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Front Cover: *Porites* colony encrusted by red algae in waters of San Salvador, Bahamas; see paper by Fowler and Griffing., p. 41. Photograph by Pascal Kindler, 2011.

Back Cover:. Dr. Jörn Geister, Naturhistorisches Museum Bern, Keynote Speaker for the 15th Symposium and author of "Keynote Address – Time-Traveling in a Caribbean Coral Reef (San Andres Island, Western Caribbean, Colombia)", this volume , p. vii. Photograph by Joan Mylroie.

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TRACKING HURRICANE AND CLIMATE CHANGE RECORDS IN A BAHAMIAN COASTAL LAKE: CLEAR POND, SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

The sedimentary record of the Bahamas is typically thought to be archived in the lithostratigraphic record. However, important, high-resolution climatic and paleoenvironmental histories can be obtained by examining the unlithified sediments found in the lakes on the islands. This study characterizes the general limnology and depositional history of Clear Pond, San Salvador Island (SSI), Bahamas for the past 4000 years, documenting seasonal salinity variation and large storm events (i.e. hurricanes) in the sedimentary record.

Three dune transects along the coastal margin of the lake were completed, as well as a bathymetric map of the lake. A salinity logger installed in June 2008 recorded salinity variability over a nine month time period, where the salinity varied from brackish conditions during the summer and fall to more marine during the winter and spring seasons.

Eleven sediment cores (50 to 150 cm long) were recovered and analyzed for organic and carbonate content, dry bulk density, grain size, sediment fabric, and ostracode composition. Additionally, X-ray fluorescence, spectrophotometry, and X-radiography analyses were completed on a select number of cores.

Large storm events were identified by an increase in grain size and dry bulk density, and additionally by x-radiographs. A catastrophic hurricane recurrence interval of 478 years and an annual landfall probability of 0.21% was observed and found to be two-fold greater than that detected on the east coast of SSI. This suggests significant spatial variation for such a relatively small island. Large storm events identified in sediment cores show a hurricane "hyperactivity period" identified in other records along the Gulf Coast of North America. Additionally, with an average sedimentation rate of 2.3 cm/ 100 years, the record recovered was at least 5200 years old and recorded a major climatic shift at 1460 ybp, corresponding with the end of a documented Caribbean dryness period.

INTRODUCTION

Clear Pond is a cutoff lagoon located approximately 3 km northeast of Sandy Point and 2.5 km north of French Bay, along the southwestern coast of San Salvador Island (SSI) (Figure 1). It is separated from the Atlantic Ocean by a 50 m wide dune to the west, and the Queen's Highway borders the pond to the east (Figure 2). The pond is northeast-southwest trending with low woody vegetation covering the western dune and some larger Auspine trees throughout. Clear Pond has an approximate surface area of 2.2 km^2 with a maximum recorded depth of <1 m (0.98 m in June, 2008). The lake has a pupfish (*Cyprinodon*) population that has been well documented (Turner et al., 2008). Unlike many of the other coastal lagoons on the island, it has no cyanobacterial mats and little or no suspended particles and well-oxygenated water (dissolved oxygen above 5.0 mg/ L in June 2008).

At the northeast-central region of Clear Pond is an ebb and flow spring that has a rock wall directly adjoining the southern opening of the conduit prograding east into the woody

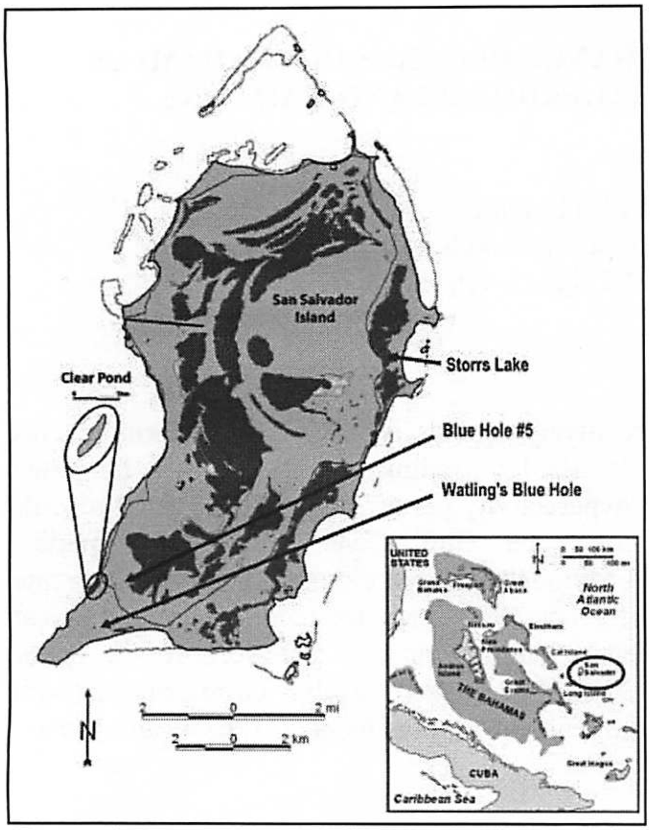

Figure 1. Location map of San Salvador Island and Clear Pond. Interior lakes are illustrated in dark gray and fringing reefs by dotted lines. Modified from Robinson and Davis(1999).

vegetation. Because of this conduit, lake levels are tidally influenced and fluctuate daily with a distinct lag time from local high and low tide. Past research has suggested that unimpeded (though with diminished tidal lag) conduit connections result in normal marine conditions; however, salinity on these lakes is often a function of precipitation (Gamble et al., 2008; Michelson and Park, 2010). Clear Pond shows an influence of both meteoric and groundwater in its salinity.

San Salvador Island Climate and Hurricanes

Climatologically, the Bahamas are positioned between the tropical and temperate zones, and are considered to be subtropical with a maritime climate (Sealey, 1994). The climate is relatively stable, ranging from 20° to 28°C with relatively high humidity. Rainfall is both spatially and temporally uneven within the Bahamian archipelago, with most precipitation occurring during storm events throughout the summer and fall (Shaklee, 1996; Gamble et al., 2008). San Salvador's rainy season is from June to December, with October being its rainiest month.

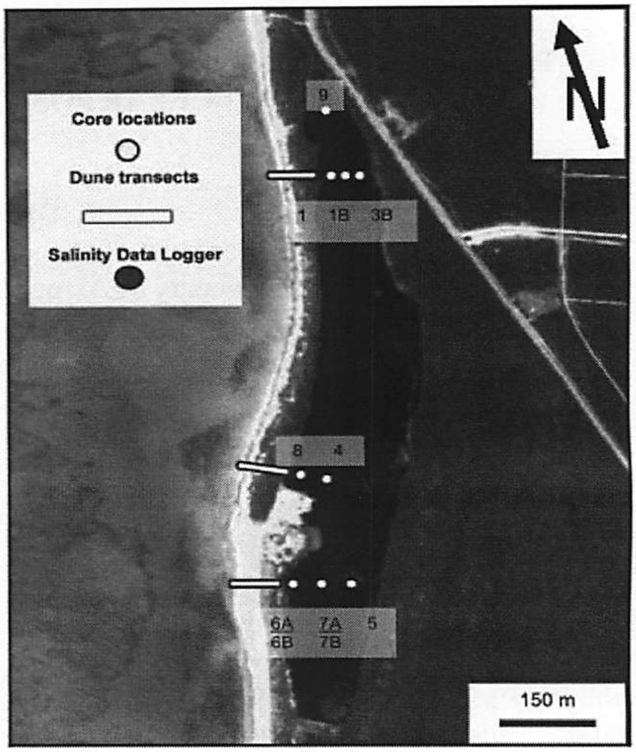

Figure 2. Satellite image of Clear Pond indicating location of dune transects, core locations, and salinity data logger. Transects 1-3 are located from top to bottom of figure, respectively. Core numbers parallel core locations and are indicated in white boxes. Cores 6A/6B and 7A/7B are consecutive cores of the same core location. Source: Google Earth, 2009.

The maritime climate of the Bahamas has not been consistent throughout the Holocene. Donnelly and Woodruff (2007) have indicated that the North Atlantic Ocean (NAO) has had intense hurricane activity for the past 5,000 years based on data from sediment cores recovered from a lagoon in Puerto Rico. Their records indicate that hurricane activity varied over hundreds to thousands of years, which they attributed to modulations in the El Niño Southern Oscillation (ENSO) and the strength of the West African monsoon. Others have suggested that increased sea surface temperatures (SST) in the Atlantic are the only component necessary to support increased frequency of intense hurricanes (Emmanuel, 2005).

Intense hurricane activity has been also highly influenced by the clockwise-rotating Bermuda High (Atlantic Subtropical Anticyclone; Liu and Fearn, 2000). As the high pressure cell grows from incoming solar insolation, hurricanes follow a trajectory along the eastern coast of North America. However, the Bermuda High and hurricane trajectories have not been consistent through time. Liu and Fearn (1993; 2000) concluded that during the 3,400 to 1,000 ybp hurricane "hyperactivity" period, the Bermuda High had shifted southwest of its current location by glacial cooling that began around 6000 ybp. The movement of the Bermuda High would cause large storm events to be directed into the Gulf of Mexico during 1000 BC to 1000 AD, whereas during the last millennium, the High would shift to its present location and more hurricanes would be predicted in and along the Atlantic coast of North America. This anti-phase record of hurricane activity has also been observed by Scott et al. (2003) in core sediments along the Atlantic Coast.

A hurricane has hit SSI on the average every 4.3 years between 1851 and 2008, with 19 recorded from 1944 through 2008 (Dijken, 2006). The first week of September is the peak of hurricane activity on the island with an average of 1 storm occurring every 15.8 years (Shaklee, 1996; Dijken, 2006). More than 15 hurricanes have passed directly over San Salvador Island during this time period and these past storm events have been recorded in the coastal lakes because they breach the dunes with storm surges and deposit sand within the basins.

METHODS

Field Methods

The western dune separating Clear Pond from the Atlantic Ocean was mapped and profiled using a modified Emery method (Emery, 1961) to characterize geomorphologic constraints that influence overwash deposits into the basin. Profile start and stop locations were marked by global positioning system (GPS) coordinates with the start point at the Clear Pond shoreline. Time and date of the profile measurement were recorded with the profile referenced to morning low tide. One dune transect was recorded for each corresponding coring transect.

In order to characterize modern salinity changes within the lake and possible effects of the ebb and flow spring, a data logger was installed in June 2008. The unit was a 12-bit PIC powered microprocessor designed by Hobart and William Smith Colleges. This unit was placed approximately 13 m from the conduit opening at a water depth of approximately 50 cm with the measuring probe at ~20 cm above the lake bottom. This location was optimal for capturing both ebb and spring and lake changes in salinity. The logger was set to measure salinity every 30 minutes.

A total of nine piston cores were recovered during June 2008 from locations throughout Clear Pond using a custom-built Livingstone piston corer. All cores were extracted using 2 inch (5.1cm) diameter black ABS piping cut to four-foot (123 cm) lengths. Cores and sediment samples were transported to the University of Akron for analysis and storage in the department's refrigeration facility.

Laboratory Analyses

To reveal internal structures and changes in sediment density (Bentley et al., 2002), cores were taken to Aultman West Hospital in Massillon, Ohio and X- rayed at 50 KeV/ 450 mAs. Vertically split cores were placed four across on an X-ray plate with metal stick pins placed every five centimeters for reference. X-ray plates were 43 cm across by 76 cm long. The sheet X-radiographs were digitally scanned at 600 DPI (dots per inch) and digitally merged via Adobe Photoshop™ software.

Cores were scanned at four cm intervals for 29 elements (P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Zr, Mo, Ag, Cd, Sn, Sb, I, Ba, Yb, Hg, Pb, and U) using an INNOV-X Alpha series handheld scanner housed at Kent State University.

All cores were examined at centimeter scale using an unobtrusive, semi-quantitative Minolta CM-2600d/2500d portable spectrophotometer that analyzes the visual infrared spectrum (450-900 nm λ) in addition to five more inclusive channels labeled *L**, *a**, *b**, *C**, and *h*. Cores were wrapped in Saran Wrap™ to minimize reflection and absorption of the xenon bulb flash.

Channel *C** measures the chroma of the surface sampled and channel h measures the hue of the sample. Channel *L** measures the luminosity (black/white color space) of light reflected off the surface and positively correlates with the color of carbonate sand (Sipahioglu, 2008; Sipahioglu et al., 2010). Spectrophotometry, gamma-ray, and color loggers all produce data based on a combination of sediment properties. Therefore, these data are relative to the lithologies tested and inherent heterogeneity in samples must be accounted for. Channels *a** and *b** measure respective red/green and blue/yellow color spaces of the sample surface. The red (positive) / green (negative) color measure of *a** can be used as a proxy for oxidation (Kokaly et al., 2007; Sellito et al., 2007; Ben-Dor et al., 2008), with the blue (negative) / yellow (positive) color measure used as a proxy for sulfides and possibly for indication of reducing environments (Ortiz et al., 2003). The technique of spectrophotometry has a limited event layer resolution that is constrained by this measuring device.

Sampling for loss on ignition was done at 1 cm intervals for the length of the core using a custom 1 cm^2 metal microcoring device with each sample placed in its own crucible. The sample and crucible were placed into a 105°C drying oven for an initial period of 24 hours and weighed before and after to determine dry bulk density and water content (Boyle, 2001). The samples were then placed into a furnace at 550°C for a period of four hours to remove any organic content. Samples were reweighed and then heated a final time at 1000°C for four hours to determine the carbonate content.

Cores were sampled at 1 cm intervals and analyzed for grain size on a Malvern Mastersizer 2000 laser diffractometer at Kent State University. Sediment was freeze-thawed twice to help separate the sediments and then the sediment was added to deionized water and sieved to 2 mm. Obscuration was between 10 and 20%. Two readings were taken for each interval with an average reading used for data analysis. Coarse grain size was used as a proxy to identify similar sized allochthonous sediments from the dune complex that are transported to the lake basin by large storm events.

One cubic centimeter of sediment was extracted at each centimeter interval and processed using established freeze-thaw methods and then sieved at 125 microns (Forester, 1990). Each interval was examined under an Olympus HSZ10 binocular stereoscope for the presence of ostracodes, mollusks (bivalves and gastropods), and foraminifera and then placed on micropaleo slides for further identification and quantification.

Organic, woody material and organic sediments were removed from two cores and sent to Beta Analytical Labs for radiocarbon dating analysis. Two AMS carbon dates were determined on core BA08CP-7A and one on core BA08CP-7B. Core BA08CP-7A was sampled at 20 and 49.5 cm for pieces of organic woody material. BA98CP-7B was sampled at a depth of 79 cm for organic sediments. The AMS radiocarbon dates were then calibrated using CalPAL online (www.calpal-online.de) which converts radiocarbon dates to calendar calibrated years.

RESULTS

Dune Profiles

Three dune profiles were measured in June 2008 and referenced to the Clear Pond shoreline. The northern two transects across the dune recorded lithified eolianites and the southern dune transect, located approximately 50 meters southwest of the overwash fan, was over the unlithified, younger dune. Beyond the dune crest, low scrub vegetation is observed along with unconsolidated sands. The dune complex is composed of unconsolidated carbonate sand that continues farther south along the coastline beyond the southern extent of Clear Pond. No cores or trenches were taken through the dune. Dune profile measurements were referenced to June 9th, 2008 at 7:30 am.

Physical Limnology

Clear Pond is a shallow, mixed lake with water temperature not varying more than 4.1°C (29.5-33.6°C) within the water column. Conductivity varied only 2.2 mS (49.3- 51.5 mS) during the sampling period (June 2008). Lake salinity, recorded via a data logger over a nine month period (June 2008 to March 2009) near the lake conduit (Figure 3), was relatively stable at about 18.5 ppt from the beginning of June through the end of August. There was a substantial increase of 5 ppt on September 1 (from an average of 18.5 to 23.5 ppt) over three days and then the salinity dropped to 19 ppt and then peaked again on October 31 at 26 ppt. From November to January 16, salinity averaged 24 ppt with increasing variability towards the end of January. Markedly variable increases in salinity are seen from mid-January to March at bi-weekly periodicities with increasing variability from February 14 to March 1 (Figure 8). This variability closely resembles bi-weekly and weekly tidal cycles and not daily tidal influences. Further work, including spectral analyses of the Clear Pond salinity record and cross spectral analyses of the Clear Pond and nearby tidal height records are needed to support the spring/neap tidal interpretation. Spring and neap tides cycles for SSI are plotted on top of salinity.

Bathymetry measurements were conducted during coring transects and were recorded as a distance from water level to lake bottom (Figure 3). In addition to these transects across the lake, a northern and southern locations were also measured. The depth of Clear Pond is relatively uniform throughout its entirety, with gently sloping sediments to a depth of 1 m in the south-central region of the pond closest to the past overwash deposit. Ultimately, close to 75% of the pond's depth is between 25 and 80 cm. The bathymetry is steepest closest to the slipface of the overwash fan and near the lake conduit's delta.

Core Facies

Physical examination of Clear Pond cores reveals consistently similar facies across all cores (Figures 2, 4 and 5). Below is a general description of core lithology based on the overall composition. The cores were generally very sandy (~50-70% sand) with a highly bioturbated, medium-brown to buff uppermost layer ranging from 15 to 30 cm in thickness, with lower layers that were laminated mud and sand, light tan to light gray in color. Cores closest to the west dune have distinctly more sandy layers compared to more distal locations. Sharp contacts were observed between sandy layers with no evaporites or algal mats found in any of the cores examined.

X-radiography and X-Ray Fluorescence

Qualitative X-radiographs of each core were taken and reveal distinct density differences between sand, mud, and bioturbated layers. Sand deposits appear as primarily white bands in the core with mud deposits predominantly as black bands due to the less dense, mud-sized particles (Figures 5 and 6). Bioturbated layers were identified as highly mixed units on the magnitude of one to several centimeters that gave a mottled white and black appearance with no distinct layering present and with no sharp contacts.

Within cores BA08CP-7A and 7B, X-radiographs indicate an upper bioturbated unit from 0 to 30 cm with increasing sand and mud dominated layers below. Cores examined from Clear Pond show increasingly less sandy event layers towards the bottom of core BA08CP-7B as observed in X-radiographs.

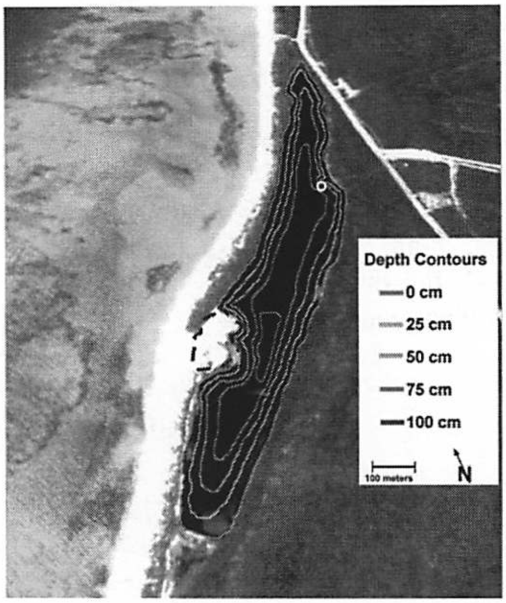

Figure 3. Bathymetric map of Clear Pond overlain onto satellite image. Note large overwash fan at central portion with minimal vegetation present. Circle designates location of conduit and dashed line indicates area of dune breach and corresponding overwash.

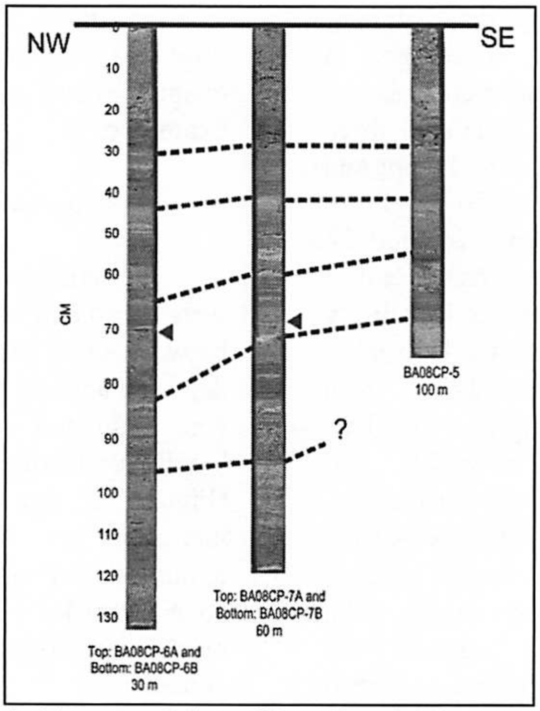

Figure 4. Photographs of cores in Transect 3 from Clear Pond. Measurements listed at the bottom of each core are distances from the western shore of Clear Pond. Triangles mark fusion of consecutive top and bottom of cores at that coring location. Dashed lines represent visual correlation between similar beds in the three cores. Vertical scale in centimeters.

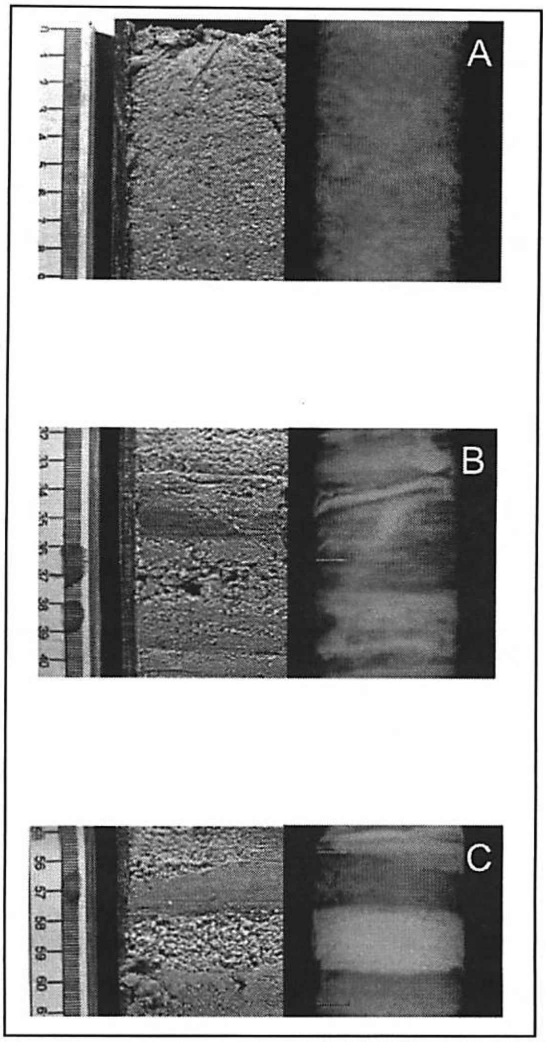

Figure 5. X-radiographs and core photographs of core BA08CP-6A. A. Bioturbated facies. B. Laminated carbonate mud. C. Loose carbonate sand layers surrounded by less dense mud layers. Scale in centimeters.

Elements present in the sediments play crucial roles in provenance studies as well as identifying human colonization. In addition to these signals, information on biochemical and geochemical processes such as diagenesis, decomposition, or productivity can be interpreted. Eight (calcium, strontium, tin, nickel, copper, cadmium, phosphorous, and lead) of nine elements co-varied through the core, with only iron having a distinctly different pattern. These eight elemental concentrations recorded an increase throughout the entire length of the core. Iron concentration was uniform from 0 to 36 cm, with a decrease in concentration at 41 cm and throughout the entire length of the core (Figures 6 and 7).

Spectrophotometry

Luminosity (L^*) is positively correlated with sandy event layers and can be a measure of overwash events, as L^* is a direct measure of color. Both a^* and b^* have been utilized as indicators of biological conditions (Sipahioglu, 2008; Sipahioglu et al., 2010); however, the dominant sandy substrate has apparently influenced signal strength as both a^* and b^* have a high noise-signal ratio.

Downcore, as L^* increased, a^* was negatively correlated, indicating non-oxidative

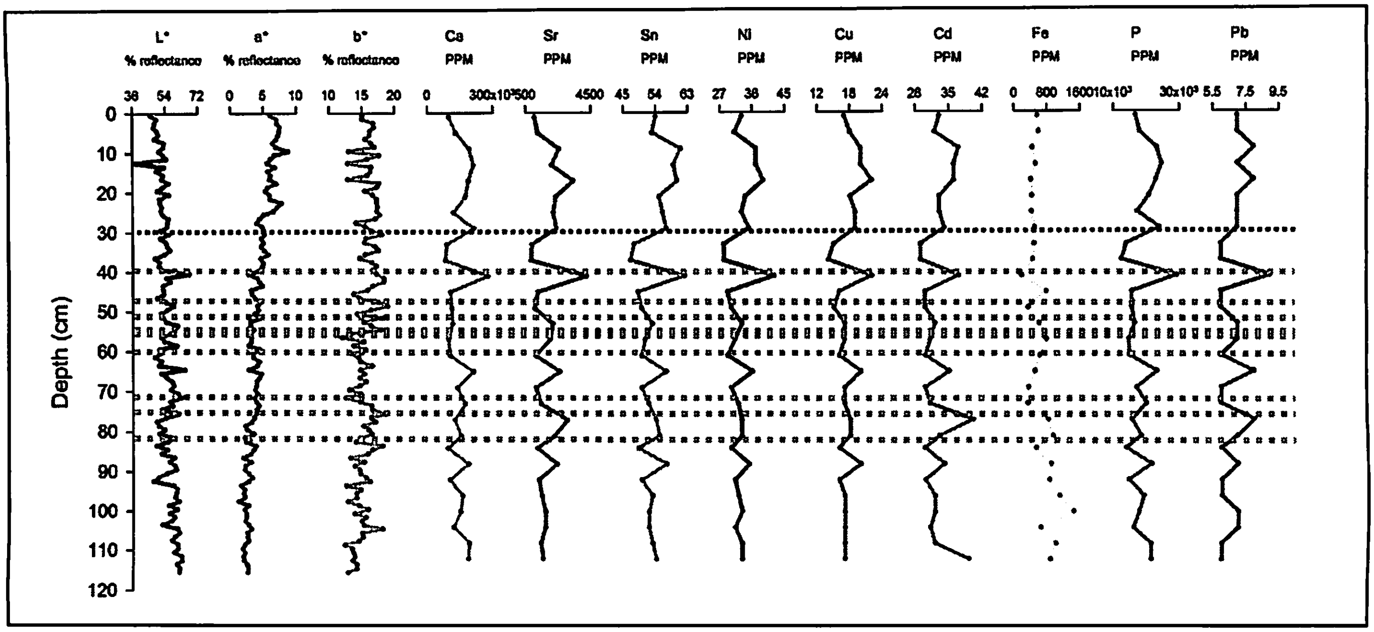

Figure 6. Composite analytical data sets from BA08CP-7A/B. Spectrophotometry (L, a*, and b*) and XRF elements (calcium, strontium, tin, nickel, copper, cadmium, iron, phosphorus, and lead, respectively). XRF values are in ppm (parts per million). Spectrophotometry is graphed as % reflectance where L* is luminosity, a* is red(+)/green (-) color space and b* is blue(-)/ yellow(+) color space. Top dashed line indicates the change from bioturbated to mud and sand dominated facies. Dashed lines indicate sandy event layers.*

conditions. Additionally, through the entire length of BA08CP-7A and 7B, *a** was increasingly less positive, suggesting a more reducing environment (Figures 6 and 7). *L** was found to increase downcore which may be a function of color. For Core BA08CP-7A and 7B, *b** was found to be negligibly influenced by mud, sand, or bioturbated facies with a weak positive relationship with *a** and dry bulk density (DBD) (Figures 6 and 7). Inherent voids in unconsolidated carbonate mud and sand sediments may have played a role in correct detection of *a** and *b** abiotic and biotic signals.

Loss on Ignition, Grain Size, and Microfossil Analysis

DBD, organic, and carbonate content were measured on all cores. Data from BA08CP-7A and B indicate that mud dominated facies contain high organic concentrations and water content, whereas sand and shell-dominated areas contain high concentrations of carbonate with relative decreases in organic and water content. This statement holds true with the exception of inter-bedded layers where carbonate, organic, and dry bulk density signals become less prominent.

Major overwash events are indicated by increases in the DBD and carbonate content and a decrease in water content and organic matter (Figures 6 and 7), as previously demonstrated by Park et al. (2009). The LOI data did not document changes in sediment composition which may be a result of sampling resolution or heterogeneity in samples (Figure 6).

Grain size measurements have been widely used to identify fine, medium, and coarse-grained sand from mud-sized particles for paleotempestological studies (Liu and Fearn, 1993; Donnelly and Woodruff, 2007; Park et al., 2009). Previous studies on San Salvador have demonstrated that dune sediments are well-sorted, sub-angular, fine to medium-grained sand, with overwash deposits recording a distinct peak at 300 μm in the lake (Park and Trubee, 2008; Park et al., 2009). However, grain-size measurements only assess sorting, and

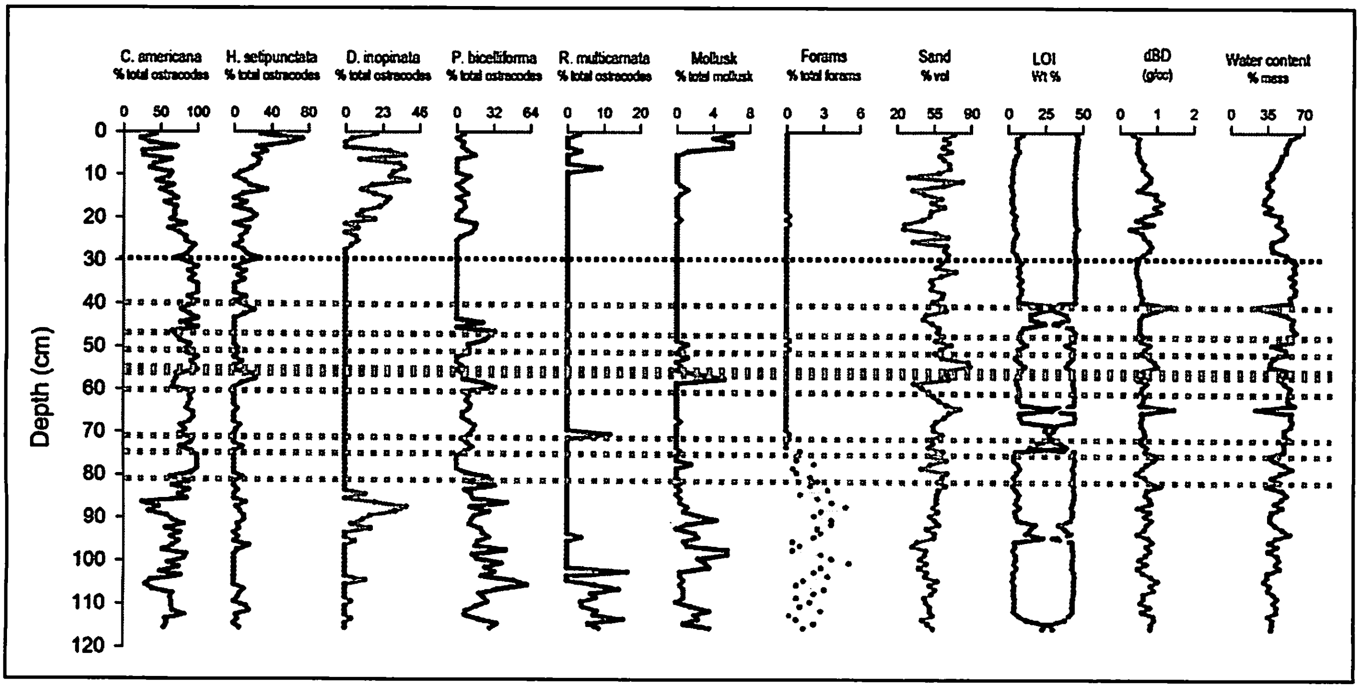

Figure 7. Composite analytical data sets from BA08CP-7A/B. Ostracodes C. americana, H. setipunctata, P. bicelliforma, D. inopinata, R. multicarnata, (plotted as percent total ostracodes), mollusks and forams (plotted as % of total mollusks and forams, respectively) in addition to grain size (sand-size particles - 63 to 2000 microns), loss on ignition (left-hand side line indicates organic matter; right-hand side line indicates carbonate content), dry bulk density, and water content (plotted as % total mass). Top dashed line indicates the change from bioturbated to mud and sand dominated facies. Lower dashed lines indicate sandy event layers.

identifying overwash deposits may be influenced by composition, because they are not directly examined via this method. Grain size did correlate with DBD and inversely with water content (Figure 7).

Ostracodes, mollusks, and forams have been used widely as proxy indicators for paleo- and modern environments to infer salinity, pH, productivity, and water depth (Crotty, 1982; Teeter and Quick, 1990; Reed, 1996). Microfossils found in Clear Pond live in brackish to normal marine conditions.

Ostracode species are present throughout core BA08CP-7A and 7B (Figure 7). The middle to bottom portion of the core is dominated by the euryhaline species *Cyprideis americana* and *Perissocytheridea bicelliforma*, and the upper portion is dominated by the increased presence of *Hemicyprideis setipunctata* and *Dolerocypria inopinata* which may reflect a more stable brackish salinity within the lake (Figure 4).

Mollusks are restricted to the upper 10 cm of the core along with punctuated observations down the core. An increase in mollusk abundance towards the bottom of the core begins at 80 cm. *R. multicarnata* had similar distribution to that of mollusks. Further downcore, and back in time, the presence of foraminifers occurs with high abundances below a depth of 70 cm, indicating more marine salinity.

Radiometric Dates

Core BA08CP-7A/B, which was taken in the central region of Clear Pond, yielded three radiocarbon dates. The uppermost date in core BA08CP-7A was 1,250 +/- 40 ybp (cal. 762 +/- 61 yrs AD) from an organic sediment layer at 20 cm. The middle date was taken on organic material at a depth of 49 cm and yielded a date of 1,850 +/- 40 ybp (cal. 159 +/- 51 yrs AD). The bottom radiocarbon date was taken 79 cm downcore from the surface in BA08CP-7B on woody material and yielded a date of 3,350 +/- 40 ybp (cal. 1,632 +/- 59 yrs BC; Figure 9).

An average sedimentation rate for the upper 20 centimeters was 1.7 cm/100 years. The average sedimentation rate for the middle 29.5 centimeters was 4.9 cm/100 years with the bottom 30 cm yielding a sedimentation rate of 2.5 cm/100 years. The overall average sedimentation rate for the entire core was 2.3 cm/100 years (Figure 9).

DISCUSSION

Long-term, high-resolution lake sediment records can document climatological, biological, and geological change. These records can be used to reconstruct salinity, pH, water depth, sedimentation, precipitation, as well as flora and fauna changes through time. The geomorphology of Clear Pond indicates that it was once open to the Atlantic Ocean and was closed off by longshore transport from the southwest. The northern dune profiles reveal lithified carbonate bedrock in the core, whereas the southern transect shows unlithified sands within the dune, suggesting longshore transport came from the southwest. The dune has been breached many times in the past by large storm events and sediment deposits have been transported into the back barrier flat in an east-northeast direction.

Clear Pond is shallow, with the entire pond within the photic zone. There is a large-scale overwash fan deposit that has carried sand 50 m into the pond. This deposit has been colonized by scrub vegetation, and based on the vegetation observed, the overwash deposit is at least 3 to 5 years old. The ebb and flow spring has a deltaic deposit of mollusk shells bordering a historic rock wall that extends into the pond.

The low nutrient and salinity conditions give Clear Pond its distinct clear quality. Its water chemistry is near marine salinity. However, the pond recorded brackish salinities during the summer to fall months with the winter to spring months being more marine as recorded by the salinity data logger. The accuracy of our data was verified as not being attributed to data logger drift through observation of other salinity data from a northern pond on San Salvador Island, Reckley Hill Pond (RHP). The RHP salinity data are almost six years old and show the same phenomenon at the same time as that of Clear Pond (Figure 8). This indicates that precipitation and conduit discharge play influential roles on the overall salinity of these coastal lakes on San Salvador Island. With hourly changes in discharge velocity (data not shown) and documented salinity fluctuations, the ebb and flow spring showed surprisingly little effect on the overall salinity of Clear Pond during the wet season. However, increasing salinity variability was observed during the winter to spring months, which is known as the dry season (Figure 8). The relative stability in salinity (18-21 ppt) during the wet season may be a result of meteoric precipitation maintaining the overall brackish salinity of the lake. As the storm season ends and the climate becomes drier, there is less input of freshwater from precipitation and the conduits' influence is not only from daily tides but also from spring and neap tidal cycles, which are not observed during the wet season. However, further cross-spectral analyses are needed to corroborate tidal influence.

The pond has also been influenced by the regional climate through large storm events. The presence of large storm deposits have been documented throughout the Atlantic Ocean and Gulf of Mexico and from the east side of San Salvador Island, but never before from Clear Pond. Because Clear Pond has no rivers or any other way to bring sediment into the lake other than through a large storm, allochthonous sediments found in the cores should be from storm surges.

There were three distinct facies observed throughout the cores extracted from Clear Pond (Figure 10). The sandy facies was associated with hurricane deposits. The identification of hurricane deposits was based on the increase in dry bulk density and grain size, x-radiography, and the sandy composition of the material.

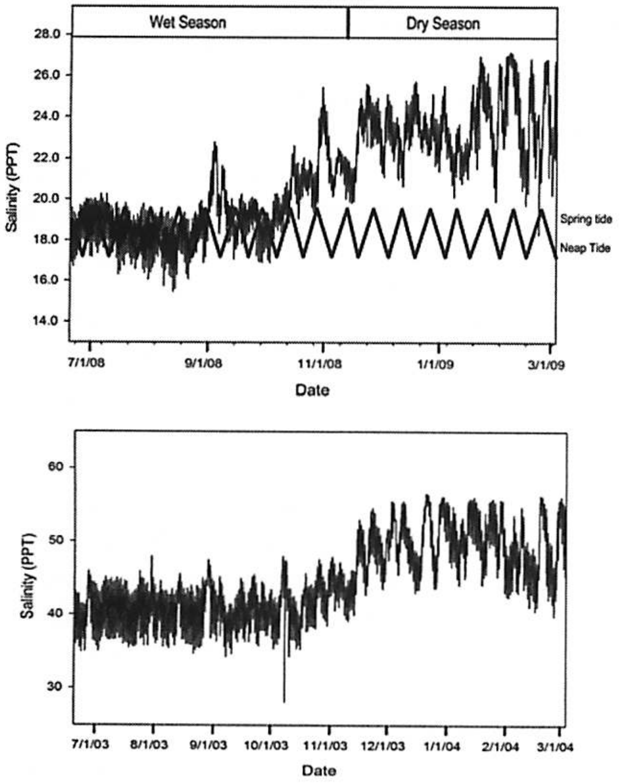

Figure 8. Lake salinity measured in Clear Pond from June 20, 2008 to March 3, 2009. Measurements were taken every 30 minutes. Solid line indicates spring and neap tide cycles for Clear Pond (Source NOAA). Bottom: plot of salinity data from Reckley Hill Pond on the northernmost part of the island from 6/20/03 to 3/4/04 for comparison.

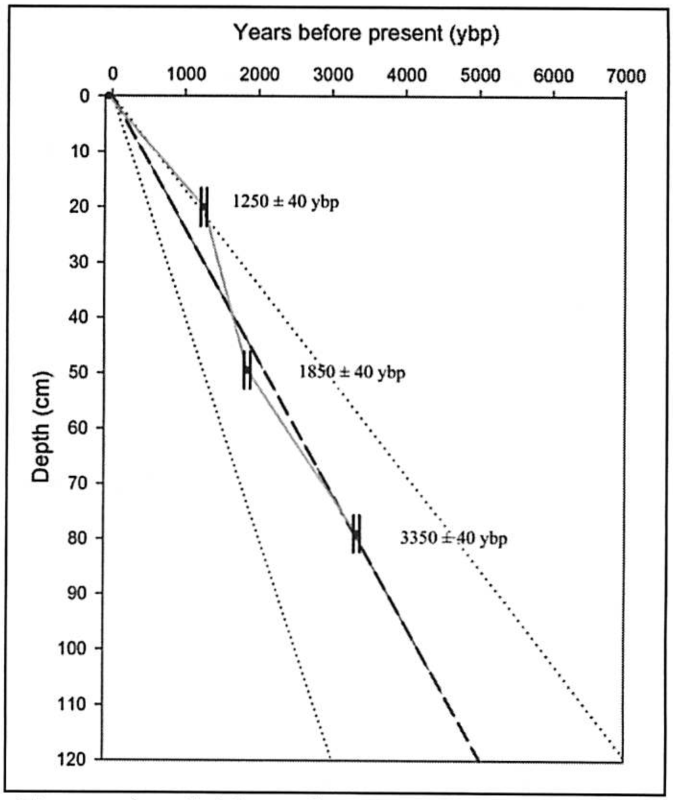

Figure 9. Calibrated age model for cores BA08CP-7A/B extracted from Clear Pond. Dashed line indicates average sedimentation rate for the entire core. Dotted lines on each side indicate 99% confidence interval for carbon dates recorded plotted through -59 ybp. Solid line indicates average sedimentation rates between carbon dates sampled. Dates calibrated using Cal Pal (www.calpal-online.de).

Additionally, spectrophotometry and XRF, correlated overwash deposits with increased luminosity and an overall increase in elemental concentrations (Figures 6 and 7). The increase in elemental concentrations from large storm events may be the result of depositing precipitated elements from marine water or from soil erosion and vegetation changes in the surrounding catchment. The transfer of detritus and vegetation into Clear Pond from the surrounding dune is through storm surge uprooting the organic matter and subsequently depositing it into the lake.

This study is the first to document that coastal lakes on the western side of San Salvador Island have recorded overwash deposits. The record obtained from Clear Pond extends back at least 3,350 ybp based on AMS radiocarbon dates. Extrapolating a linear sedimentation rate of 2.3 cm/100 years, the radiocarbon dates suggest a depositional history that might extend back to 5,200 ybp based on the length of core recovered (Figure 9). If this were true, it would support past research that suggested that most of the exterior lakes began to form within the last 6,000 ybp (Bunt, 2001; Turner et al., 2008). Clear Pond was most likely a lagoon before it got cut off from the ocean around 3,400 ybp. Therefore, species invasion and colonization within this pond would have been well within the last 6,000 ybp when lakes would have become restricted (Turner et al., 2008).

Hurricanes have been recorded in lake sediments and have shed light on hurricane activity in the Caribbean. Being able to identify paleohurricane overwash events in sediment records is necessary to understanding past events and crucial to predicting future hurricanes through climate modeling. Seven major overwash layers were identified throughout core BA08CP-7A/7B, over the last 3,350 years (Figures 10 and 11), providing an annual landfall probability of 0.21%, or a CAT 4 or 5 hurricane return period of 478 years. Lakes on the eastern side of the island have recorded a return period for CAT 4 or 5 hurricanes of every 233 years (Sipahioglu, 2008; Sipahioglu et al., 2010). San Salvador Island has had six CAT 4 or 5 hurricanes within the last 157 years. The inconsistency between the two reoccurrence intervals may be a result of Clear Pond being on the leeward side of the island, whereas Storr's Lake is on the windward side of the island which would not be protected from the initial hurricane storm surge (Gamble et al. 2000). Other areas in the Gulf of Mexico and Caribbean show return periods of 300 years or annual probabilities of 0.33% (Liu and Fearn, 2000). The increased presence of hurricanes, such as Hurricane Floyd (1999), Hurricane Lili (2002), and Frances (2004), on San Salvador during the recent century may indicate that another hurricane hyperactivity period may be starting as a result of global climate change (Delworth and Dixon, 2000).

The depositional history of Clear Pond documents a major shift in environment that corresponds to approximately AD 540 (1,460 ybp; Figure 10). In looking at the entire core recovered, this shift is from a laminated mud- and sand-dominated facies in the bottom of the core to a more recent, massive bioturbated unit. This time period also corresponds to the end of a documented dry episode within the Caribbean. The massively bedded upper core unit does not record any overwash deposits and may be indicative of the environment teeming with infauna that increases sediment mixing. The youngest sediments (top 8 cm) in Clear Pond were deposited during the historical events of Columbus' landing, both colonial periods, and presence of the US Navy (Figure 10). Few proxies change within this time period except for the increased presence of *R. multicarnata* and gastropods which indicate a diverse salinity at this time.

The change in facies is also correlated with an increased presence of *D. inopinata* and *H. setipunctata,* a decreased presence of *C. americana*, along with a broad peak in elemental concentrations at 15 cm which corresponds to AD 1,100 (900 ybp) (Figures 6, 7). The increased presence of elemental concentrations around AD 1,100 is around the time pine pollen abundance began to increase along with an increased presence of charcoal that is indicative of slash and burn processes (Berman and Pearsall, 2000). This period has been widely debated as the time when the Lucayans colonized SSI (Berman and Gnivecki, 1995; Berman et al. 1999, Berman and Pearsall, 2000). Additionally, this period coincides with the drought-related collapse of the Mayan civilization during a rapid climate change (RCC) event that lasted from 1,200-1,000 ybp (Mayewski et al., 2004). The facies shift around AD 540 may result from a change to a more stable marine to brackish environment from an otherwise saline environment, allowing for a larger diversity and abundance of epi- and infaunal species to thrive. The lack of overwash event layers within this unit and a more bioturbated, muddy sand could suggest being at the most distal end of an overwash fan as described by Sedgwick and Davis (2003). They noted that there is an absence in bedding associated with an overwash fan at the most distal end. However, since the cores extracted both proximal and distal to the west dune in Transect 3 record this same bioturbated facies, it is unlikely that this unit is a function of the overwash fan, but rather of the stable, low-energy environment during the past 1,500 years.

The lower sand and mud-dominated facies that occurs from 30 to 120 cm blf (below lake floor), record distinct quiescent periods as indicated by mud-sized particles and high organic-matter content, punctuated by sandy layers between 1,640-3,350 ybp. These deposits are composed of sand-sized particles that are

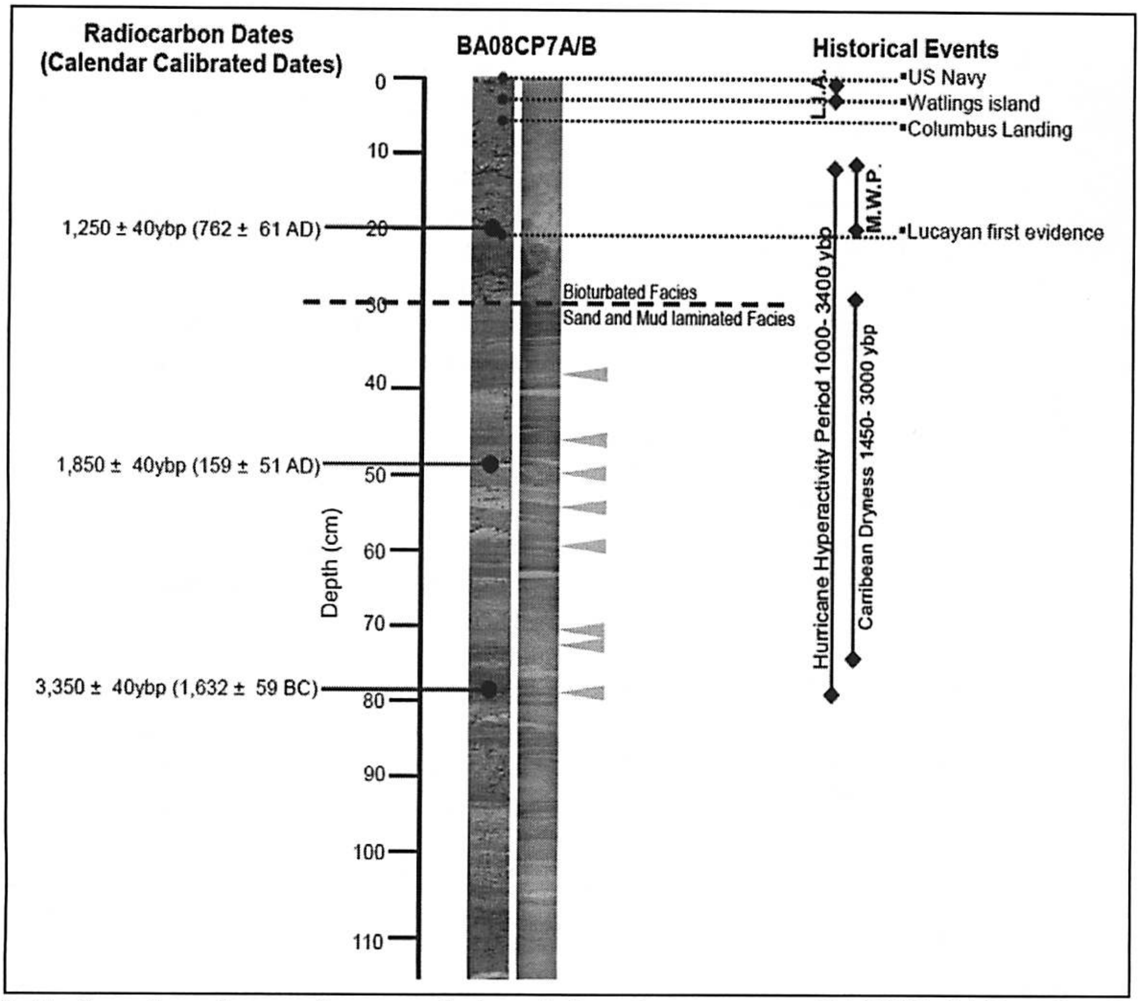

Figure 10. Radiocarbon date and overwash deposit locations on cores BA08CP-7A/B within Transect 3. Core picture and X-radiograph images are shown in the middle. Radiometric dates are on left with calendar calibrated dates in parentheses. An abbreviated list of historical events for San Salvador Island and the Bahamas is listed on the far right. Arrows indicate overwash deposits. Scale is in centimeters. LIA and MWP are abbreviated for Little Ice Age and Medieval Warming Period, which occurred at 1,650-1,850 and 800-1,300 AD, respectively.

correlated with increased dry bulk density and are similar in sorting, grain size, and composition to sand observed from the dune (Park et al., 2009). These sandy layers are deposited under high-energy conditions as suggested by X-radiography (Figure 6). All seven of the punctuated overwash event layers correlate significantly well with a hurricane hyperactivity period (1,000-3,400 ybp; Figure 11; Liu and Fearn, 1993, 2000; Sipahioglu, 2008; Park et al. 2009).

From the bottom of the core at 5,200 ybp, the presence of mollusks and foraminifers indicates a period of open but restricted connection to marine waters up to 3,350 ybp, which is 70 cm down core. Clear Pond was, however, not an open shelf at this time, as sea level only reached its current height approximately 3,000 ybp and the sediment cores have recorded low-energy, fine-grained mud during this period as well. These conditions became fresh enough at times to record the presence of *P. bicelliforma*, but were dominated by *C. americana* and *R. multicarnata* at the deepest part of the core, indicating a more marine setting for the oldest stratigraphic sediments. The older stratigraphic units were found to have an overall less oxidative signature

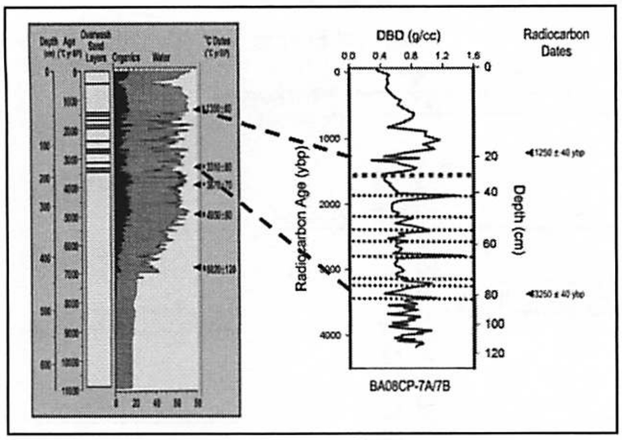

Figure 11. Hurricane hyperactivity period identified in core data from Western Lake, Florida (left), compared to core data from Clear Pond, San Salvador Island (right). Dashed lines indicate sandy event layers corresponding to core proxy data (modified from Liu and Fearn, 2000). Thick dashed line indicates facies shift from sand and mud laminated facies to a bioturbated massive unit. DBD is dry bulk density.

as recorded by spectral reflectance but, most importantly, the inherent heterogeneity of cores taken from Clear Pond along with the spectrophotometer machine resolution, does not provide a resolved account of oxidation and reduction within these cores as others have found (Sipahioglu, 2008; Sipahioglu et al., 2010). The variable results obtained from X-ray Fluorescence and spectrophotometry are attributed to the resolution of the machine and inherent errors in sampling a non-homogenous (mud, sand, and water), rough (voids in the sampling surface), and non-dry (water and organics) samples.

Thus, the resultant proxy data, along with AMS radiocarbon dates, explain that Clear Pond was less restricted and more marine during 3300 to 5,200 ybp as apparent through microfossil presence and then progressively became more restricted during the most recent 1,000 ybp, as evident by *D. inopinata* and *P. bicelliforma*, whose presence indicates brackish conditions.

Due to the close proximity of Clear Pond to a well known archaeological site, Three Dog (Berman and Pearsall, 2000), and its subsequent brackish to marine water conditions along with a man-made rock wall from possibly an early colonial period, this study will help to provide a geological context in which to examine the nature of human colonization of San Salvador Island. The rock walls present at Clear Pond may have served as a holding area for live food such as fish, mollusk, and turtles similarly to Watling's Blue Hole (Berman and Pearsall, 2000), although no evidence was found in this preliminary survey of Clear Pond.

CONCLUSIONS

1. The modern water geochemistry of Clear Pond is within normal marine range. Salinity varies seasonally from brackish conditions during the summer to fall, to more saline during the winter and spring. The lake salinity is influenced by seasonal changes in precipitation and may be influenced by a previously uncharacterized karst conduit.

2. The microfaunal change and the southern transect of the dune separating Clear Pond from the Atlantic Ocean indicate that the closure of Clear Pond occurred after 3,350 ybp and was more than likely due to longshore transport of sediments, possibly based on the differential cementation at the northeast and southwest ends of the dune ridge separating the pond from the ocean.

3. This study provides the first documented observation of paleo-overwash on the western coast of San Salvador Island and was identified in Clear Pond by an increase in dry bulk density, grain size, luminosity, and by X-radiography.

4. Hurricane overwash deposits in Clear Pond stratigraphically date to 1,600-3,400 ybp and support a previously documented hurricane "hyperactivity period" from 1,000 to 3,400 ybp.

5. The sedimentological record of Clear Pond documents an environmental facies shift from a sand and mud-dominated facies to a massive bioturbated muddy sand unit about

1,460 ybp (AD 540), that corresponds to the end of a documented dryness period in the Caribbean.

6. Based on an average, linear sedimentation rate of 2.3 cm/100 yrs, the sediments recovered from Clear Pond were deposited within the past 5,200 years.

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