerous entangled ropes, nets, and other debris caught in the reef. The entangled debris was likely brought to this and other sites along the eastern shore of San Salvador not just by Hurricane Frances but during numerous storms of lesser intensity that deliver trash entrained in currents of the North Atlantic gyre to this windward side of the island.

Stratified trash site. Approximately 540 m south of the Thumb is a locale we called the 'stratified trash site' (GPS coordinates: 2655236N, 555286E) where the storm surge deposits from the 2004 Hurricane Frances and other hurricanes or storms are visible.

We measured a beach profile at this site (Figure 6E) that shows three terrace levels. The maximum storm surge height of Hurricane Frances at this location based on the upper elevation of flotsam and jetsam was measured at a height of 5.5 m. A heavy accumulation of Frances storm surge debris is also noted across the lower terrace 1. Terrace 1 lies at an elevation of about 3 to 3.5 m above mean sea level. It is broadly equivalent to the low terrace observed at the Thumb but at a slightly higher elevation. The terrace is vegetated predominately with coastal grass. Two upper, higher terraces (labeled terrace 2 and terrace 3) are stablized with thick vegetation and trees. One lower bench in the profile is a storm berm formed after Hurricane Frances.

Erosion of the back beach area exposed a 170-cm-thick stratigraphic section that marks the eastern edge of terrace 1. The section (Figures 6C and 6D) contains a lower 50-cm thick section of aeolian sand overlain by 40-cm-thick layer of trash and storm debris. The section is capped by an 80-cm-thick bed of aeolian sand. The top surface of the section is the grass-vegetated terrace 1 surface. The stratified trash indicates that debris from a previous storm or hurricane was deposited

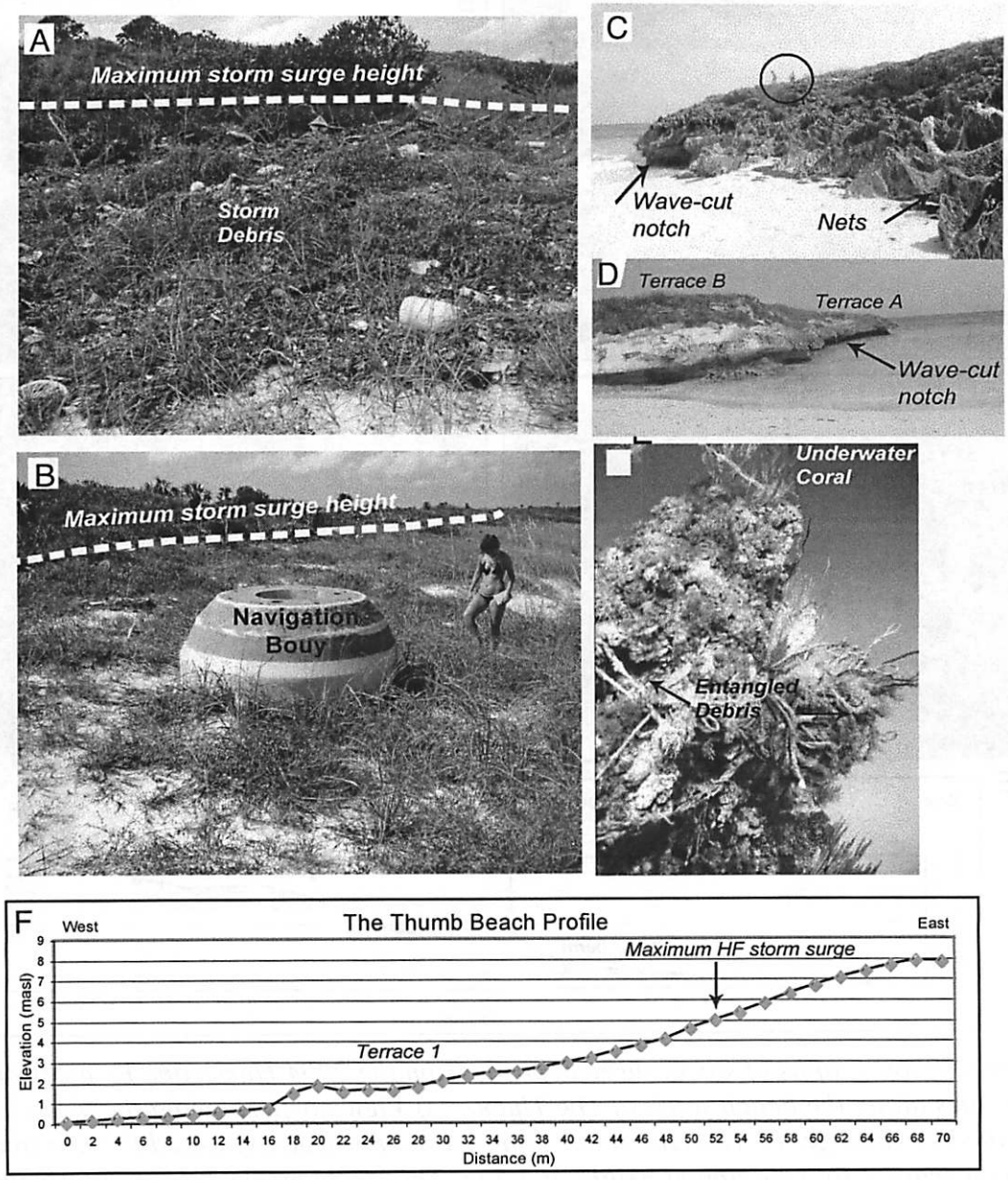

Figure 5: The Thumb is a southeast-trending tombolo located along the east coast of San Salvador (see Figure 3 for map location). A) Photograph of the large amount of flotsam and jetsam accumulated along the southwestern side of the spit and sand dune connecting the Thumb to shore. View to the west with the maximum storm surge height marked. B) View northward of the debris collected on the coastal dunes showing the maximum height of debris marking the storm surge height. C) The bedrock outcrop of the Thumb is marked at its base by a prominent wave-cut notch. The weathered craggy outcrop is strewn with nets and ropes across its height indicating submergence of the bedrock knob during the hurricane. View to the west. Circle marks two persons for scale. D) View of the south side of the Thumb showing the wave-cut notch and two terrace levels. The vegetation has been defoliated by the storm surge. E) Underwater photograph of a patch reef just to the southeast of the end of the tombolo showing damaged reef with numerous entangled ropes, nets, and other debris. F) Beach profile from the base of The Thumb on the west to the top of the coastal ridge on the east. The position of the maximum Hurricane Frances (HF) coastal debris from the storm surge is marked at a height of 4.9 m.

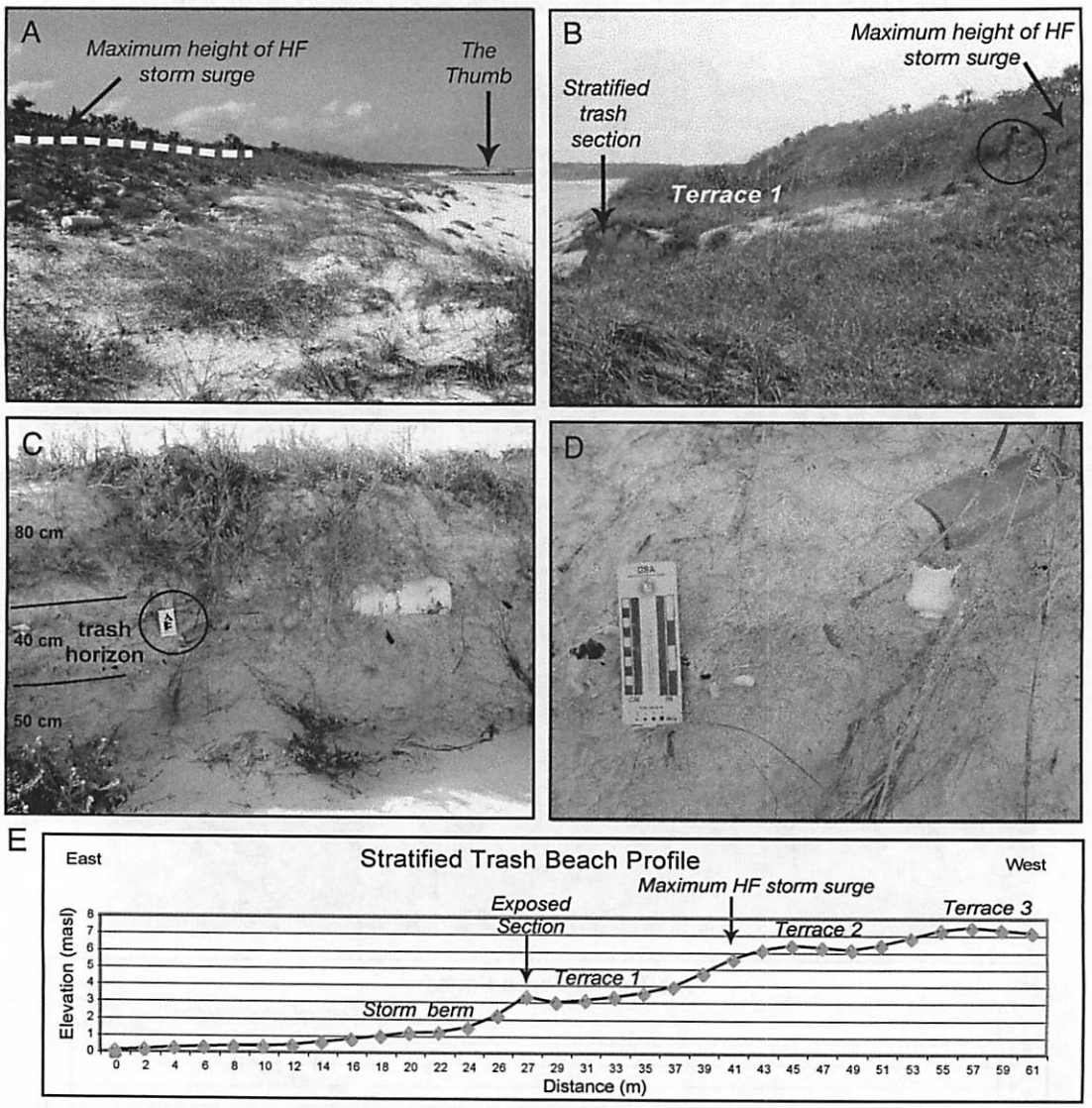

Figure 6. Photographs of storm surge deposits from the 2004 Hurricane Frances and other hurricanes along the beach south of The Thumb. A) View north showing the trash deposited from the storm surge. B) The Hurricane Frances storm surge deposited flotsam and jetsam across terrace 1 to a maximum height of 5.5 m. The circle marks a person for scale. View toward the south. C) Erosion of the backbeach dune exposed a 170-cm-thick stratigrapic section showing storm debris from a previous event interbedded with aeolian sand. Scale within the circle is 15 cm. D) Detailed view of the stratified storm deposit showing plastic fragments and objects, charcoal, a glass bottle, a light bulb and other trash. E) Beach profile showing the maximum storm surge height of Hurricane Frances (HF) based on the upper elevation of flotsam and jetsam. The stratified trash section in photos C and D marks the eastern edge of Terrace 1. One lower bench in the profile is the post-hurricane accumulation of a storm berm. Two upper, higher terraces (labeled terrace 2 and terrace 3) are stablized with thick vegetation and trees. Location of the beach profile is shown in Figure 3D.

in this back-beach berm and then subsequently buried by windblown sand. A close-up photograph of the stratified storm deposit shown in Figure 6D highlights the various objects found in the tempestite including plastic materials of all types, charcoal, a glass bottle, a light bulb, and other trash (Figure 6D). The exposed stratigraphic section indicates that terrace 1 was built from deposition of previous storm events and modified by aeolian deposition. At this location Hurricane Frances deposits were found at higher elevations. These data suggest that the Hurricane Frances storm surge may have been more intense than the previous storms that hit the island in the recent past.

North Pigeon Creek and the Southeast Areas

Along the southeast end of the island generally paralleling the shoreline, there is a northeast-southwest trending water body that is known as Pigeon Creek. This water body is a tidal estuary that contains three shallow basins (south Pigeon Creek, central Pigeon Creek, and north Pigeon Creek) developed around a tidal channel (Figures 2 and 3). The tidal channel leading to the south basin of the Pigeon Creek estuary opens to the Atlantic Ocean through a tidal inlet. Because of the connection to the ocean, Pigeon Creek experiences tides. There is a lag period between the coastal high and low tides and the tides in Pigeon Creek due to the delay in flood and ebb through the inlet. The Pigeon Creek tidal inlet is located about 1.5 km north of the southeast point of the island called Sandy Hook (Figure 3D). Sediment flushing out of Pigeon Creek through the tidal inlet has formed a shallow sandy tidal flat within Snow Bay. The bay is protected from intense wave action by a line of offshore islands—Nancy Cay, High Cay, Cay, Middle Cay, and Low Cay (Figure 3).

Our investigation of Hurricane Frances storm deposits and sites of erosion and damage concentrated on three different regions around Pigeon Creek (Figure 3):

(1) The storm surge caused water to spill out the debris pile have their source in a line of coco- of the north end of Pigeon Creek in the vicinity of the South Victoria Hill Settlement and to the northeast (Figure 7).

(2) At the tidal inlet of Pigeon Creek and south along the shore of Sandy Hook, beach erosion was prevalent (Figure 8).

(3) And along the south end of Pigeon Creek in the area called 'The Gulf', the Hurricane Frances storm surge caused coastal erosion and overwash into the estuary (Figure 9).

North Pigeon Creek. Along the northern end of Pigeon Creek (Figure 3C), water overtopped the normal shoreline leaving a line of debris marking the high water mark. At the northeast corner of the estuary, water surged out of the lake causing defoliation of vegetation and an overwash into two small ponds located north of the road (Figure 3B). In the area of the abandoned South Victoria Hill settlement, the maximum high water level was marked by a 1- to 2-m-wide debris pile that ringed northwest Pigeon Creek about 15-20 m inland of the normal shoreline (Figure 7).

We hand dug a trench through the debris pile at a site (GPS coordinates: 24° 00.726 N, 074° 28.250 W, with an elevation of 3 m) just south of the extant buildings of the settlement and south of the pier (Figure 7). The debris pile is made almost entirely of organic matter. A stratigraphic section drawn through the 33-cm-thick debris pile (Figure 7D) shows four layers. The upper 10 cm was largely leaves, palm fronds, sticks, roots, coconuts, and other vegetative matter overlying a 5- to 7-cm-thick mixed layer of leaves and composted organic debris. These upper layers rest on a moist thin layer of compost and a basal layer composed of medium-grained sand mixed with decayed organic matter.

It is clear that during the six months between deposition of the storm debris and the time of these observations that the material had already heavily decayed. There was a noticeably absence of any material other than sand and organic debris. No plastic debris or other man-made materials were present. The large number of coconuts in nut palm trees that grow along the east side of the

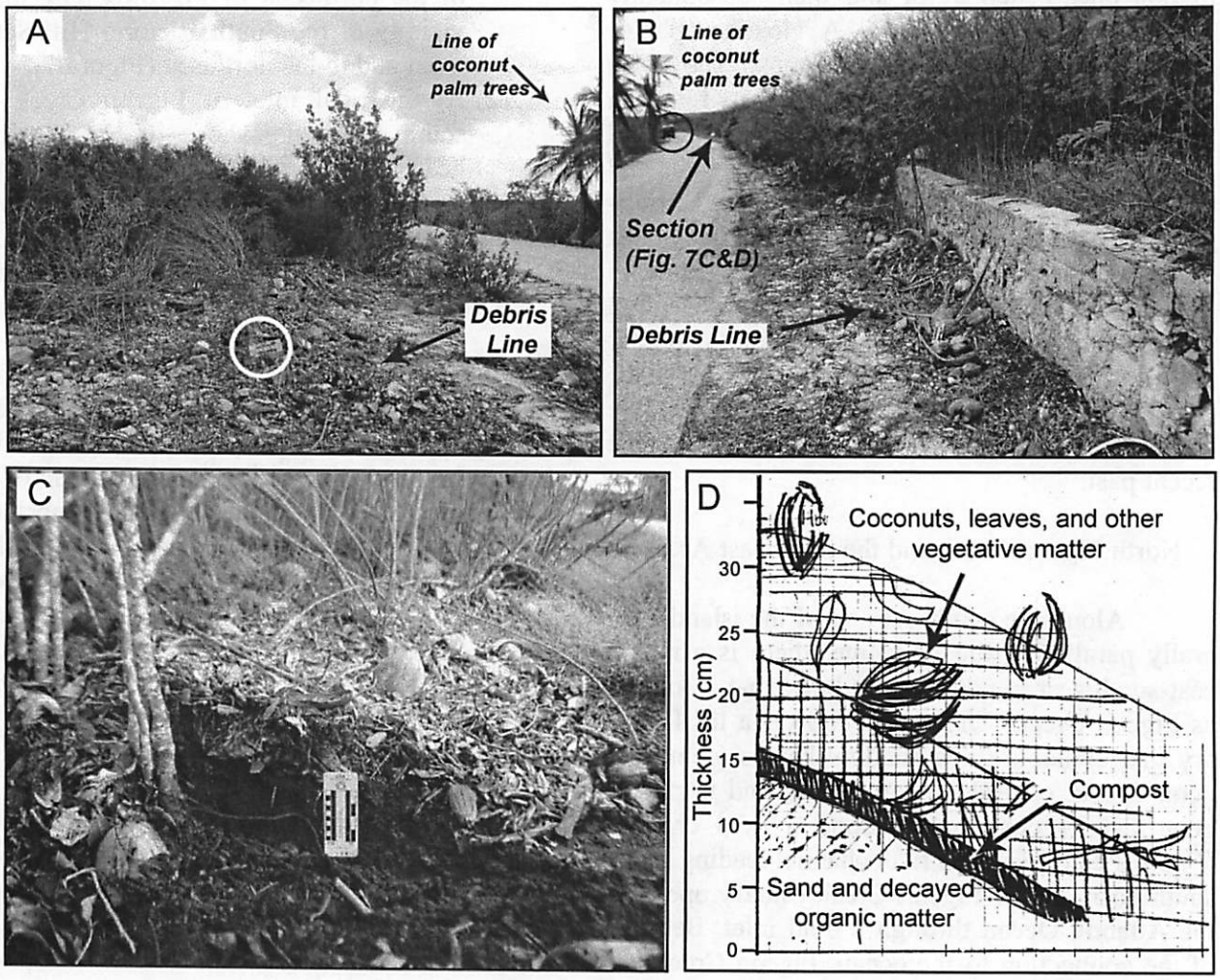

Figure 7. Water overtopped the normal shoreline of the northern end of Pigeon Creek leaving a largely organic debris pile marking the high water mark. (See Figure 3 for location map). A) View north showing the debris line on the west side of the road in the South Victoria Hill Settlement area of north Pigeon Creek. Circle outlines 10 cm photographic scale. B) View south showing the organic debris high water line east of the road and against an old wall of the South Victoria Hill Settlement area. Circle outlines a vehicle for scale. C) Hand-dug section exposure through the debris pile. The large number of coconuts in the debris are derived from a line of palm trees located on the east side of the road. View toward the north. D) Stratigraphic section drawing through the debris pile. The organic material is predominantly palm, mangrove, and other leaves, sticks, coconuts and other organic material that has decayed and composted. Drawing by Tani Sutherland.

road at this location (Figure 7). The other organic matter also has a local source. The mangrove and coastal vegetation surrounding this area of Pigeon Creek has been visibly defoliated. The stripped leaves were deposited in the debris pile.

The appearance of coconuts sitting within a composting debris pile suggests that over time new coconut trees should germinate and take root along the line marking the high water level. Under ideal conditions of moisture and temperature, a coconut should germinate within three to six months (Watson, 1996). As we have observed coconuts among the other flotsam and jetsam marking the Hurricane Frances storm surge deposits as high as 5 m above the shoreline, we hypothesis that coconut palm trees found at higher elevations may mark prior hurricane storm surge deposits. This is particularly true for the lone coconut tree (Figure 4) observed between Salt Pond and Storr's Lake.

Pigeon Creek tidal inlet. The southeast point on the island of San Salvador is called Sandy Hook (Figure 3). Analyses of the Thematic Mapper Satellite image from October 1, 2004 (Figure 2) shows that the east-facing beach of Sandy Hook experienced erosion of coastal vegetation, inland deposition of coastal sediment and accretion of beach sediment. We surveyed the area just south of the mouth of Pigeon Creek at its tidal inlet and at one site about 750 m north of the point to assess the hurricane damage and document the changes in the coastal environment.

The vegetation line at Sandy Hook has retreated about 40 m from its pre-Hurricane Frances position. To the south of the eroded beach, there was accretion. Analysis of satellite images from August and October 2004, we were able to determine this accretion to be about 30 m.

At low tide an area is exposed that measures about 70 m wide that contains remnants of mangrove roots and plants (Figure 8 A-C). Boulders are strewn over the surface. Some areas show signs that they have been newly exposed based on the lack of surface weathering. Examination of the satellite imagery from before (August 30, 2004) and after (October 1, 2004) Hurricane Frances clearly shows that the width of non-vegetated coastline has about doubled (Figure 2). This increase in width of the coastal zone is mostly likely due to the removal of coastal vegetation and deposition of sand and boulders inland.

Large slabs of rock ripped up from the surf zone have been transported inland. The boulders are stacked with a dip toward the east. This imbrication indicates the boulders were transported to the west. The boulders were of local origin. Individual slabs could not be traced back to their original location. Ten large boulders were measured and are recorded in Table 2. The maximum length of the boulders is nearly 1 m (98 cm) and the average length of the boulders measured is 77 cm. If we assume that the classic Hjulstrom diagram that plots relationship between the stream velocity necessary to transport a particle of a given diameter is applicable to wave storm surge velocities, then a particle with an average length of 77 cm would require a water velocity in excess of 600 cm/s.

Table 2: Measurements of large boulders imbricated along the back beach region of Sandy Hook.

Length	Width	Height
65 cm	60 cm	15 cm
75 cm	73 cm	12 cm
68 cm	50 cm	18 cm
43 cm	42 cm	22 cm
91 cm	70 cm	17 cm
95 cm	57 cm	15 cm
72 cm	50 cm	12 cm
98 cm	56 cm	19 cm
90 cm	47 cm	20 cm
72 cm	70 cm	5 cm

There was evidence of past imbrications, aligned in the same orientation as the boulders from Hurricane Frances. These boulders are seen in the background of Figure 8A and 8C and are covered with a black patina from algae, implying that these boulders are part of the supratidal zone (Hinman, 1994), and were transported in previous storm surge events.

One of the structures that sustained significant damage during Hurricane Frances is lo

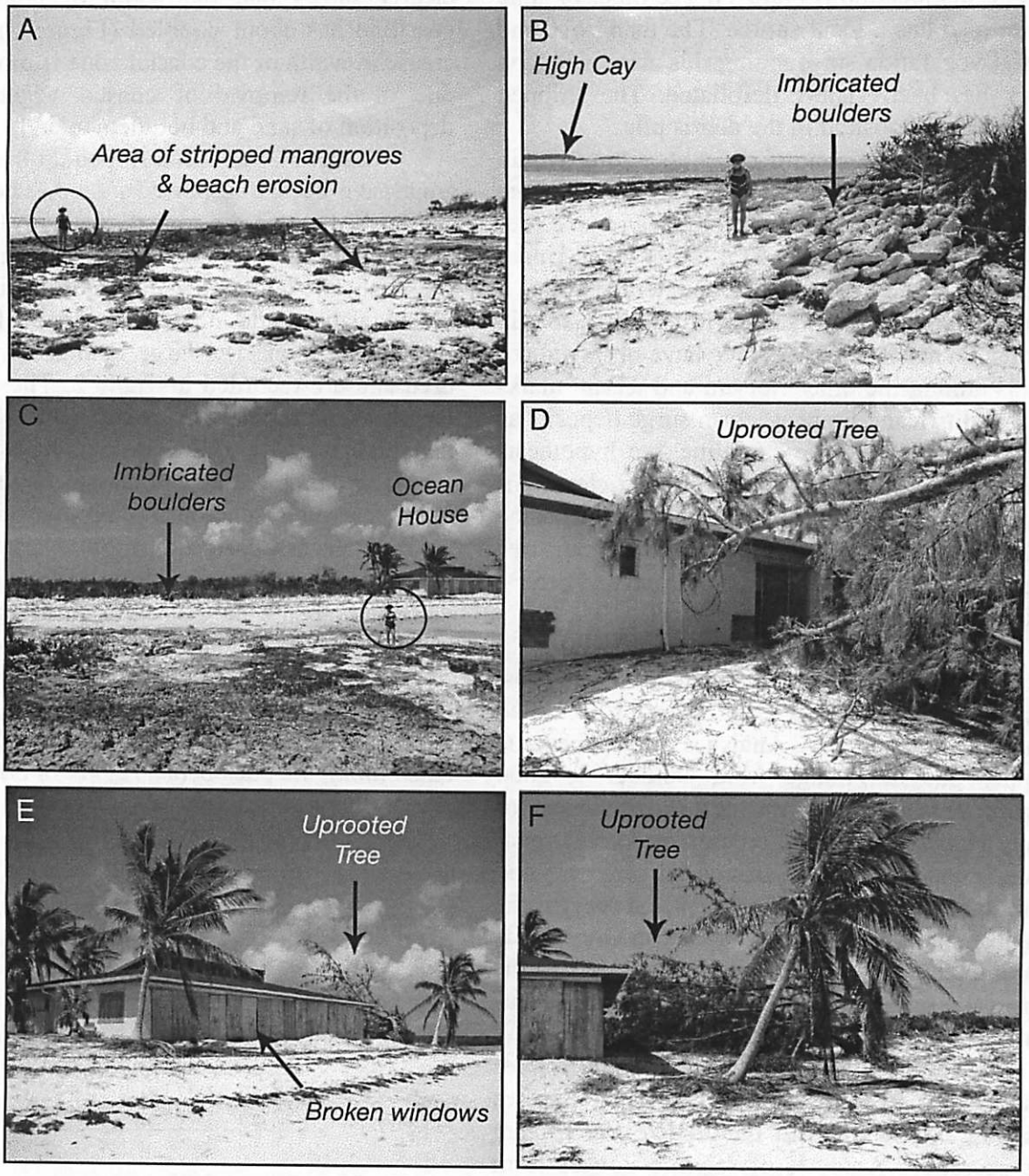

Figure 8: Erosion and hurricane damage to Ocean House located at the tidal inlet of Pigeon Creek on the southeast side of San Salvador Island (See Figure 2 and 3 for map location). A) View south across the area of stripped mangroves and beach erosion. B) Imbricated boulders stacked along the back beach area. View southwest with High Cay island in the background. C) View northwest across the eroded platform that was stripped of mangroves. Ocean House in the background. Person for scale. D) Uprooted Australian pine tree (Casuarina equisetifolia) on the north side of Ocean House. E) View north showing the damaged Ocean House. F) View west of a tilted palm and toppled Australian pine tree.

cated at the Pigeon Creek tidal inlet. This property is known as Ocean House and is shown in Figure 8. The house was built without pilings and just above sea level. The windows throughout the house were knocked out and the storm surge is likely to have swept through the structure. An Australian pine (*Casuarina equisetifolia*) tree on the north side of the house was uprooted and fell toward the house.

The Gulf. The south end of the island of San Salvador extends from a point on the west called Sandy Point that protects French Bay from westerly and northwesterly winds to a point on the east called Sandy Hook. Very deep water and the fringe reef wall are located about 25 m from the shore along the eastern side in an area known as "The Gulf" (Figure 3). Because of the very narrow shelf, wave action is intense and the beach is rocky.

The width of the coast along the Gulf between the Atlantic Ocean on the south and the southern end of Pigeon Creek is very narrow measuring only about 75 - 100 m. We documented several locations with a series of photographs showing the effects of Hurricane Frances along the coastal zone of the Gulf. Large slabs of bedrock are broken and imbricated with slopes toward the south the result of numerous storms that batter the coast (Figure 9A). Some boulders larger than 1 m in length were transported as much as 50 m inland and were deposited along the road (Figure 9B). The storm surge came on shore and stripped the coastal vegetation of foliage. Sand, vegetation, and flotsam and jetsam were deposited on the coastal road (Figure 9C). At two locations, sand and other storm debris washed into the south end of Pigeon Creek forming an overwash fan (Figure 9D).

DISCUSSION AND CONCLUSIONS

Hurricane Frances was a strong Category 4 hurricane that directly struck San Salvador on 2 September 2004. The storm made landfall on the island at 3:00 p.m. (EDT) along the southeast side of the island (Parnell et al., 2004). Hurricane Frances approached San Salvador as a Category 4 hurricane and stalled over the island where it became a Category 3 hurricane. Maximum intensity of Hurricane Frances was reached with a double peak (Figure 1). The lowest barometric pressure and highest wind speeds were first reached on August 31- September 1. A second low pressure and high wind speed peak was reached midday on September 2nd when it made landfall on San Salvador (Figure 1).

Our measurements of the maximum storm surge height of 4.8 to 5.5 m were determined by leveling to the highest evidence of flotsam and jetsam at locations along the east side of the island. These values correspond well with the upper limit of storm surge height for a Category 4 hurricane (Table 1). Tidal chart data for the island for 2 September 2004 indicate low tide at 5:06 p.m. and high tide at 11:11 p.m. (Mobile Geographics online). The tide does not seem to be a factor in the storm surge height. One factor that may have increased the storm surge height in this location to the right of the hurricane eyewall is the combined forward motion of the storm center adding to the onshore-directed winds (Figure 10; Liu, 2004).

We could only measure the maximum storm surge height where the coastal topography provided a high enough barrier marking the upper boundary of debris deposition. Areas with lower topography that were overtopped by the storm surge experienced extensive defoliation of the coastal vegetation. We investigated five sites where overwash sediment entered coastal estuaries, lakes, and the back beach areas. These sites included the south end of Storr's Lake, the central Storr's Lake basin from Dim Bay, Salt Pond, Sandy Hook, and the south island along the Gulf. At each of these sites large boulders of local beachrock were transported landward and deposited in a seaward dipping, imbricated pattern. A 300 m length of coastline between Salt Pond and Storr's Lake was defoliated by the storm surge and overwash.

In areas along the east side of the island where the shoreline is bordered by sand dunes, the beach has been widely eroded. Sand from the east

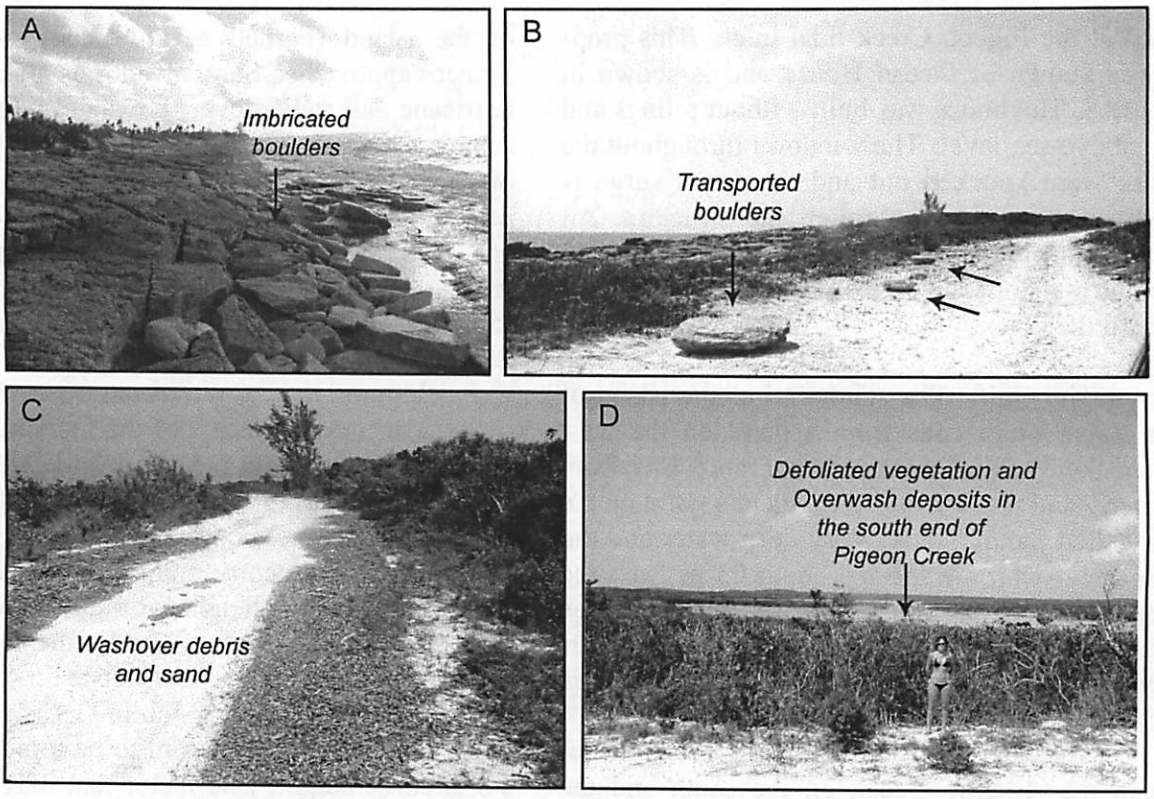

Figure 9. The Gulf is a site located along the south side of San Salvador island where the fringe reef and deep water lie close to the shore line. (See Figure 3 for a location map). A) Photograph along the coast showing imbricated large bedrock slabs and boulders. View to the east. B) Hurricane Frances transported large boulders from the shoreline onto the adjacent road. View to the west. C) In additon to buoys, ropes, plastic and other flotsam and jettsam, the washover debris included large amounts of leaves and organic material stripped from the coastal vegetation and sand. This photograph shows some of the overwash debris. View to the west. D) Overwash sediment was deposited into the southern end of Pigeon Creek. Defoliated vegetation marks the loction of where the storm surge passed.

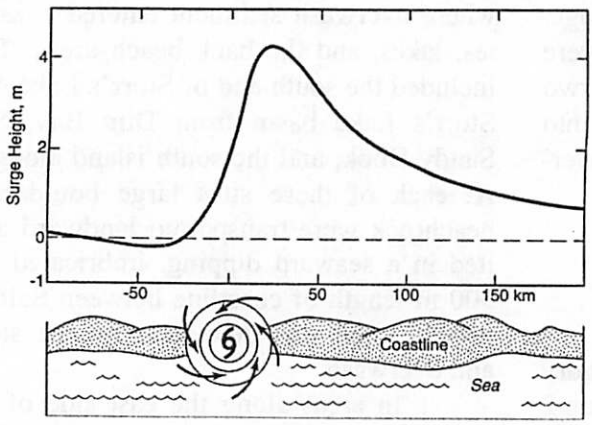

Figure 10. Schematic diagram of the distribution of storm surge heights along a coastline relative to the landfall of the eye of an intense hurricane. The storm surge height is greater on the right side of a hurricane due to the combined forward motion of the storm center and the onshore directed winds. (Figure from Liu, 2004).

face of the sand dunes has been removed as is evident in the development of steep scarps. Adjacent to Salt Pond the coastal sand dune was largely stripped of vegetation and overtopped leaving a blanket of sand in the lake basin. The south side of the island know as 'The Gulf' is composed of lithified Pleistocene reef which is highly resistant to beach erosion. Some blocks in addition to trash and vegetation were washed inland into the south end of Pigeon Creek in the storm surge.

The storm surge from Hurricane Frances or possibly the wind caused Pigeon Creek tidal inlet to overtop its banks along its northwest and north shore. A trench dug in the debris pile west of the road near the abandoned South Victoria Hill settlement exposed a mixture of sand and organic material such as leaves, seeds, and coconuts. Much of the material was decomposed making it an excellent medium for rooting coconut and seeds carried inland by the storm surge. At other locations, lone coconut trees, which are not native to the island, were found at high elevations along these beaches suggesting evidence of past storm surge deposition.

Evidence of Hurricane Frances and other storms were also found in stratified trash deposits south of and around tombolo known as 'The Thumb'. A 1.7-m-thick section was measured that showed 80 cm of aeolian sand burying a 40 cm thick horizon of stratified trash. At this location Hurricane Frances deposits were found at higher elevations and further inland. These data indicate that the Hurricane Frances storm surge was likely more intense than the previous hurricanes that hit the island during the 1990's

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