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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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AFTER THE HURRICANE HITS: RECOVERY AND RESPONSE TO LARGE STORM EVENTS IN A SALINE LAKE, SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

The nature of response of invertebrate faunas to hurricane and other disturbrance events largely has been undocumented. The shallow, saline lakes of San Salvador Island, Bahamas contain important high resolution records of faunal dynamics, hurricane deposition and salinity changes that can be used to examine the effects of storms on these ecosystems. Two cores, measuring approximately 60 cm each, were taken from the depocenter of Salt Pond, a hypersaline lake on the eastern side of the island. Multiproxy analyses of loss on ignition, grain size distribution, sediment fabric, as well as ostracode and mollusk faunal composition were performed. These cores record sedimentation punctuated by hurricane and other large storm events. They also record a salinity history that varies from brackish to hypersaline, with the formation of salts such as halite and gypsum. Four species of ostracodes - *Cyprideis americana*, *Dolerocypria inopinata*, *Hemicyprideis setipunctata* and *Perissocytheridea bicelliforma* - were used to reconstruct the salinity history of the lake. Faunal diversity and abundance appears to increase after storm events due to the freshening of the lake, suggesting that while the system continues to reset itself, it recovers quickly from each major disturbance.

INTRODUCTION

Hurricanes and other major storm events act as large-scale perturbations on many different ecosystems along impacted coastlines. While studies have been done on both the vegetative and coral reef responses to hurricanes (Liu and Fearn, 1999; 2000), few, if any studies have been done on aquatic faunas found within coastal inland ponds in the same areas. How hurricanes impact the sedimentological and faunal dynamics of these inland ponds is not well understood. Preliminary studies on the lakes of San Salvador Island show that there may be a distinct biotic response to those storm events (Park et al., 2006; Metzger, 2007). The high resolution record that can be recovered from lakes in the Bahamas can yield important information on hurricane frequency and intensity as well as the biotic response to these environmental changes. This paper addresses primarily the latter.

Regional Setting

San Salvador Island (SSI), Bahamas (24.0°N/74.4°W), although similar to other Bahamian islands, is somewhat distinct in that it possesses high ridges and a number of inland lakes with varying water chemistries. During Pleistocene sea-level highstands, deposits of dune, beach and sub-tidal carbonates accumulated across the San Salvador platform. The island's shoreline is characterized by low sea cliffs of eroded Holocene and/or Pleistocene beach accretional ridges and eolianite deposits with and beaches of fine-to-medium grained carbonate sands and Holocene beachrock between headlands. Thus, it represents a unique 'natural laboratory' in which to examine questions concerning hurricane activity and the sedimentological and biological response to these storm events.

Modern lakes on SSI vary in salinity, controlled by the degree of development of the lake drain system, the presence of local fresh groundwater lenses, the size of the lake, its elevation relative to sea level, and rainfall (Teeter, 1985; 1995; Park and Trubee, this volume). Ponds and blue holes that have unimpeded connections to the open ocean exhibit normal-marine salinities and tidal change, although the range is diminished and timing lags behind ocean tides. Water in ponds having poor interchange with the ocean has longer residence times and higher salinities (Park, et al., 2003). Some ponds, such as Salt Pond, can range in salinity from 90 to 300 ppt. This pond is marked by the precipitation of gypsum and halite during its history (Shamberger, 1998; Furman et al., 1992). It is thought to have formed during the early Holocene from dunal development that closed off the Granny and Storr's Lake estuaries, creating a closed basin and resulting hypersaline conditions. Thus, the water budget of Salt Pond is reliant primarily on precipitation (ranging from 195 cm/year to 47 cm/year) and less on 'lake drains' or conduits that might connect the pond to the marine realm. Precipitation from large storms or hurricanes can significantly freshen the water column and result in both algal mat growth as well as a change in water chemistry (Shamberger and Foos, 2004; Yannarell, et al., 2007).

Hurricanes on SSI

San Salvador Island is particularly susceptible to hurricane activity because of its location. Hurricanes commonly cross the Bahamian Archipelago as they enter or exit the region, and as a result, the Bahamas experience more hurricanes than any other area in the Caribbean Basin or southwestern Atlantic (Liu and Fearn, 2000). Studies from the Gulf Coast of the Florida panhandle suggest that at least 12 catastrophic 4 or 5 hurricanes struck that area during the past 3400 yrs, with the most occurring between 1000 and 3400 14C yr B.P. (Liu and Fearn, 2000). This period followed one of relative quiescence. Whether or not there was a similar pattern on SSI has not been documented.

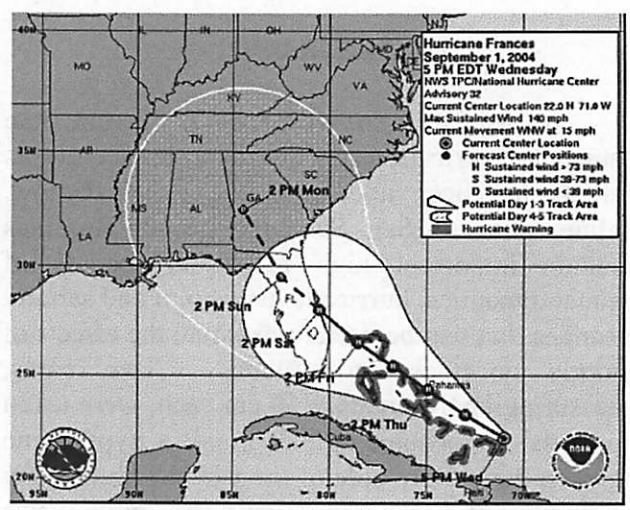

Figure 1. Storm track of Hurricane Frances, September 1, 2004. Source NOAA.

A tropical storm or hurricane of some magnitude has hit the San Salvador Island, on average, every 2.4 years since 1851 (Dijken, 2006). From 1899 until 1996, the Bahamas have experienced 66 hurricanes with 13 crossing directly over SSI (http://stormcarib.com/climatology/) (Figure 1). Recently however, SSI has experienced a decline in hurricane frequency that extends across the entire Archipelago.

In the period from 1960 – 2008, SSI has experienced only 7 hurricanes and 2 tropical storms. This may be due to a shift in regional and global weather patterns as a result of global climate change (Shaklee, 1996; Dijken, 2006; http://stormcarib.com/climatology/). The 1930's had a remarkable number of hurricanes with seven hurricanes crossing the island between 1932 and 1935 (Shaklee, 1996). The hurricanes that are most likely to affect SSI originate in the east-central areas of the North Atlantic and the Caribbean Sea, and occur between the months of June and November.

The last hurricane to hit the island was Hurricane Frances in September, 2004 (Figure 1) that was a Category (CAT) 3 storm as it went over the island. Prior to Frances, Hurricane Floyd hit the island in September, 1999, as a CAT 4. Hurricane Dennis hit that same year as a CAT 1. Salt Pond occurs on the stoss side of the island and is within the wash-over area for hurricanes and therefore can record these events because of the associated allochthonous sediments that get deposited within the basin.

Salt Pond Physical and Faunal Characteristics

The salina Salt Pond is a hypersaline lake with a maximum depth of 2 m, on the eastern side of the island and is within the wash-over area for hurricanes. It is separated from the Atlantic Ocean to the east by a ridge of Pleistocene bedrock, vegetation, and a carbonate sand beach (Shamberger, 1998) (Figure 2). The fauna in Salt Pond has a low diversity due to its extreme salinity. Typically only four species of ostracodes (bivalved microcrustaceans) are present: *Cyprideis americana*, *Hemicyprideis setipunctata*, *Perissocytheridea bicelliforma* and *Dolerocypria inopinata*, all of which are euryhaline (Figure 3). A few (4-5) species of mollusks, bivalves and gastropods, can also be found.

Ostracodes have been important paleoclimate indicators, studied for both marine and non-marine environments. They are common in many aquatic environments, and are easily preserved in the geological record. There are 60 known ostracode species found on San Salvador Island, but only one species has been found in all of the lakes (Park, 2006; 2007; Park et al., 2003; 2006; Park and Trubee, this volume). The lakes with the highest salinities have the lowest species diversity (Trubee, 2002).

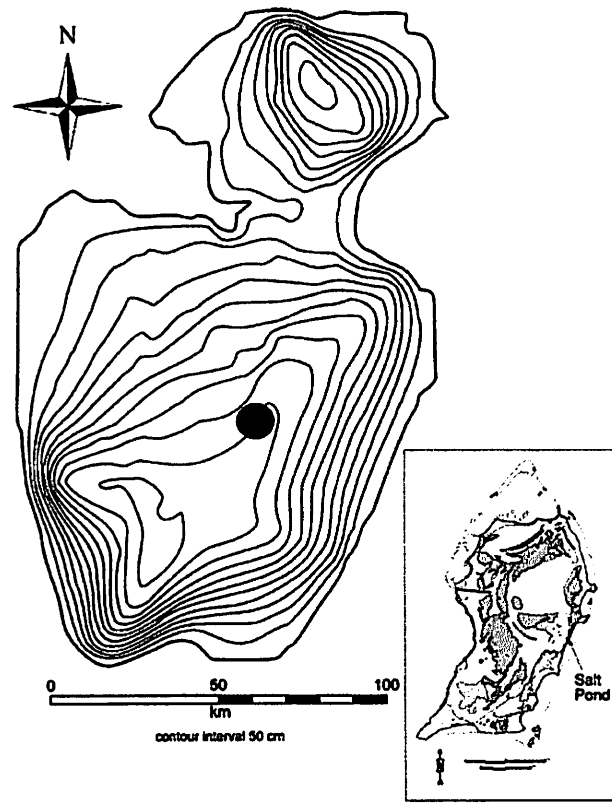

Figure 2. Bathymetric map of Salt Pond on San Salvador Island, Bahamas, showing location of the study site, as well as the core location. Contour interval is 50 cm.

Ostracode Ecology

Ostracodes occur in both stenohaline and euryhaline settings, although those from Salt Pond are all euryhaline forms, with salinity tolerances ranging from about 10 to 100 ppt. The four ostracode species found in Salt Pond have variable salinity tolerances (Figure 4)(Park and Trubee, this volume). *Perissocytheridea bicelliforma* is found in salinities ranging from 8.1 to 27.1 ppt, most commonly between 10 to 20 ppt.

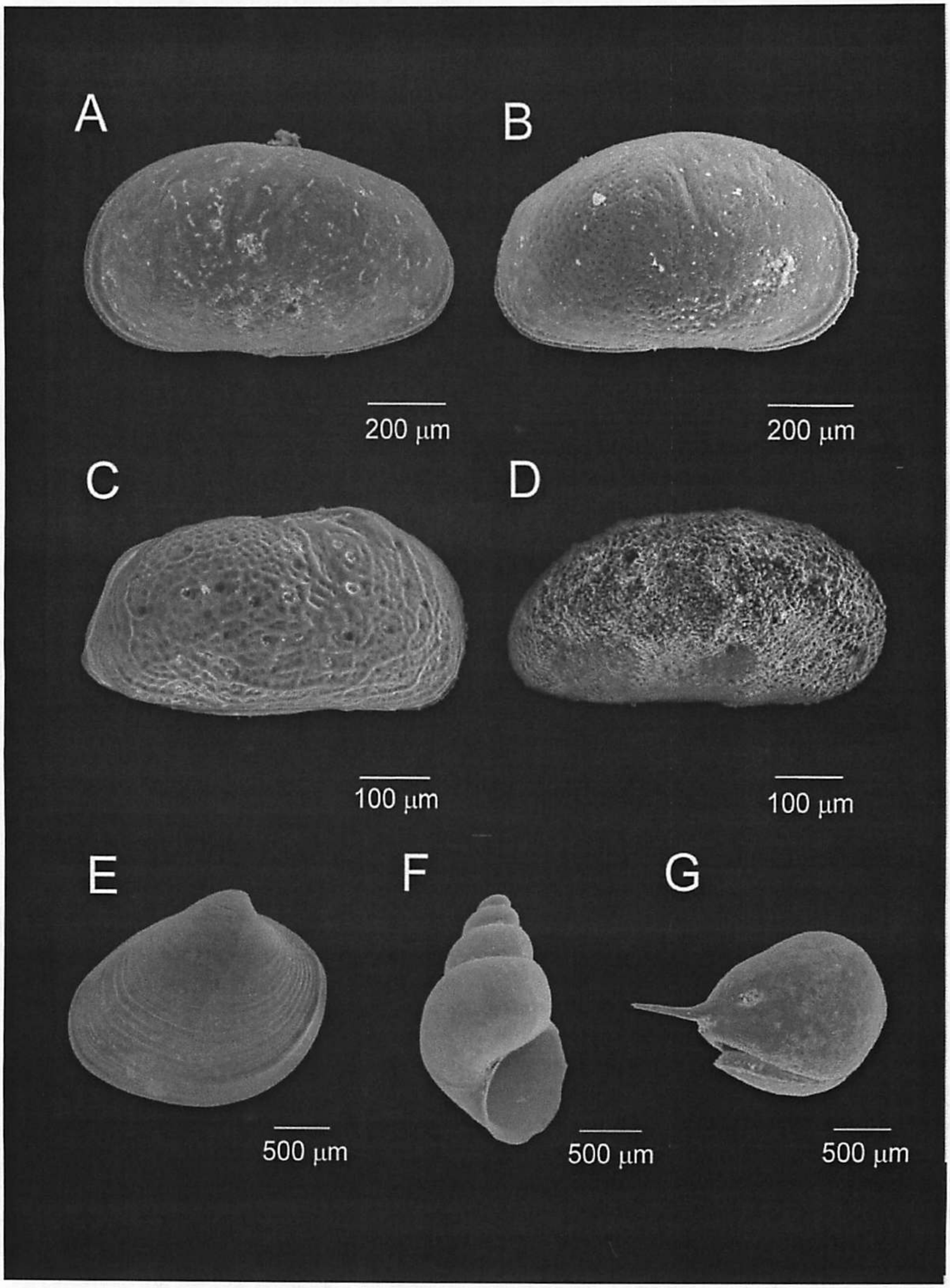

Figure 3. Scanning electron microscope images of A) Hemicytheridea setipunctata, *B)* Cyprideis americana, *C)* Perissocytheridea bicelliforma, *D)* Dolerocypria inopinata, *as well as E) a typical bivalve F) a gastropod shell and G) a seed. Scales are as indicated.*

Cyprideis americana is found in a wide salinity range between 10.8 to 98.5 ppt. It is least abundant in salinities from 30 to 50 ppt. *Hemicyprideis setipunctata* has a salinity tolerance of 11.3 to 60.9 ppt and a peak abundance between 30 to 40 ppt. They morphologically resemble *C. americana*, but are more dorso-ventrally rounded. *Dolerocypria inopinata* occur in salinities from 10.0 to 76.0 ppt and have a slightly elongated carapace. These forms are ideal not only as proxies for overall faunal response to hurricane events, but they can also but used as geochemical tools for obtaining oxygen isotopes as well as Mg/Ca and Sr/Ca trace element ratios (Park and Trubee, this volume).

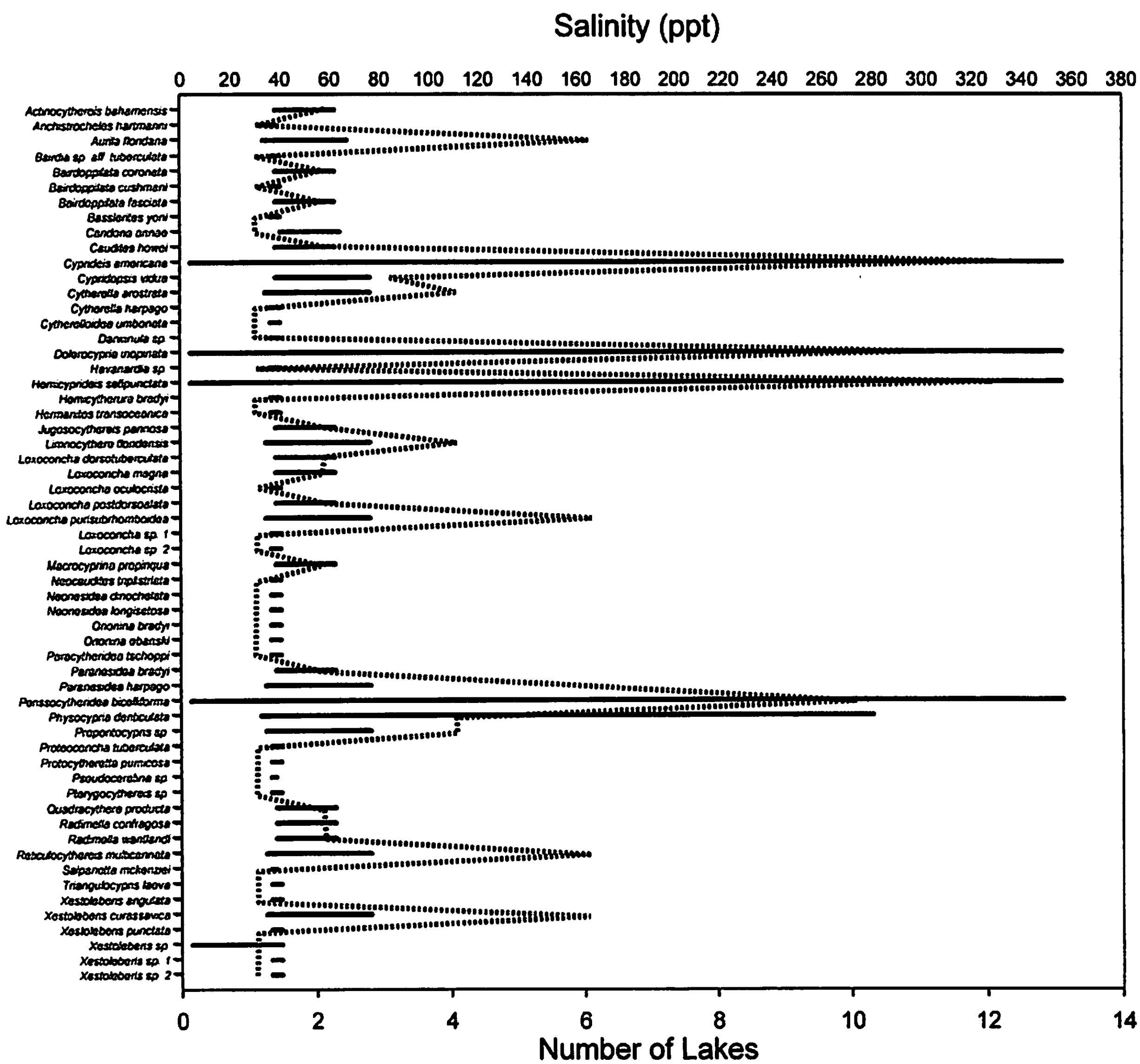

Figure 4. Salinity tolerances based upon species occurrences in the various ponds on San Salvador Island and their salinity ranges.

METHODS

Coring

Two 61 cm Livingstone piston cores were extracted from Salt Pond in January, 2006. The coring site was chosen because it was the depocenter of the lake and correlated with the "40 m" core of Shamberger (1998) (Figures 2 and 5). This area of the lake is constantly submerged. At the time of collection, water depth was approximately 1 meter. Complete recovery of the coring interval was obtained. The cores were refrigerated on the island and were transported to the University of Akron for analysis. The cores were initially described with respect to Munsell colors and any changes in sedimentation style and/or bedding features were noted.

Loss on Ignition and Grain Size Analyses

Loss on ignition (LOI) was done for dry and wet bulk density, water content, organic matter and carbonate content, using standard methods (Boyle, 2001). Dry bulk density may be an indicator of allochthonous sediments, such as carbonate sand that could be washed into Salt Pond during a tropical storm.

Grain size analyses were performed using a Malvern Mastersizer 2000 grain size analyzer (0.3 to 10,000 microns). Sediments were put into a slurry and dissolved before placing them into the Malvern. Five replicated measurements were done and an average was taken for each 1 cm interval of core. In addition to analyzing the core, a sample of beach sand from nearby 'Junk Beach' was also analyzed.

Ostracode Processing and Analysis

Ostracodes were sampled in 1 cm increments using standard freeze-thaw preparatory methods (Forester, 1990). Four species, *Cyprideis americana*, *Hemicyprideis setipunctata*, *Perissocytheridea bicelliforma* and *Dolerocypria inopinata* were identified and counted for alpha and beta diversity. In addition, mollusks, most notably gastropods and bivalves were also picked and counted. The ostracodes and mollusks were used as proxies to examine species composition, diversity, and abundance changes throughout the core. Ostracode diversity counts were done on the entire sample, using only adults. The total count was calculated to find the percentage of total ostracodes for each 1 cm increment. Both right and left valves were initially counted and then the total was divided by 2 for the number of individuals. Photomicroscopy was done on a FEI Quanta 200 , at the University of Akron (Department of Geology and Environmental Science).

Geochemical analyses were performed on ostracode valves from four species--*C. americana*, *D. inopinata*, *H. setipunctata*, and *P. bicelliforma* (*sensu* Chivas et al., 1983). Valves were cleaned and placed in a bath of 100% reagent grade bleach for twenty-four hours. Samples were removed and rinsed three times with triple distilled (i.e. MilliQ®) water. Analyses of both the dissolved ostracode valves were performed on an ICPMS and OES and oxygen and carbone isotopes were analyzed on a KIEL device at the University of Kansas.

Grain size, LOI, and fossil abundance were analyzed by Principal Components Analysis (PCA) using Multi-Variate Statistical Package (MVSP). First axis PCA scores represented 96% of the variance and were plotted against all of the variables to determine which variable was most correlative to storm events.

From these analyses, patterns of sedimentation were constructed to test the influence of climate, anthropogenic and large storm events on the depositional and faunal history of these lakes.

RESULTS

Lithologic and Grain Size Analyses

After careful visual analysis, the core was sudivided into 27 distinct intervals. Some of the intervals repeated with similar intervals later in the core. Using color, grain size, LOI, and water content, the intervals were divided into four facies with common characteristics (Figures 5 and 6). These facies included: (1) evaporites and flocculated mud, (2) carbonate mud, (3) algal laminated mud, and (4) carbonate sand.

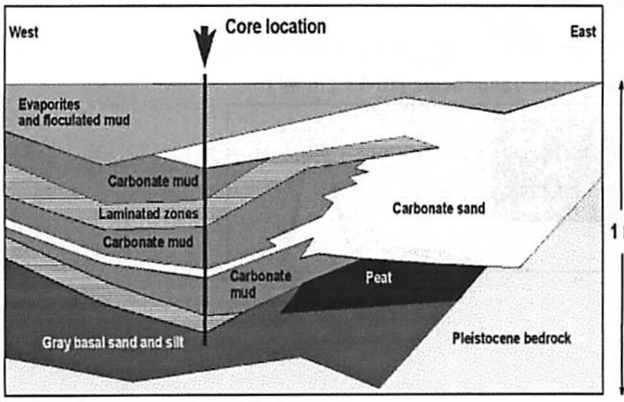

Figure 5. Cross-section of Salt Pond (based on Shamberger, 1998). Core location for this study is at the 40 m from shore mark. Note carbonate sand in eastern portion of lake, denoting storm overwash deposition.

Analyses of grain size show increases in grain size in regular intervals. The interval with the coarsest grain size was interval 4 (10-11 cm) that had a grain size distribution almost identical to that of the beach sand sample. The mean grain size of sediments in interval 4 was very similar to that of the nearby beach sand (Figure 6). The beach sand had a mean size of 300 μm. There were also sediments with more than 40% sand size particles (63 μm to 2 mm) in intervals 10, 14, 21, 25. They also had means slightly less that 300 μm (Figure 6).

Loss on Ignition

Dry bulk density and water content were inversely correlated throughout the core (Figure 7). The dry bulk density peaked in interval 4 at the core depth of 10-11 cm and was high (1.3 g/cm^3) in intervals 13 and 19 at core depths of 26-27 cm and 38-39 cm, respectively. Water content was lower in areas of suspected storm events due to the input of beach sediments. This also corresponds with an increase in percent of sand sized grains (Figure 7). Water content was inversely correlated with dry bulk density, and attained its lowest levels in intervals 4, 13, and 19.

Faunal Diversity

The number of mollusks and forams was highest within or preceding core depths 10-11 cm, 26-27 cm, 37-38 cm, and 51-54 cm downcore. In addition, the only significant number of seeds found were wtihin and preceding the storm interval 4 at 10-11 cm and interval 19 at 37-38 cm (Figure 7).

After the sand-dominated intervals ostracodes showed an increase in diversity. This occurred at 10-11 cm, 26-27 cm, 37-38 cm, and 51-54 cm downcore. These sand layers are overlain by algal-dominated muds having an increase in the number of ostracodes (Figure 7). The four species present in the core that include *Cyprideis americana, Hemicyprideis setipunctata, Perissocytheridea bicelliforma* and *Dolerocypria inopinata.* These ostracodes have been shown to occur in most of the ponds on San Salvador Island (Park and Trubee, this volume). *C. americana* is the most dominant species, occurring throughout the core, appearing within the most intervals as well as dominating the fauna when present. There appears to be an inverse relationship between *C. americana* and *P. bicelliforma* in many cases (Figures 8 and 9). Faunal abundances tracked the sand deposits in the core.

Mg/Ca and Sr/Ca ratios on species of *C. americana, H. setipunctata* and *P. bicelliforma* are inversely correlated. The Sr/Ca ratios are positively correlated with $\delta^{18}O$ isotope values. Principle component analyses on the datasets indicate that sand grain size % is the most accurate proxy for determining storm deposits. This summation of the multi-proxy variables indicates the storm signature that can be used to interpret the rest of the record

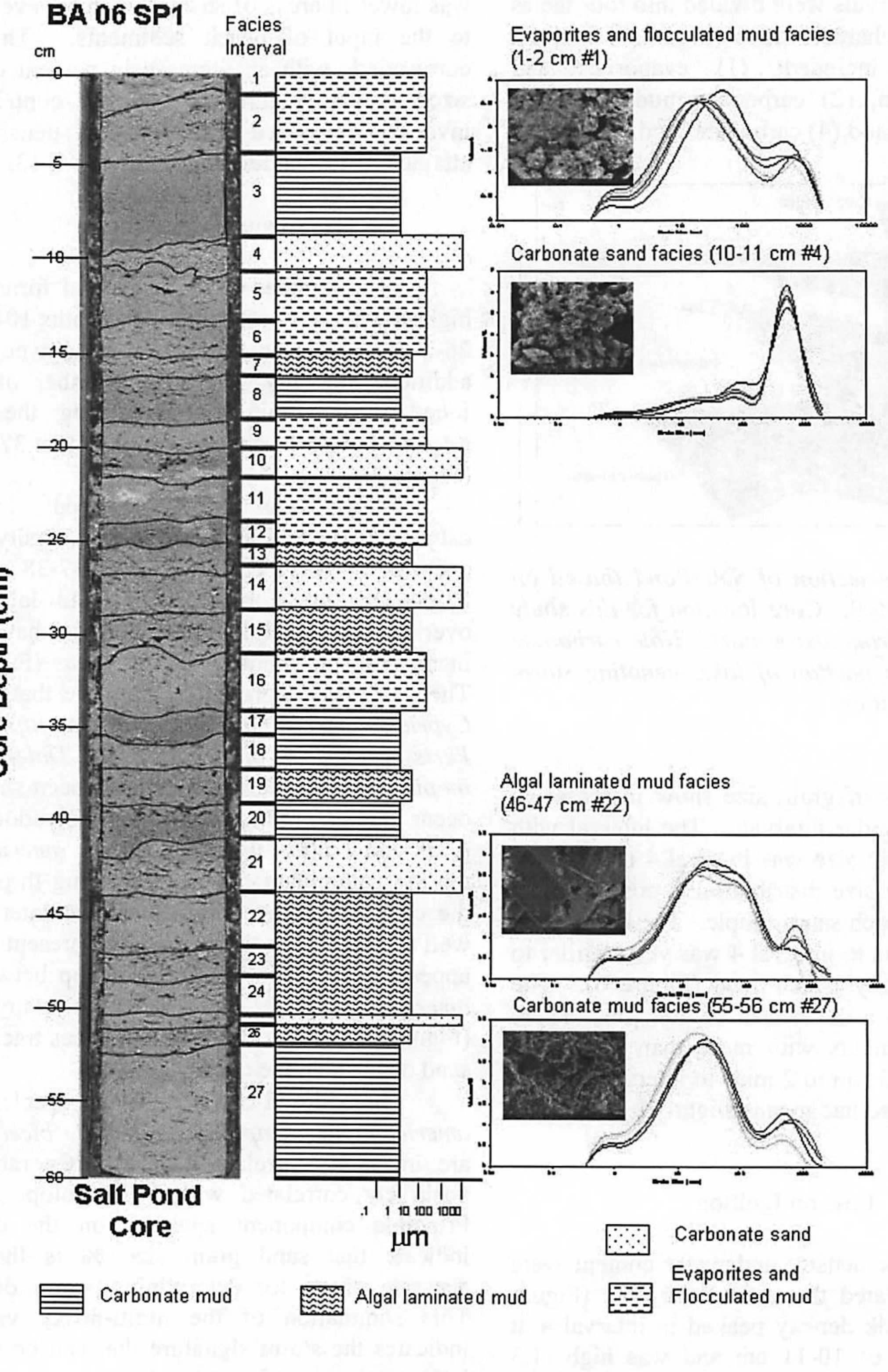

Figure 6. Core with grain size distributions and photos in intervals as indicated.

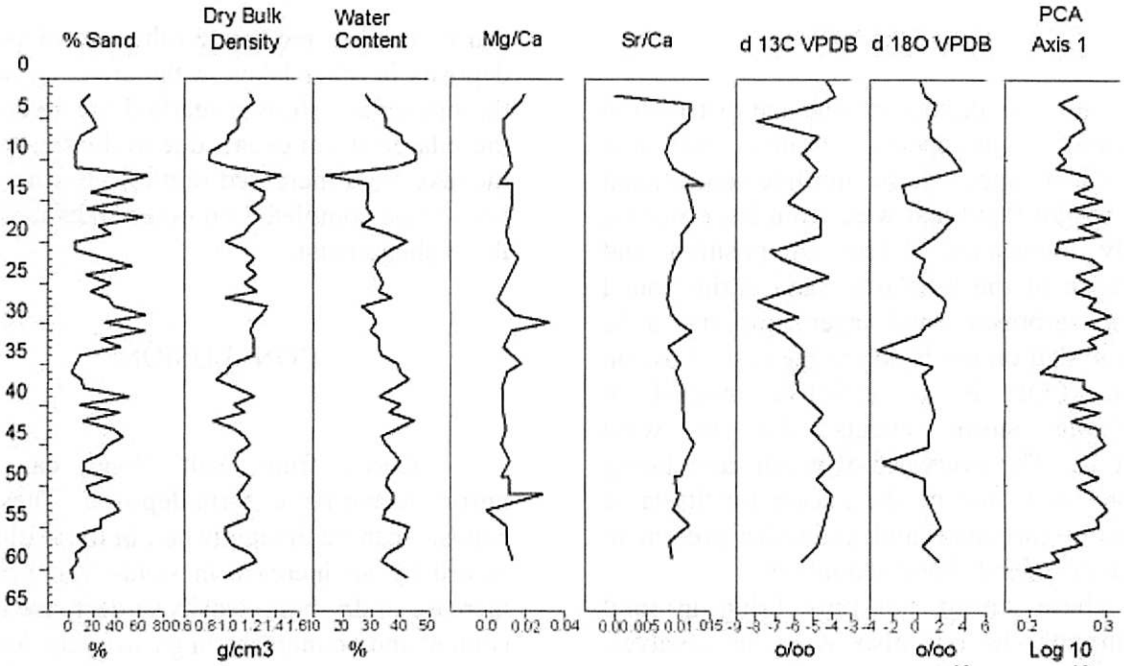

Figure 7. Sand content, dry bulk density, water content, Mg/Ca, Sr/Ca as well as $\delta^{13}C$ and $\delta^{18}O$ from C. americana and P. bicelliforma ostracode shells from Salt Pond core. PCA Axis 1 is on all seven datasets and represents >95% of all the variation within the combined datasets. Scales as indicated.

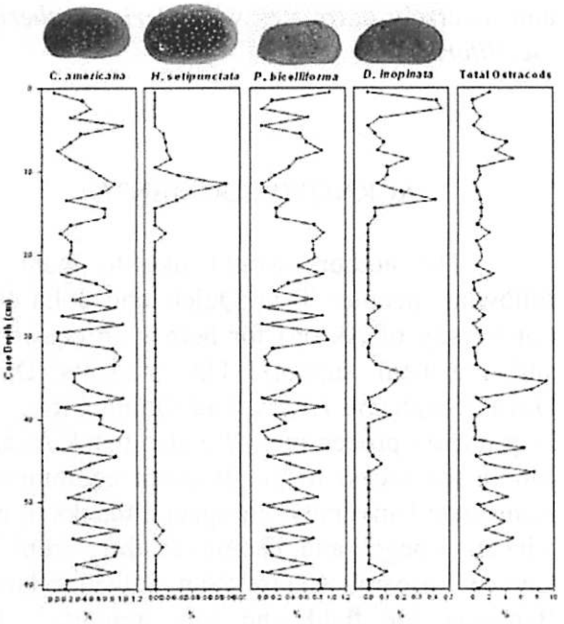

Figure 8. Ostracode % abundances for the four most common species in Salt Pond: Cyprideis americana, Hemicyprideis setipunctata, Perissocytheridea bicelliforma and Dolerocypria inopinata. *Total ostracodes are on the far right.*

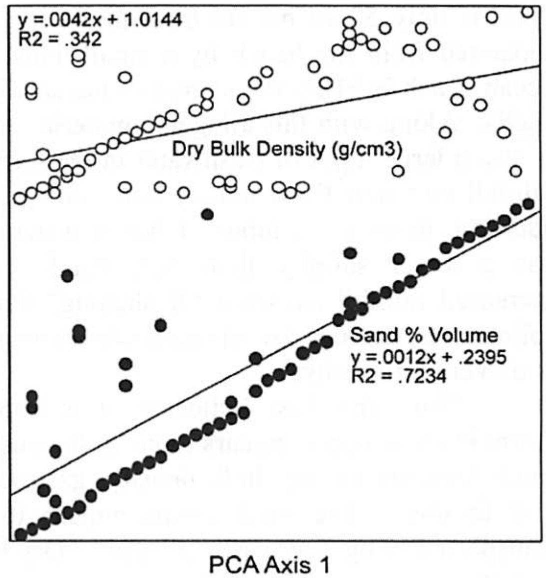

Figure 9. PCA Axis 1 vs. sand% and dry bulk density %; regressions indicate that sand % is the most effective proxy for determining storm deposition.

DISCUSSION

Based on the occurrence and distribution of bivalves, gastropods, forams, and sand particles there appear to be multiple depositional events in Salt Pond that were from large storms, possibly hurricanes. The composition and appearance of the bioclastic sand grains found in these carbonate sand layers appears to be similar to that on the beach to the east. Loss on Ignition (LOI) is an effective method of determining storm events due to wind deposition. The overwash of beach sand during large storms would be the reason for the large increase in carbonate and grain-size present in these layers of Salt Pond sediments.

These storms not only bring in sand from the beach, but also wash in bivalves, gastropods, seeds and forams. This is evidenced by the increase in shells that coincide with the sand deposits and also the fact that these species are not normally found in Salt Pond. Therefore they are most likely to have been washed or blown in by a large storm event. Since Salt Pond is only 50-75 meters from the ocean and separated from the beach by a small dune, the ocean beach is likely the source of the sand and shells. Along with this allogenic material, there is also a large input of freshwater in the form of rainfall into Salt Pond during large storms. In addition, there is an input of ocean water that has a lower salinity than Salt Pond. The increased rainfall causes a "freshening" that is followed by an increase in ostracode abundance and overall diversity.

Thus, the best indicator of a tropical storm in these cores appears to be an increase in sand-sized grains, dry bulk density, gastropods and forams. The sand grains appear to be transported in by overwash and wind. Dry bulk density increases during these times because grain size increases and the carbonate mud and algal layers decrease. Gastropods and forams appear to increase due to the possible freshening of the water to a more normal marine salinity. These sedimentary and paleontological components provide a "storm signature" that can be used to recognize other storm washover deposits in other lakes in the area. In addition, the ostracodes show a marked "recovery" after these large storm events due to the freshening of the lake from increased rainfall. Further studies need to be completed on other lakes to compare these phenomena.

CONCLUSIONS

Cores from Salt Pond can record hurricane and large storm deposits. These storm deposits can be distinguished in the sedimentary record by an increase in sand-sized grains, an increase in dry bulk density, a decrease in water content and an increase in gastropods, forms and seeds. Mollusk and ostracode abundance increased after documented storm deposits. *Cyprideis americana* is the most dominant ostracode species throughout the pond's history and inversely correlates with *Perissocytheridea bicelliforma.*

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