PROCEEDINGS OF THE 13th SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited By
Lisa E. Park and Deborah Freile

Production Editor
Lisa E. Park

Gerace Research Centre
San Salvador, Bahamas
2008

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.

Produced at
The Department of Geology and Environmental Sciences, The University of Akron

ISBN 0-935909-82-6

THE 2004 HURRICANE FRANCES OVERWASH DEPOSITION IN SALT POND, SAN SALVADOR, THE BAHAMAS

Janice M. McCabe and Tina M. Niemi
Department of Geosciences
University of Missouri-Kansas City
Kansas City, MO 64110
NiemiT@umkc.edu

ABSTRACT

The island of San Salvador experienced the direct hit of the Hurricane Frances on 2 September 2004 as a Category 4 hurricane. The high storm surge from the hurricane breached the sand dunes east of Salt Pond causing an overwash into the basin. Our leveling transect across the dunes and into Salt Pond show that the height of the eroded dune crest is 2.15 m across the main washover. Comparison of this transect to the elevation of the dune crest to the south suggests that as much as 62 cm of sand may have been eroded from the dune. Some of this sand was deposited westward as an overwash fan into the Salt Pond basin. Four shallow trenches were dug at Salt Pond on the mudflat exposed in March 2005 in order to document the sediment and sedimentary structure of the storm surge washover deposits from the 2004 Hurricane Frances. In addition, four cores were collected adjacent to the trenches and were analyzed for grain size and organic content. In all four trenches, the Hurricane Frances overwash fan can be divided into a lower coarse-grained sand with cross bedding and grading that contains shells and shell fragments capped by an upper, medium-grained sand. Parallel asymmetrical ripples are preserved across the upper sand layer near Trench 5. These data indicate that the lower sand formed by migrating sand waves from higher velocity waves compared to the upper sand. The maximum overwash sediment thickness from our study was 12 cm. Capping all of the overwash sand was a 0.5- to 1-cm-thick layer of desiccated cyanobacterial mat. The surface of the exposed lake bed was reddish brown from the mat. The mats draped over the ripple beds. At the base of the crust was a dark brown layer. Our cores penetrated older sediment that underlies the Hurricane Frances overwash sand. Layers of coarse-grained sand with shells and shell fragments that grade up section into finer-grained sand are likely to be the record of previous storm deposits. The data from the four cores suggest that there have been at least two other times that Salt Pond has received storm surge deposits. However, the basal scour of the Hurricane Frances overwash deposits indicates that the record of past hurricanes is likely to be incomplete due to the erosion of sediment in the location where we studied the deposits. Cores from the deeper more distal part of the lake are likely to have a more complete record of storm overwash sedimentation.

INTRODUCTION

The 2004 Atlantic Hurricane season was an active season with an above average six major hurricanes including Hurricanes Charley, Frances, Jeanne, and Ivan that wreaked havoc on islands in the Caribbean, the Bahamas, and making landfall in the United States (NCDC, 2004). The 2004 season was followed by the devastating 2005 hurricane season that spawned an unprecedented 27 named storms and four Category 5 hurricanes including Hurricanes Katrina and Rita (NCDC, 2006). The recent increase in the number and ferocity of hurricanes (Emanuel, 2005) has led to a debate as to whether global warming and the concomitant rise in sea surface temperatures (Mann and Emanuel, 2006) or natural climatic variability (Goldenberg et al., 2001) is the cause for the increased intense hurricanes. Clearly, longer records of past hurricanes are needed to help resolve this debate.

The emerging field of paleotempestology (Liu, 2004; Donnelly and Webb, 2004) has become a powerful tool for assessing the long-term cycles of hurricane activity beyond the period of historical records. Major intense hurricanes, those of Category 3 to 5 on the Saffir-Simpson scale that pass within 50 km to a coastal lagoon or lake, can produce a storm surge large enough to overtop a coastal barrier. The storm surge transports coastal and nearshore sand into the lake where it is deposited as an overwash (or washover) sediment fan. This so-called tempestite is thicker near the coastal barrier and thins toward the center of the lake. In this way, cores recovered from a coastal lake record past intense hurricane landfalls.

This study focuses on hurricane deposition on the Bahamian island of San Salvador. The islands of the Bahamian archipelago are approximately located between latitudes 21°N and 26°N along the Atlantic hurricane track east of Florida and north of Cuba. Most hurricanes cross the region along a track from southeast to northwest, or along a track the moves over the islands from south to north from the Caribbean (Shaklee, 1996). Between the period of 1899 and 1995, Shaklee (1996) reports that thirteen hurricanes have directly tracked over the island of San Salvador. Historical records show a distinct low level of hurricane activity during the three decades of the 1960s through the 1980s (Shaklee, 1996), which corresponds to a general low Atlantic hurricane activity (Nyberg et al., 2007). More recently, San Salvador has been struck by Hurricane Lili in 1996 (Garver, 1996), Hurricane Floyd in 1999 (Curran et al., 2001), and Hurricane Frances in 2004 (Beven, 2004).

Hurricane Frances made initial landfall on the southeast side of the island of San Salvador (Figure 1) with a direct hit of the eyewall on September 2, 2004 at 3 p.m. EDT (Parnell et al., 2004). Just prior to making landfall, Frances was a Category 4 hurricane with sustained maximum winds of 233 kilometers per hour (145 miles per hour). The hurricane stalled over the island and dropped to a Category 3 hurricane. Barometric pressure readings recorded on the island at the Gerace Research Centre at 3 p.m. reached a low of 954 millibars before the instrument failed (Parnell et al., 2004). The heaviest damage to structures was reported in the United Estates settlement on the northeast side of the island, although 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 of 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 were reported by Parnell et al. (2004). The maximum storm surge from Hurricane Frances recorded from the highest elevation of flotsam and jetsam along the southeast shore of the island was 4.8 to 5.5 m (Niemi et al., 2008; this volume). These data and other evidence of coastal damage from Hurricane Frances are presented in a company paper in this volume.

Our study investigates the back-barrier lake know as Salt Pond on the east side of San Salvador (Figure 2). This lake is separated from the ocean by a road and a low coastal dune that acts as a coastal barrier to storms. During Hurricane Frances, the storm surge overtopped and breached the dune and deposited a blanket of sand into the Salt Pond. Our goals were to document the sediment composition and sedimentary structures of the Hurricane Frances overwash deposits in order to provide a modern analog for investigating the frequency of past episodic storm deposition within this and other lake basins. Salt Pond also provides a unique opportunity to monitor the recovery of the coastal sand dune barrier by repeat leveling and visual surveys.

SALT POND

Salt Pond, a small, shallow coastal lake, is ideally situated to preserve a sedimentary record of ancient hurricane deposits. The lake is located along the eastern (windward) side of the island San Salvador (Figure 2) and is separated from the Atlantic Ocean by a narrow coastal sand dune barrier to the east. Bedrock exposed along the northeast shore of the Salt Pond separates it from the

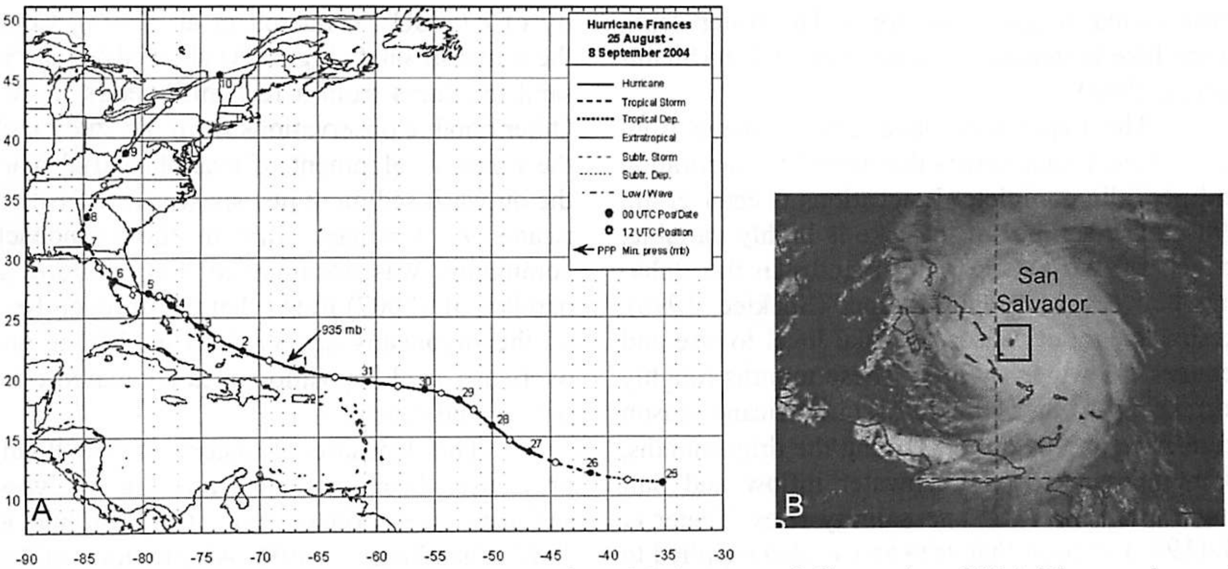

Figure 1. A) Storm track of Hurricane Frances from 25 August to 8 September, 2004. The numbers along the track mark the days. The storm reached its lowest barometric pressure and Category 4 hurricane status on September 1, 2004. Hurricane Frances struck most of the Bahamian Islands as a Category 3 hurricane and Florida as a Category 2 hurricane. (Source of image: Beven, 2004). B) Satellite image showing the eye of the Hurricane Frances passing directly over the island of San Salvador (outlined in the box) (NOAA-16 satellite Advanced Very High Resolution Radiometer (AVHRR) three channel color composite daytime image of Hurricane Frances from 2 Sept. 2004, 18:42 UT).

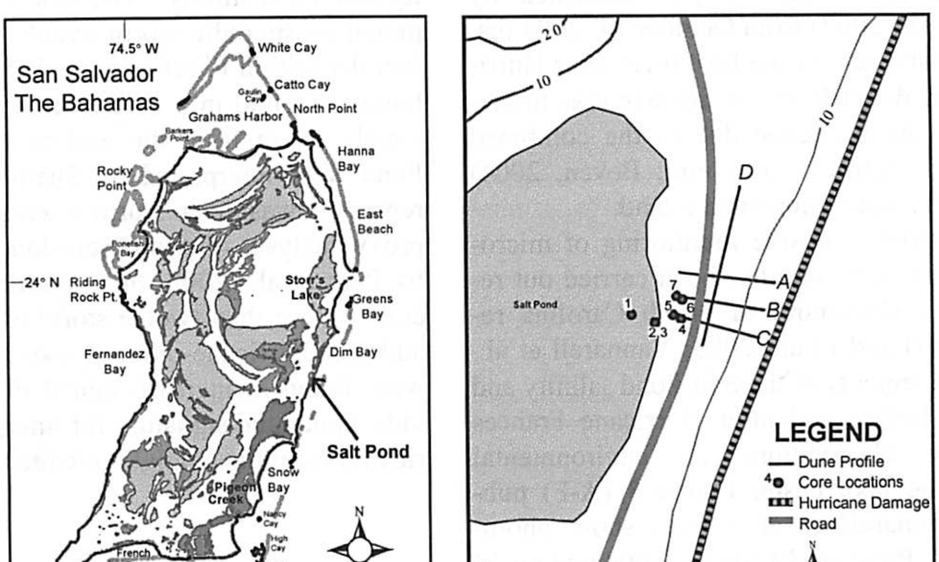

Figure 2. A) Salt Pond is located on the east side of San Salvador. Images are plotted from the GIS database of R. Laurence Davis and Matthew C. Robinson (1999, University of New Haven and the Gerace Research Centre). B) Location of profiles and cores SP05 1-7 collected from Salt Pond during March 2005. Four pits (4-7) were hand dug into the storm surge overwash fan adjacent to cores 4-7. The map also shows the location of three topographic profiles perpendicular to the eroded coastal dunes, labeled A-C, and one topographic profile along the dune crest, labeled D (Profiles shown in Figure 5). Contour interval on map is 10 feet.

Storr's Lake basin to the north. The water depth of the lake in general does not exceed 2 m (Shamberger, 1998).

The hypersaline lake gets its name from halite depositional crusts that form by evaporation and periodic complete desiccations (Teeter et al., 1987). The salinity of the lake is highly variable. In general during the rainy months in the Bahamas between May and October (Shaklee, 1996), freshwater input causes the lake level to rise and 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. Teeter et al. (1987) suggest that seawater is also supplied to Salt Pond through subsurface seepage along the eastern margin of the basin.

High lake level water lines are marked across the bare bedrock that is exposed along the northeast shore of Salt Pond. When we conducted our field research during March 4-11, 2005, the level of Salt Pond was low (Figure 3). This is in marked contrast to photographs published by Yannarell et al. (2007) from October 14, 2004 that show a dramatic rise in the lake level after Hurricane Frances. Water levels of the lake rose immediately after the hurricane due to the combined rainfall (~5.5 inches or 140 mm; Beven, 2004) and the marine water inundated inland.

The most extensive monitoring of microbial activity in Salt Pond has been carried out recently by the University of North Carolina research group (Paerl et al., 2003; Yannarell et al., 2007). Measurements of the Salt Pond salinity and photographs before and after Hurricane Frances provide key observations on environmental changes in the lake basin. Figure 3 (A-F) published in Yannarell et al. (2007) show photographs of Salt Pond on 30 August 2004 and on 14 October 2004. These data closely bracket the effects of Hurricane Frances that struck the island on 2 September 2004. The salinity of the lake on 30 August 2004, reported as 280 PSU (practical salinity units; 35 is normal sea water), was reduced on 9 September 2004, just one week after Hurricane Frances impacted the island, to a salinity of 87 PSU (Yannarell et al., 2007). Cores of the outwash sand (Figure 3) showed variations in sand thickness from a few millimeters to 10 cm. Other notable observations from the study include the rapid development of cyanobacterial mats on the outwash sediment just six weeks after the hurricane. A dominant shift in the cyanobacteria community was documented. Furthermore, Yannarell et al. (2007) found that the nitrogen fixation of the organisms appeared to be higher on the overwash sand deposition sites compared to areas with a mud substrate.

The depositional history of Salt Pond has previously been studied from the analyses of sediment cores (Teeter et al., 1987; Furman et al. 1992; Shamberger, 1998). All previous studies of cores indicate that the sedimentary cover overlying bedrock is quite thin. The longest core recovered from the lake is 84 cm in length. These studies show that Salt Pond sediment is composed of organic-rich carbonate mud interbedded with sand layers and evaporites (namely gypsum and halite) representing alternating periods of low lake salinity and hypersalinity. The sand layers were interpreted as sporadic storm events or possible aeolian deposition (Teeter et al., 1987). Twelve sand horizons found in a core extracted from approximately 30 m from the eastern edge of the Salt Pond were interpreted by Shamberger (1998) to represent washover storm events. Recent multi-proxy analyses of two 60-cm-long sediment cores by Park et al. (2008; this volume) found considerably more than twelve storm event horizons. In addition, hurricane-induced lake freshening events were found to increase faunal diversity and provide a potential signature for interpreting past hurricanes from the stratigraphic record.

COASTAL DUNE PROFILES

East of Salt Pond are low-lying coastal sand dunes that are stabilized at their base by bedrock (Shamberger, 1998). The dunes were eroded and overtopped by the Hurricane Frances storm surge (Figure 4). Some of the imbricated

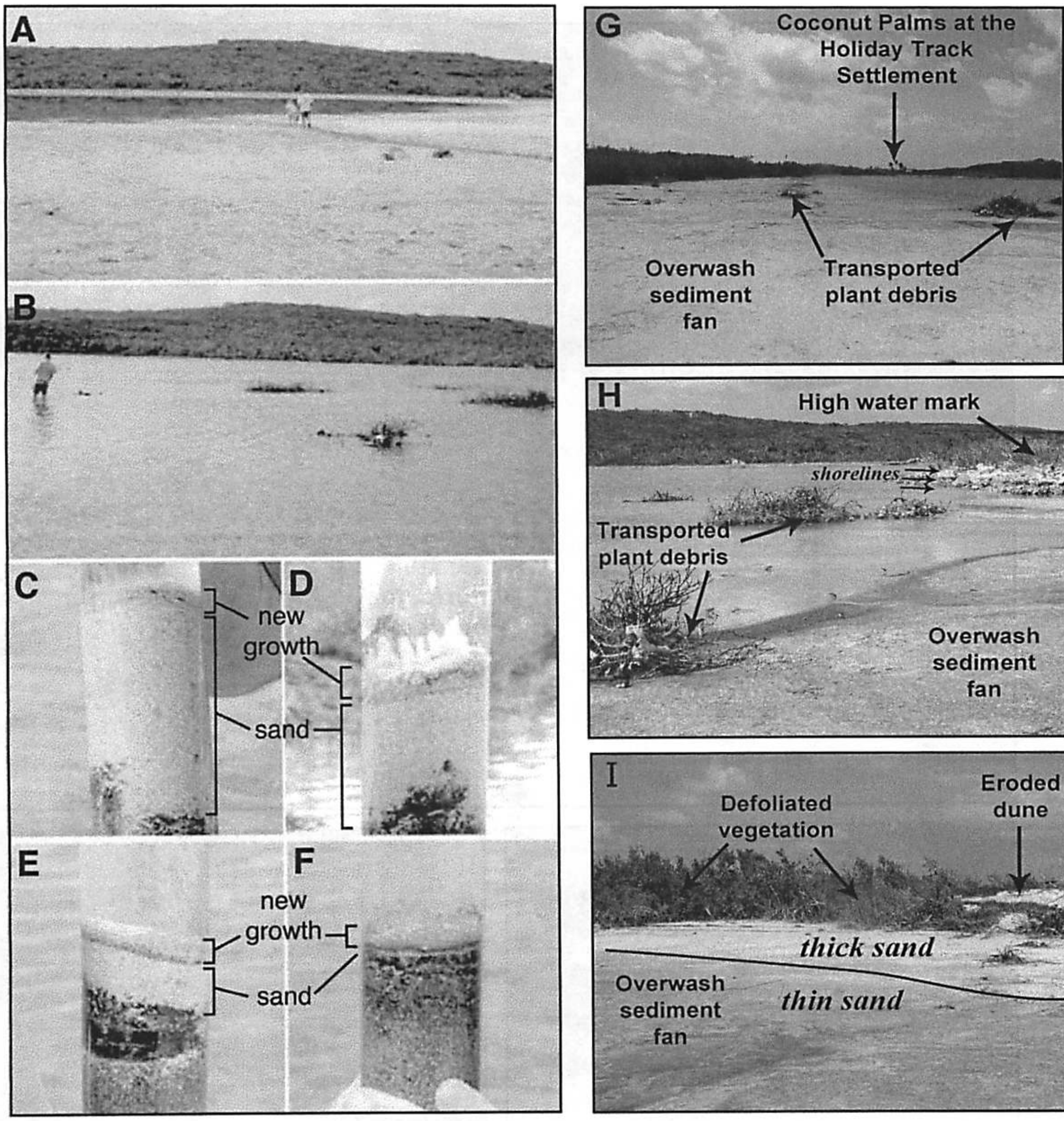

Figure 3. Photographs of Salt Pond from from August 2004, October 2004, and March 2005. Photographs A-F were published in Yannarell et al. (2007). A) View toward the west across Salt Pond from 30 August 2004 before Hurricane Frances (Yannarell et al., 2007). B) View toward the west across Salt Pond from 14 October 2004 after Hurricane Frances (Yannarell et al., 2007). C-F) Cores taken of the Hurricane Frances storm surge sand showing the buried microbial mats and the new growth of cyanobacteria on 14 October 2004 (Yannarell et al., 2007). G) View south across the Hurricane Frances overwash sand deposited as a fan into the northeastern edge of Salt Pond in March 2005. H) View northwest across Salt Pond in March 2005. Bushes transported into the lake by the storm surge are shown. Shorelines shown as water marks on bedrock (arrows). I) Photograph showing the overwash sediment fan in Salt Pond viewed toward the northeast and the Atlantic Ocean in March 2005. The vegetation along this shoreline has been defoliated by the storm surge. The low sand dune that acted as a barrier between Salt Pond and the Atlantic Ocean was extensively eroded and is shown in the background of the photograph.

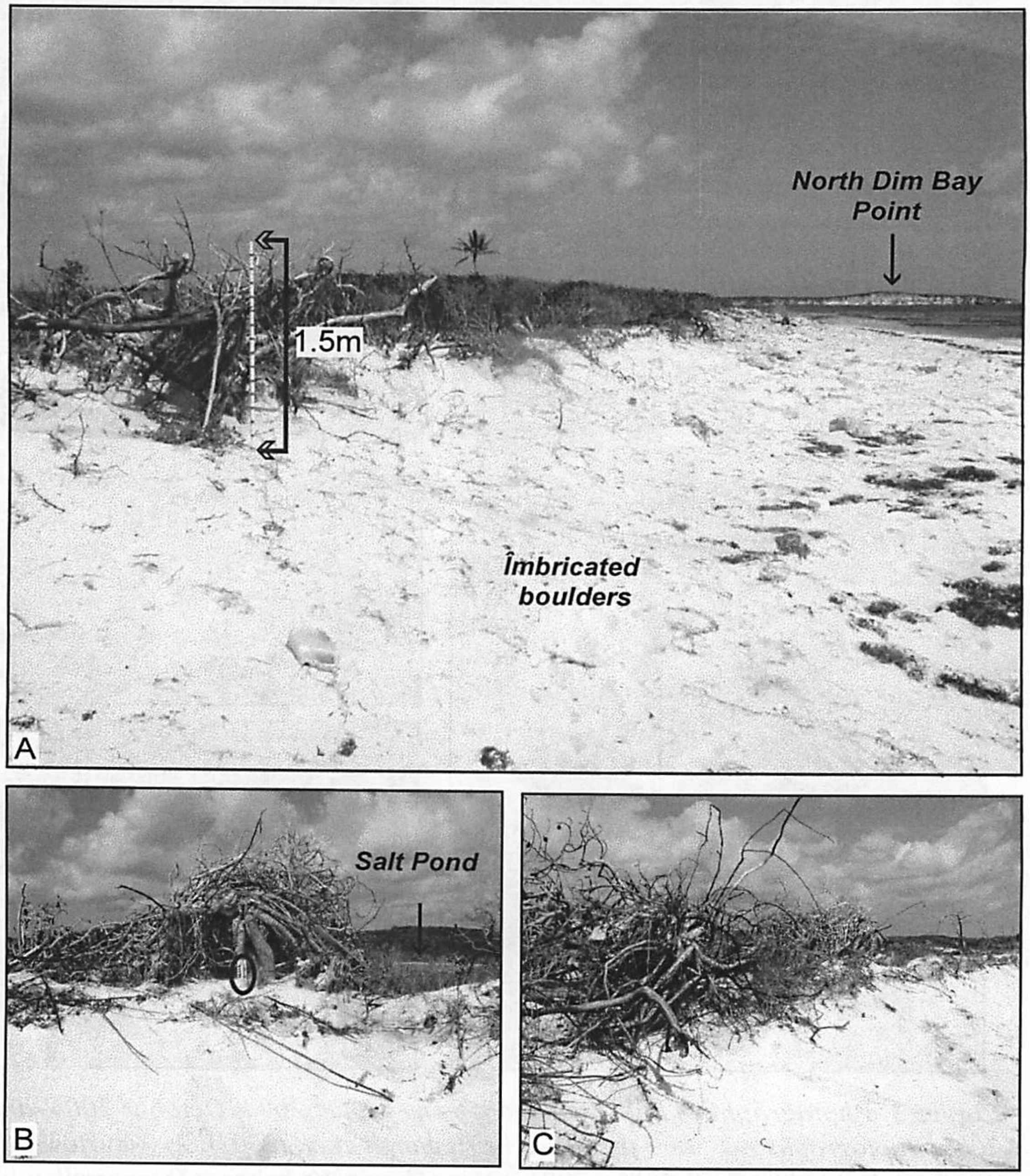

Figure 4. Photographs of the coastal dune barrier between Salt Pond to the west and the Atlantic Ocean to the east from March 2005. A) The low coastal dunes east of Salt Pond were eroded and overtopped by the Hurricane Frances storm surge. View northward along the dunes with the point at the north end of Dim Bay shown. In the foreground are imbricated beachrock boulders dipping seaward that were transported inland by the hurricane storm surge and previous storms. B) The coastal vegetation was uprooted, removed, and defoliated on the sand dunes adjacent to Salt Pond. View toward the west and Salt Pond. Oval circle marks a 15-cm photo scale. C) The 70-m-long sand dunes east of Salt Pond were eroded and overtopped. Some of the debris was deposited inland into the Salt Pond basin. View toward the northwest.

beachrock slabs that dip seaward were likely transported landward to the base of the eroded sand dune by the Frances storm surge (Figure 4). The coastal vegetation was uprooted, overturned, removed, and defoliated. Vegetation where the washover occurred was scarce and consisted largedly of new growth in March 2005. Shrubs from the eroded sand dune were also transported into the lake (Figure 3). Bioclastic carbonate sand eroded from the dunes, beach, and subtidal environment by the storm surge was transported inland and deposited in the Salt Pond basin. The median grain size of the beach sand adjacent to Salt Pond as determined by Park et al. (2008, this volume) is 300 microns (medium-grained sand).

Topographic profiles were constructed in March 2005 along three transects from the low tide to Salt Pond and one along the dune crest (Figure 5). The profiles were measured by using a hand level and a 1.5 m stadia rod divided into 10 cm increments. We recorded the elevation variations along the profile at each major inflection point. Transects were measured across the north (Profile A) and south (Profile C) limits of the major washover. The middle profile B was placed at the point of maximum erosion. The washed out dune was measured longitudinally between points of heavy vegetation from the north and south along the dune crest and across the eroded vegetation in Profile D.

The profiles shown in Figure 5 represent the state of the beach and dunes six months after Hurricane Frances. We do not have data for this location prior to the tropical cyclone. Our data show that the height of the dunes was lowest (2.15 m) along profile B and was slightly higher along the north and south profiles (2.55 m and 2.77 m, respectively). The topographic contour map of this coastal location (Figure 2) indicates that the dunes may have been as high as the 10-foot contour (3.0 m) prior to the storm.

The width of the sand dunes east of Salt Pond was narrowest (11 m) along the southern profile. Also along the south profile, a steep eastward-facing scarp was formed by erosion of the sand dune. This type of erosion was prevalent along the eastern coast of San Salvador in locations where the dunes were not overtopped by the storm surge but eroded at their base. The longitudinal profile (D) shows the location of the 30-m-long washover into Salt Pond between Profile C in the south and Profile A in the north. South of profile C, storm surge washover was minimal as the coastal dune is here higher. North of profile A, the Hurricane Frances storm surge overwashed the coastal dunes and defoliated the vegetation along an additional 250 m length of this shoreline (Niemi et al., 2008, this volume).

Our profile data show that the distance from the low tide mark to the shore of Salt Pond is between 43 m and 53 m. The Salt Pond basin floor was lower than our starting point on the beach. At the time of our observations in March 2005, flotsam and jetsam brought into the Salt Pond basin by the storm surge was still visibly caught in the coastal shrubs along the northeast shore of the lake. Washover into Salt Pond deposited debris 1.5 m above the shore of the high water line of the lake. The highstand lake level appeared to be about 0.35 m above the March 2005 levels.

HURRICANE DEPOSITION IN SALT POND

In order to investigate the thickness, depositional style, and sedimentary structures of the overwash sediment, we collected and described the deposits in cores and in shallow trenches. We used a 5-cm-diameter, clear plastic, piston corer from the Gerace Research Centre to collect cores. Three cores (SP05 1-3 in Figure 2) were taken within the shallow water of Salt Pond on the distal portion of the overwash fan. The recovery of these cores was low (measuring only between 10 cm to 13 cm) and disturbed within a slurry of water. This paper describes the analyses of the four cores (SP05 4-7 in Figure 2) that were collected on the exposed mudflat and overwash fan. Cores SP05-4 and SP05-5 were located about 2 m and 10 m (respectively) from the eastern margin of the Salt Pond basin along the south profile C (Figure 5). Cores SP05-6 and SP05-7 were the same distance from the basin edge as cores SP05-4 and SP05-5 but along the middle profile B (Figure 5). In the

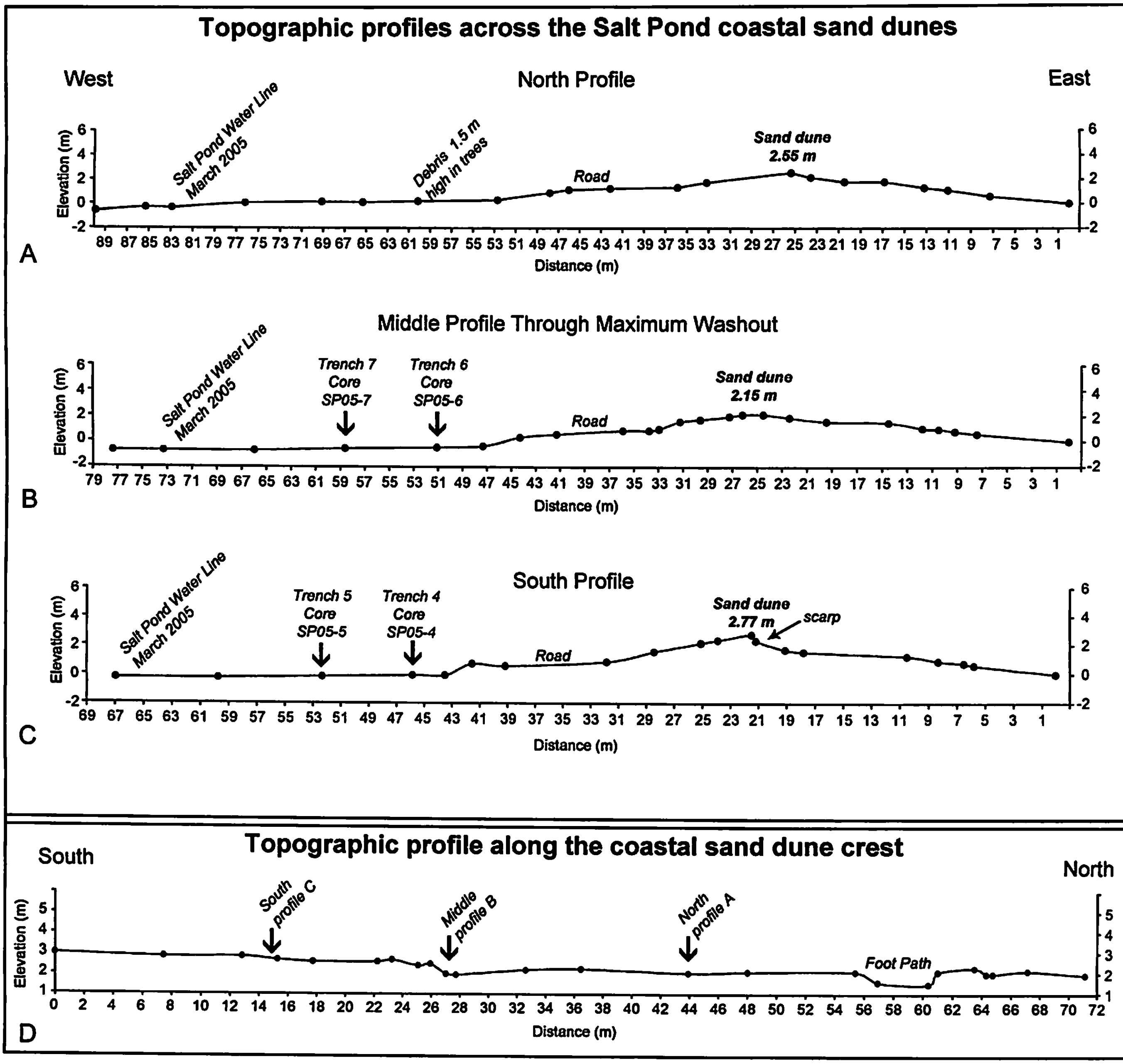

Figure 5. Topographic profiles of the coastal sand dunes east of Salt Pond constructed by leveling in March 2005. A) The northernmost topographic profile from the low tide beachface into the Salt Pond basin to the west. B) Topographic profile through the lowest washout in the sand dunes adjacent to Salt Pond. The location of Trenches 6 and 7 and Cores SP05-6 and SP05-7 are shown. C) The southernmost topographic profile across a partially eroded sand dune. A steep eastward-facing scarp was formed by erosion of the sand dune (see photographs in Figure 4). The location of Trenches 4 and 5 and Cores SP05-4 and SP05-5 are shown. D) Topographic profile along the crest of the sand dune east of Salt Pond. The location of the cross profiles are shown. The 30-m length of sand dune between the south and north profiles was heavily eroded with large tracts of coastal vegetation completely removed. A second zone of erosion is seen north of the northermost topographic profile. This low-lying area appears to be an area of little vegetation and enhanced erosion due to a foot path for beach access and boat launch. Extensive storm surge overwash occurred northward to the south end of Storr's Lake.

field, the cores were described while they were still in the clear acrylic core barrel. The cores were then extruded, wrapped, and shipped to UMKC for further study.

Adjacent to cores SP05 4-7, we hand excavated shallow trenches to expose the sedimentary structures and the lateral variations of the sand sheet. The trench dimensions were about 30 cm by 50 cm. Trenches 4-7 were about 12 cm in depth, while Trench 7 was excavated to a depth of 17 cm. Because of water infiltration, only the upper 7-9 cm of sediment was clearly exposed. Field sketches, descriptions, and photographs were made of the trench exposures.

Additional analyses on the core sediment were conducted in the UMKC laboratory. Cores were sampled every 4 cm. Grain-size analyses were determined using the sieve method of Folk (1974). Samples were first oven dried for 12 hours. The dried sand was reweighed and sieved using U.S. Standard Sieve Series mesh sizes 40 (0.42 mm) for coarse-grained sand, 60 (0.25 mm) for medium-grained sand, 120 (0.125 mm) for fine-grained sand, and 220 (0.074 mm) for very fine-grained sand. Sand trapped on each sieve was weighed. The weight percentage for each of the grain-size categories was calculated and plotted on a graph verse depth of sample. The percent organic matter of approximate 0.1 grams of each sample was determined using the loss-on-ignition method (Dean, 1974). The following section describes the results of both the field and laboratory analyses of each of the trench exposures and core samples.

Description of Trench Exposures and Cores

Trench and Core 4 The exposure of Hurricane Frances overwash sand in Trench 4 and in Core SP05-4 is shown in Figure 6. The upper layer of Trench 4 and Core SP05-4 is a post-Hurricane Frances cyanobacterial mat layer and surface crust. This layer is composed of a 3 mm dark, organic mat buried at a depth of 1 cm below a thin, surface sand and crust. The surface sand is organic rich and appears red in color similar to the exposed mudflat crust. Below the cyanobacterial mat layer and surface crust (designated unit 1), approximately 11 cm of sand were deposited from the Hurricane Frances storm surge. The deposit can be divided into two distinct sand layers with an apparent erosional lower contact. The upper 4- to 6-cm-thick unit 2 is a medium- to fine-grained sand. The lower unit 3 is a coarse- to medium-grained sand that contains organic debris, shells, and shell fragments. Unit 3 appears to contain cross laminations and several cycles of graded bedding.

Grain-size analyses of sediment from Core SP05-4 clearly show that the sand is predominantly medium grained (0.5 to 0.25 mm) in size throughout the entire 36 cm length of the core. Grading of the lower Hurricane Frances sand (unit 3) is evident in the data. The core also provides data for pre-Hurricane Frances storm deposition. At least two lower cycles of beds with fining upwards (graded) sequences with a higher percentage of coarse-grained sand at the base and fine-grained sand at the top are seen in unit 6 and units 4-5 in the core stratigraphy. At the present resolution, the organic matter data do not show a significant change with depth in this core.

Trench and Core 5 Trench 5 and Core SP05-5 (Figures 2, 5, and 7) were located farther into the Salt Pond basin than the location 4. One of the most unique features of this area is the surface bedforms exposed across the lake bottom. The exposed lake floor shows parallel ripples draped with red-colored cyanobacterial mats. The ripple bed migration is toward the southwest (Figure 5A). The stratigraphic section in Trench 5 shows an upper post-Hurricane Frances surface organic mat similar to Trench 4. The Hurricane Frances storm surge deposit at this location was 3 cm thick and consisted of three faint layers (units 2a, 2b, and 2c). These layers show a slight change in color that may reflect a slight compositional change. The base of unit 2 is flat and appears to be aggradational, and resting conformably on the underlying organic-rich unit 3. This is in contrast to other

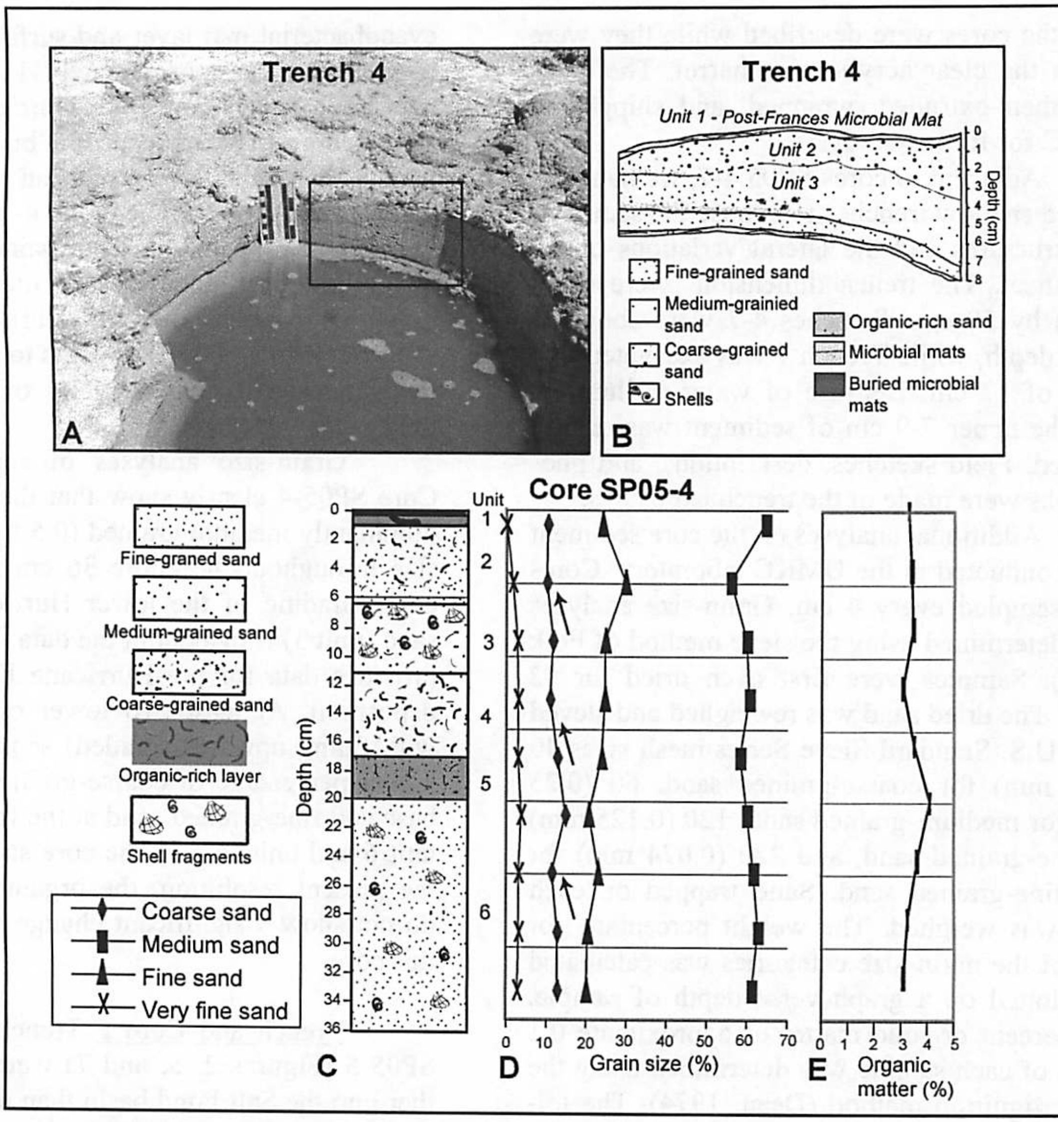

Figure 6. Exposure of Hurricane Frances overwash sand in Trench 4 and in Core SP05-4. A) Photograph of Trench 4 viewed toward the southeast. Approximately 11 cm of sand were deposited from the Hurricane Frances storm surge in two distinct sand layers. The box outlines the area drawn in Figure 6B. B) The base of the storm surge is defined by an erosional lower contact. The11-cm-thick storm surge sand appears to be divided into a lower coarse- to medium-grained sand that contains organic debris and shell fragments (unit 3), and an upper medium- to fine-grained sand (unit 2). Faint indications of graded bedding and cross laminae are present. C) Lithologic section through Core SP05-4. D) Grain-size analyses of sediment from Core SP05-4 clearly show that the sand is predominantly medium grained in size throughout the entire 36 cm length of the core. The arrows show beds with fining upwards (graded) sequences. E) The percentage of organic matter in the core showing a layer at 20 cm depth with a slight increase.

locations where the base of the Hurricane Frances storm surge sand is erosional.

Beneath the Hurricane Frances storm surge overwash fan is a 5-cm-thick, organic-rich sand (unit 3) with 14% organic matter (Figure 7F). The upper 1 cm of unit 3 is a buried, dark-colored organic mat. This buried mat was also observed in cores of Yannerell et al. (2007; Figs. 3 A-F). A thin white-colored, sand layer below this buried mat may represent overwash deposition from the 1999 Hurricane Floyd (Figure 7). The exposed sediment in Trench 5 appears similar to photographs published in Paerl et al. (2003) of the microbial mats taken after that Floyd.

A detailed drawing of a portion of this unit (Figures 7B and 7C) shows that it is composed of several horizontally bedded layers of coarse- to medium-grained sand with shells interbedded with black organic mats. Along one portion of unit 3, an angular contact between sand and the underlying organic mats indicates an erosional event. The organic-rich layers and sand layers appear predominately as interbedded sheets indicating that episodic overwash deposition of sand has buried the microbial mats at this location. An adjacent portion of the Trench 5 wall shows bioturbation and is homogenized possibly indicating previous storm remobilization or disturbance by people walking on the mudflat.

Several layers of shell-rich, coarse- to medium-grained sand layers (units 4-6) are found to a depth of 20 cm in core SP05-5. Grain-size analyses of sediment from core SP05-5 indicate that between 40-60% of the sand is medium grained in size. Several coarse-grained sand layers with shell fragments probably represent previous storm deposits in Salt Pond.

Trench and Core 6 Approximately 12 m north of cores 4 and 5, Trench 6 and Core SP05-6 were located in the Salt Pond basin along the path of the maximum washout of the coastal dune (Profile B, Figure 5). The sandy surface of the overwash storm surge fan is here, as in the other locations, composed of a crust with a cyanobacterial mat within medium-grained sand to a depth of 0.5 cm. The storm surge sand has a lower erosional contact that scours the underlying sand (Figure 8). The wavelength of the scour appears to be approximately 15 cm. The cross lamination in the lower coarse-grained sand shows sedimentary migration toward the southwest. The upper fine- to medium-grained sand (unit 2a) is an even 1 cm-thick deposit that is lighter in color from the deposits above and below it. It may represent a post-storm surge deposit.

Underlying the Hurricane Frances sand in Core SP05-6, unit 3 is a 5- to 7-cm-thick mixed organic-rich sand. It is coarse to medium grained and contains wood and other debris at its base. It is likely to present an amalgamation of previous storm surge deposits. The mixed nature of the deposit also suggests that it may be bioturbated, perhaps from people walking over the surface.

Between a depth 10 cm and the base of the core at 36 cm, two depositional events are evident that may be interpreted as storm related. The first event occurs at about 17 cm depth (unit 4), and the second at 230 cm (unit 5). These events are identified based on an increase in the coarse- and medium-grained sands and a decrease in fine-grained sand and organic material (Figure 8).

Trench and Core 7 Located just 8 m west of Trench 6, Trench 7 contains the thickest overwash sediment from our study. The 12 cm-thick Hurricane Frances storm surge deposits (Figure 8) contained a lower, cross-bedded sand (unit 2b). Unit 2b is coarse grained at its base and grades upward to medium- and fine-grained sand. The storm surge layer did not extend evenly across the trench. The base of the sand was marked by a deep (>7 cm), erosional scour. The scour trough trends northwest-southeast across the trench. The erosion truncated a 2 cm-thick microbial mat and underlying 5 cm-thick mixed organic-rich sand with wood debris. Unit 2b truncates and buries the cyanobacterial mat. The upper 2-3 cm of the storm surge deposit

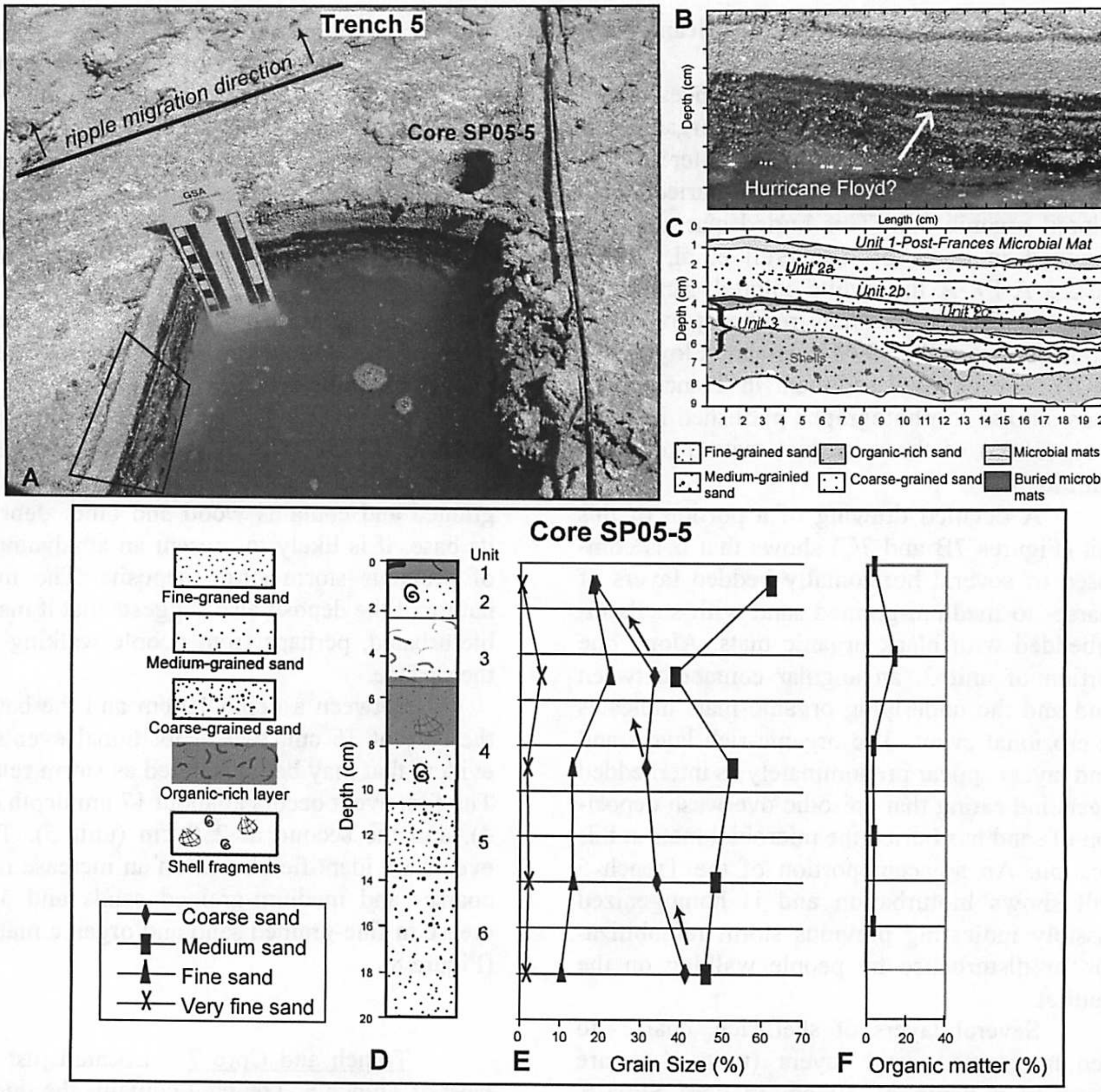

Figure 7. Stratigraphic sections from Salt Pond Trench 5 and Core SP05-5. A) Photograph of Trench 5 showing the locations of Core SP05-5 and area of close-up detail (Figs. 7 B and C). The surface of the exposed lake basin floor shows parallel ripples draped with red-colored microbial mats. The ripple bed migration is toward the southwest. B) Detailed photograph of the south wall of Trench 5. C) Sketch of the stratigraphic layers. The upper layer consists of the post-Hurricane Frances microbial mat. The Hurricane Frances storm surge deposit is 3 cm thick and buries layers of microbial mats and thin sand sheets. D) Lithologic section of core SP05-5 showing division into 6 units. The Hurricane Frances storm surge overwash fan (unit 2) overlies an organic-rich sand (unit 3) and several layers of shell-rich coarse- to medium-grained sand layers. E) Grain-size analyses of sediment from core SP05-5 indicate that between 40-60% of the sand is medium grained in size. The arrows show beds with fining upwards (graded) sequences. F) The percentage of organic matter was measured using the loss-on-ignition method (Dean, 1974). Unit 3 was shown to have nearly 14% organic matter.

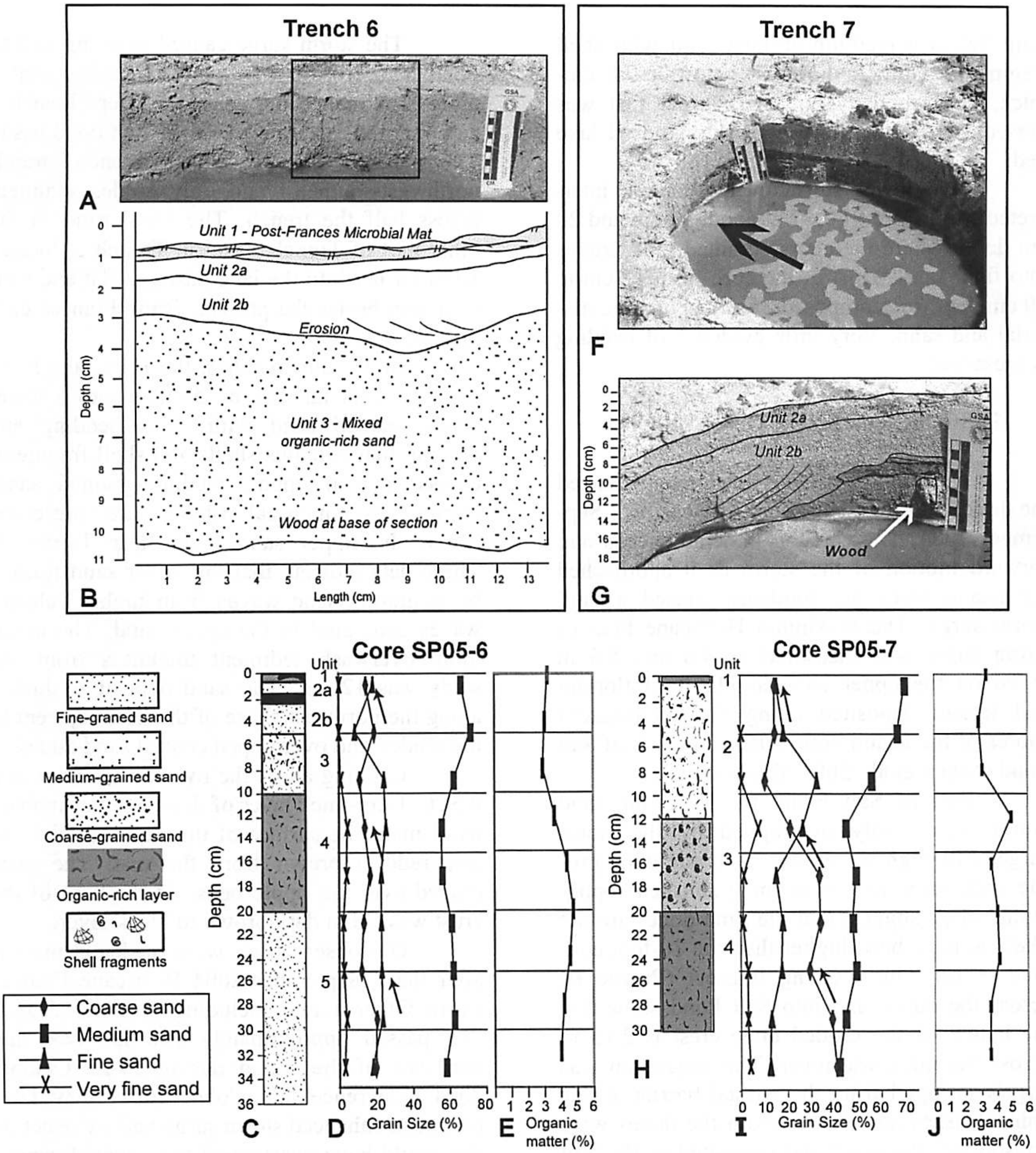

Figure 8. Subsurface exposures of Trenches 6 and 7 and stratigraphic data for Salt Pond core SP05-6 and core SP05-7. A and B) View of Trench 6 showing the irregular erosional base of the Hurricane Frances storm surge sand. Top layer consists of a microbial mat. C) Lithologic section of Core SP05-6. D and E) Grain-size and organic content data for Core SP05-6. See text for discussion. F) Photograph of Trench 7 viewed toward the north. The arrow points to the pit wall that is detailed in Figure 8G. G) Detailed view of the basal scour of the Hurricane Frances storm surge. The overwash sediment apron here consists of a lower cross-bedded sand (Unit 2b) and and upper ripple-bedded sand (Unit 2a). H) Lithologic section of core SP05-7. I and J) Grain-size and organic matter data for core SP05-7 . See text for discussion.

(unit 2a) is a medium-grained sand with shell fragments. Unit 2a lies just below a 0.5 cm-thick, desiccated cyanobacterial mat that was present across the surface of the exposed lake bed.

Two lower storm events can be interpreted from Core SP05-7 at about 17 cm and 28 cm depth where the coarse-grained sand grades into finer sand. Most of the core from 12 cm to 30 cm depths is composed of mixed organic material and sand. Very little evidence of bedding is preserved.

DISCUSSION AND CONCLUSIONS

The island of San Salvador experienced the direct hit of the Hurricane Frances on 2 September 2004. The category 4 wind speeds and forward motion of the storm as it approached the island from the southeast caused a high storm surge. The maximum Hurricane Frances storm surge was measured as 4.8 and 5.5 m based on the upper elevation limit of flotsam and jetsam deposited along the southeastern shores of the island both north and south of Salt Pond (Niemi et al., 2008; this volume).

East of Salt Pond, the low-lying sand dunes were easily overtopped by the storm surge. Although we do not have any dune profile data prior to the storm, published topographic maps suggest that the sand dunes are not likely to have been higher than the 10-foot contour (3 m). Our leveling transect (Profile B) across the dunes and into Salt Pond show that the height of the eroded dune crest is 2.15 m across the main washover. The vegetation was largely stripped from the coastal barrier at this point. Bushes and shrubs from the dunes were transported westward and deposited in the Salt Pond basin. A comparison of profile B with a transect to the south with a dune crest of 2.77 m and considerably less removal of dune vegetation suggests that perhaps as much as 62 cm of sand was removed from the coastal barrier. Some of this sand from the dunes was deposited westward as an overwash fan into the Salt Pond basin.

The storm surge caused scouring in Salt Pond. This erosion is evident in trenches located more proximal to the coastal barrier (Trench 4 and 6) at the eastern edge of the Salt Pond basin. The trough of the deep scour in Trench 7 trends northwest-southeast and only erodes sediment across half the trench. The basal sand in the other part of Trench 7 and in Trench 5, located 10 m farther into the lake basin, is flat and conformably buries the pre-Hurricane Frances dark organic mat.

In all four trenches, the Hurricane Frances overwash fan can be divided into a lower coarse-grained sand with cross bedding and grading that contains shells and shell fragments capped by an upper, medium-grained sand. Parallel asymmetrical ripples are preserved across the upper sand layer near Trench 5. These data indicate that the lower sand formed by migrating sand waves from higher velocity waves compared to the upper sand. The maximum overwash sediment thickness from our study was 12 cm. The sand deposit is thicker along the northeast shore of the lake adjacent to the eroded and overtopped coastal sand dunes.

Capping all of the overwash sand was a 0.5- to 1-cm-thick layer of desiccated cyanobacterial mat. The surface of the exposed lake bed was reddish brown from the mat. The mats draped over the ripple beds. At the base of the crust was a thin dark brown to black layer.

Our observations were made six months after the 2 September 2004 Hurricane Frances storm. Other storms, including Hurricane Jeanne that passed approximately 100 km east and northeast of the island during 19-25 October 2004 (Lawrence and Cobb, 2005) may have produced enhanced storm surge and wave action that could have overtopped the lowered coastal barrier. It is not possible from our study to definitely ascribe all of the sedimentary structures observed in the trenches and upper layers of the cores to Hurricane Frances.

However, the study and photographs published by Yannarell et al. (2007) provide support to the interpretation that cyanobacterial mats were already growing on 14 October 2004.

The Yannarell et al. (2007) study documented microbial mat activity after Hurricane Frances and before Hurricane Jeanne. Since the cyanobacterial mats drape the ripple beds it suggests that both the lower and upper sand seen in the trenches are Hurricane Frances storm surge deposits.

The Yannarell et al. (2007) study also showed both a surface growth of a microbial mat, and modification of the sediment to a depth of about 1 cm. The study clearly demonstrates that microbial activity is not limited to the sediment-water interface.

Hurricane Floyd (1999) overwash deposition was documented by Paerl et al. (2003). These authors note that a thin layer of carbonate sand was deposited on top of the microbial mats and provided a clear marker bed for the study. The Floyd overwash appeared as a white sand layer overlying a black organic mat. In the Paerl et al. (2003) study, the surface microbial mats were shown to be horizontally stratified in three layers: 1) the upper brown-colored cyanobacterial mat, 2) a lighter-colored subsurface photosynthetic bacterial layer, and 3) a deeper, balck anerobic sufide layer. We observed similar layering in Trench 5 where horizontally interbedded sand and black organic-rich layer was buried by the Hurricane Frances overwash deposit. The upper thin sand sheet in this buried unit (3) may possible represent the Hurricane Floyd overwash sand.

Our cores penetrated older sediment that underlies the Hurricane Frances overwash sand. Layers of coarse-grained sand with shells and shell fragments that grade up section into finer-grained sand are likely to be the record of previous storm deposits. The data from the four cores suggest that there have been at least two other times that Salt Pond has received storm surge deposits. However, the basal scour of the Hurricane Frances overwash deposits indicates that the record of past hurricanes is likely to be incomplete due to the erosion of sediment in the location where we studied the deposits. Cores from the deeper more distal part of the lake are likely to have a more complete record of storm overwash sedimentation.

ACKNOWLEDGMENTS

We thank Vincent Voegeli, past Executive Director of the Gerace Research Centre, for discussions and guidance in locating Hurricane Frances storm deposits on San Salvador. Funding for this project was made available through the UMKC Students Engaged in Artistic and Academic Research (SEARCH) and through funds from the UMKC Department of Geosciences. We thank Alexander Daehne, Jennifer Goucher, and Ta'ni Sutherland for assistance in the field. We would also like to thank Dr. Donald T. Gerace, Chief Executive Officer, and Dr. Thomas A. Rothfus, present Executive Director of the Gerace Research Centre, San Salvador, Bahamas for assistance and use of the field station on San Salvador. This study was conducted under permit number 07-05 and earlier permits from the Department of Agriculture, The Bahamas.

REFERENCES

Beven II, J.L., 2004, Tropical cyclone report: Hurricane Frances 25 August-8 September 2004: NOAA National Weather Service, National Hurricane Center, http://www.nhc.noaa.gov/2004frances.shtml, posted 17 December 2004.

Curran, H.A., Delano, P., White, B., and Barrett, M., 2001, Coastal effects of Hurricane Floyd on San Salvador Island, Bahamas, *in* Greenstein, B.J., and Carney, C.K., eds., Proceedings of the 10th Symposium on the Geology of the Bahamas and Other Carbonate Regions: San Salvador, Bahamas, Gerace Research Centre, p. 1-12.

Dean, W.E. Jr., 1974, Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods: Journal of Sedimentary Petrology, v. 44, p. 242–248

Donnelly, J.P., and Webb III, T., 2004, Back-barrier sedimentary records of intense hurricane landfalls in he Northeastern United States, *in* Murnane, R.J., and Liu, K.-B., eds., Hurricanes and Typhoons: Past, present, and future: Columbia University Press, New York, p. 58-95.

Emanuel, K.A., 2005, Increasing destructiveness of tropical cyclones over the past 30 years: Nature, v. 436, p. 686-688.

Folk, R.L., 1974, Petrology of Sedimentary Rocks: Hemphill Publishing Company, Austin, TX.

Furman, F.C., Woody, R.E., Rasberry, M.A., Keller, D.J., and Gregg, J.M., 1992, Carbonate and evaporite mineralogy of Holocene (<1900 RCYBP) sediments at Salt Pond, San Salvador Island, Bahamas, preliminary study, *in* White, B., ed., Proceedings of the Sixth Symposium on the Geology of the Bahamas: Bahamian Field Station, San Salvador, Bahamas, p. 47-54.

Garver, J.I., 1996, Some Effects of Hurricane Lili on San Salvador Island, Bahamas. http://minerva.union.edu/garverj/geo35/hurricane/Damage.htm, Geology Department, Union College, Posted 15 December 1996.

Goldenberg, S.S., Landsea, C.W., Mestas-Nuñez, A.M., and Gray, W.M., 2001, The recent increase in Atlantic hurricane activity: causes and implications, p. 474-479.

Lawrence, M.B. and Cobb, H.D., 2005, Tropical Cyclone Report: Hurricane Jeanne 13 - 28 September 2004: NOAA National Weather Service, National Hurricane Center. http://www.nhc.noaa.gov/2004jeanne.shtml, posted 22 November 2004. Revised: 7 January 2005.

Liu, K.-B., 2004, Paleotempestology: Principles, methods, and examples from Gulf Coast lake sediments, *in* Murnane, R.J., and Liu, K.-B., eds., Hurricanes and Typhoons: Past, present, and future: Columbia University Press, New York, p. 13-57.

Mann, M.E., and Emanuel, K.A., 2006, Atlantic hurricane trends linked to climate change: Eos, v. 87, p. 233-241.

NCDC (National Climatic Data Center), 2004, Climate of 2004 Atlantic Hurricane season: National Climatic Data Center, NOAA: http://www.ncdc.noaa.gov/oa/climate/research/2004/hurricanes04.html, last updated - 13 December 2004.

NCDC (National Climatic Data Center), 2006, Climate of 2005 Atlantic Hurricane Season: NOAA http://www.ncdc.noaa.gov/oa/climate/research/2005/hurricanes05.html, last updated 21 August 2006.

Niemi, T.M., Thomason, J.C., McCabe, J.M., and Daehne, A., 2008, Impact of the September 2, 2004 Hurricane Frances on the coastal environment of San Salvador, The Bahamas, *in* Park, L.E. and Freile, D., eds., Proceedings of the Thirteenth Conference on the Geology of the Bahamas and Other Carbonate Islands, This Volume, p. 42-62.

Nyberg, J., Malmgren, B.A., Winter, A., Jury, M.R., Kilbourne, K.H., and Quinn, T.M., 2007, Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years: Nature, v. 447, p. 698-701.

Paerl, H.W., Steppe, T.F., Buchan, K.C., and Potts, M., 2003, Hypersaline cyanobacterial mats as indicators of elevated tropical hurricane activity and associated climate change: Ambio, v. 32, p. 87-90.

Parnell, D.B., Brommer, D., Dixon, P.G., Brown, M.E., and Gamble, D.W., 2004, A survey of Hurricane Frances damage on San Salvador: Bahamas Journal of Science, p. 2-6.

Park, L.E., Metzger, T.J., Sipahioglu, S.M., Siewers, F.D., and Leonard, K., 2008, After the hurricane hits: recovery and response to large storm events in a saline lake, San Salvador Island, Bahamas, *in* Park, L.E. and Freile, D., eds., Proceedings of the Thirteenth Conference on the Geology of the Bahamas and Other Carbonate Islands, This Volume, p. 63-75.

Shaklee, R.V., 1996, Weather and Climate: San Salvador Island, Bahamas: San Salvador, Bahamas The Bahmaian Field Station limited, 67 p.

Shamberger, E.A., 1998, Depositional history of a coastal evaporite salina Salt Pond, San Salvador Island, Bahamas, [M.S. Thesis]: University of Akron, Akron, Ohio, 144 p.

Teeter, J.W., Beyke, R.J., Bray, T.F., Brocculeri, T.F., Bruno, P.W., Dremenn, J.J., and Kendall, R.L., 1987, Holocene depositional history of Salt Pond, San Salvador, Bahamas, *in* Proceedings of the Third Symposium on the Geology of the Bahamas: San Salvador, Bahamas, Bahamas Field Station, p. 145-150.

Yannarell, A.C., Steppe, T.F., and Paerl, H.W., 2007, Disturbance and recovery of microbial community structure and function following Hurricane Frances: Environmental Microbiology, v. 9, no. 3, p. 576-583.