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PALEOENVIRONMENTAL RECONSTRUCTION OF TRIANGLE POND (SAN SALVADOR ISLAND, BAHAMAS) THROUGH STRATIGRAPHIC AND ELEMENTAL ANALYSIS OF A SEDIMENT CORE

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ABSTRACT. Triangle Pond is one of the numerous brackish to hypersaline, inter-dunal lakes on San Salvador Island, the Bahamas. Located on the northwest side of the island, Triangle Pond offers an opportunity to study the effects that both climatic change and anthropogenic activity had on the paleoenvironment of a sub-tropical coastal lake as it is in close proximity to two prehistoric Lucayan sites and three historic Loyalist era plantations. This paper presents analyses of a 170 cm long core from Triangle Pond (TP3) collected in 2009. Sediment grain size and composition, macrofossil identification, and elemental analysis were performed and six depositional environments were defined. These data suggest that Triangle Pond began approximately 3,400 yr BP as a sub-aerial depression dominated by terrestrial input with the occasional inundation of marine water from storm deposits. The depression became more influenced by marine input as sea level rose and Triangle Pond became a restricted tidal creek. The tidal creek then was overtaken by a mangrove marsh approximately 2,500 yr BP. The mangrove coastal marsh was destroyed approximately 500 yr BP by a thick sand deposit. The event that destroyed the mangrove coastal marsh was also responsible for separating Triangle Pond from the ocean resulting in the current state of a hypersaline, microbial mat-dominated pond.

Inductive Coupled Plasma Mass Spectrometry analyses of TP3 lake sediment shows that there are elemental traces within the sediment correlating to Lucayan activity approximately 1,300 yr BP. The elemental peaks occur when Triangle Pond was a mangrove coastal marsh open to the ocean. The correlation between these anthropogenic markers and the prehistoric archaeological sites fit well with known Lucayan settlement patterns. Therefore, an analysis of sediment deposition in Triangle Pond not only allows for an understanding of coastal lake evolutionary processes, but also indicates that human alterations within the watershed are evident from elemental concentrations.

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INTRODUCTION

San Salvador Island is located on the eastern side of the Bahamas archipelago. The Bahamas platform is tectonically stable, isostatically subsiding at 1-2 m every 100,000 years. The islands' geology consists of sequences of late Pleistocene and Holocene carbonate rocks of subtidal, intertidal, and aeolian origin. Terra rossa paleosols developed during periods of prolonged exposure and lower sea levels with input of long-range transfer of African and other dust (e.g., Carew and Mylroie, 1995; Curran and White, 1995; Hearty and Neumann, 2001; Muhs et al., 2007). The process of regression and progradation means that San Salvador Island grows laterally as younger standline and dune deposits are added seaward, and lakes form between these dunes (Hearty and Kindler, 1993). San Salvador Island, although only 21 km long and 8 km wide, has a significant number of these interdunal lakes (Figure 1).

Triangle Pond is located on the northwest side of San Salvador, and, like most of its lakes, it is shallow and brackish to hypersaline (Figure 1). The lake is located in the low-lying area formed

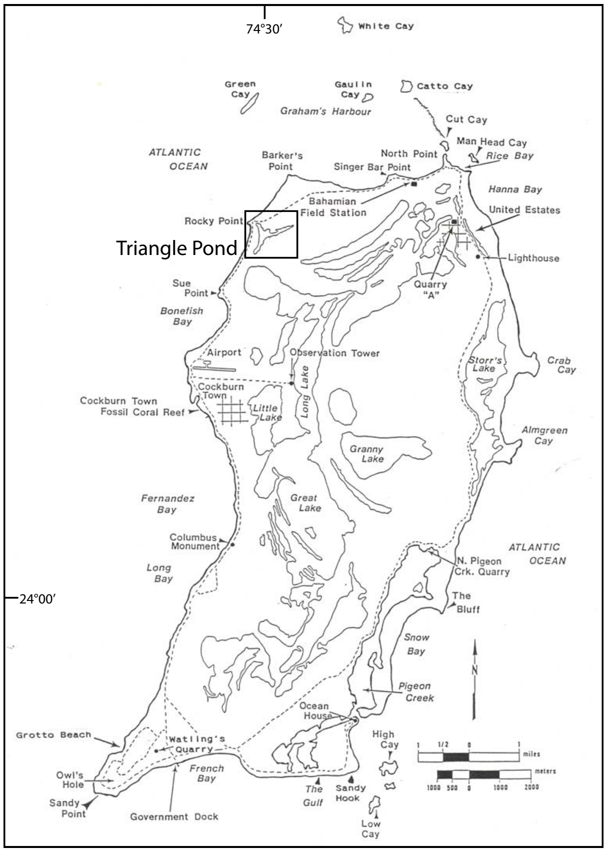

Figure 1. A map of San Salvador Island with the study area indicated by rectangle (after Mylroie and Carew, 2010).

by the juxtaposition of two strandplains and backbeach dune fields with different orientations to form a cape. Triangle Pond has an arm oriented in the east-west direction and one in the north-south direction (Figure 2). The two strandplains consist of strata assigned to the Hanna Bay Member of the Rice Bay Formation of late Holocene age that started forming around 3,200 yr BP (Hearty and Kindler, 1993; Carew and Mylroie, 1995).

Located near Triangle Pond are two prehistoric Lucayan sites, Minnis-Ward (850–1400 A.D.) and Palmetto Grove (1100–1400 A.D.) (e.g., Berman and Gnivecki, 1995; Blick and Bovee, 2007) (Figure 2). The Lucayans were the native people of the Bahamas and began settling the archipelago in the late 7th century, with one of the earliest Lucayan localities being the Three Dog Site (660–1500 A.D.), located on the southwest

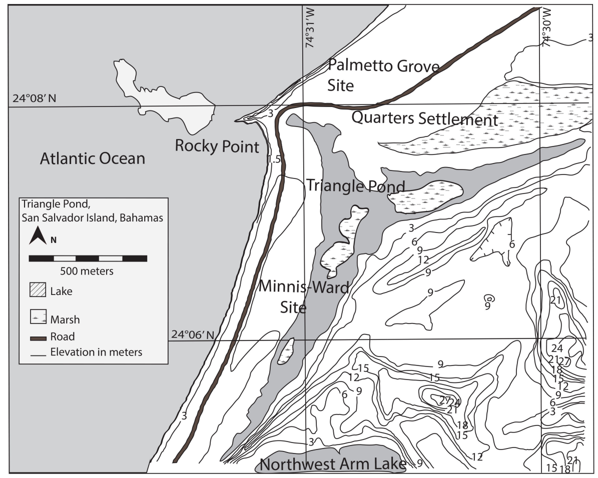

Figure 2. A topographic map of the study area on the northwest side of San Salvador island in The Bahamas. The location of Lucayan sites, Minnis-Ward and Palmetto Grove, are indicated to the west and northwest of the lake. The Loyalist-era Quarters Settlement is located north of the lake.

side of San Salvador (Berman and Gnivecki, 1995; Wilson, 2007). San Salvador has 32 open-air Lucayan settlements. The Pigeon Creek Site (1100–1560 A.D.) is the largest and most examined Lucayan settlement in the Bahamas (Craton and Saunders, 1999; Whyte et al., 2005). Lucayan settlements are found at locations with easy access to the sea, with most being found along coves, inlets, and lagoons. These locations allowed for optimal marine/nearshore foraging and were inhabited for long periods of time (Rose, 1987; Craton and Saunders, 1999; Fitzpatrick and Keegan, 2007; Blick and Brinson, 2007). Both Minnis-Ward and Palmetto Grove sites were not occupied when Europeans arrived in 1492 as proved by radiocarbon dating of the cultural layer as well as lack of any Spanish artifacts at either site (Blick and Bovee, 2007).

The arrival of Europeans had a devastating effect on the Lucayan people. Through disease and labor exploitation, the native population was decimated within 25 years of Columbus' arrival (Craton and Saunders, 1999; Wilson, 2007). Following the enslavement and removal of the Lucayans, San Salvador Island remained uninhabited until the resettlement by British Loyalists and their slaves after the Treaty of Versailles in the late 18th and early 19th centuries (Craton and Saunders, 1999). The Loyalist period on San Salvador Island was short lived, with most of the plantation owners abandoning the island by 1830, but the plantation system of agriculture had devastating effects on the ecology of the island. Although prehistoric human activity resulted in some alterations of the island environment, those changes paled in comparison to the activity of post-European human occupation (Craton and Saunders, 1999; Fitzpatrick and Keegan, 2007).

Evidence for changes brought on by both the prehistoric and historic human occupation as well as variations in the regional climate of San Salvador Island, Bahamas is stored in the paleolimnological record of the lakes on the island (e.g., Pacheco and Foradas, 1987; Brenner and Binford, 1988; Burney and Burney, 1994; Oldfield et al., 2003; Niemi et al., 2008). Lake sediments provide a good source for understanding environmental and climatic changes in a surrounding area as they offer a continuous record of the activity and past conditions within their watershed (e.g., Schnurrenberger et al., 2003; Last and Smol, 2004). Furthermore, stratigraphic and geochemical analysis of sediment permits quantification of these changes (e.g., Last and Smol, 2001).

The aim of this study was to determine how the paleoenvironment of Triangle Pond changed over the course of its existence and builds on the initial study of Aaron et al. (2010). Furthermore, the study was designed to investigate the potential correlation between the environment and anthropogenic activity using terrestrial elemental makers, such as increase in deposition of iron and nickel. Populations living on carbonate islands in the subtropics, such as the Bahamian islands, are particularly vulnerable to small changes in resource availability. Therefore, understanding how natural systems and human-induced factors may have caused ecological changes in the environment of the past should help in identifying and mitigating present and future threats to the environment.

METHODS

Sediment cores were extracted from Triangle Pond in June 2009 at five separate locations along two transect lines (Figure 3), one approximately perpendicular to the Minnis-Ward archaeological site and the other parallel to the shore along the deepest part of the basin. At the time of collection, the depth of the lake was 26 cm in the deepest part, relatively high for the lake given anecdotal observations over the past decade. The cores were collected using a modified Livingstone-type, rod corer with a piston (Myrbro and Wright, 2008). The coring platform was constructed from two recycled Catamaran pontoon hulls covered by plywood with an opening in the middle to allow for the lowering of the coring device to the lake's sediment-water interface. Pre-split and taped PVC-pipe was attached to the core housing, and the piston was placed at the bottom of the corer.

The top 15-20 cm of organic material was not collected in the cores. The gelatinous properties and high porosity of this upper microbial mat material made it difficult to collect at the sediment-water interface. The corer was

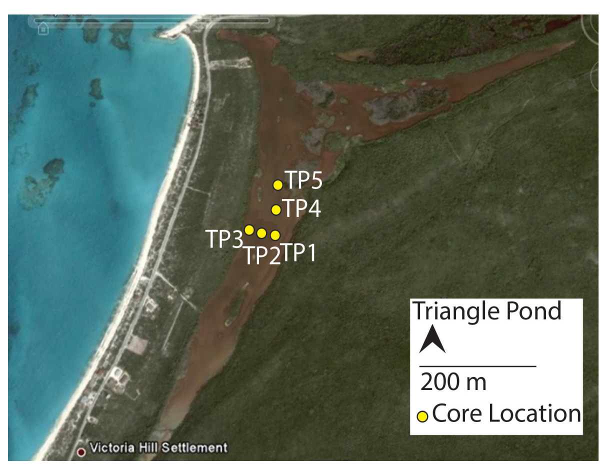

Figure 3. Location of sediment cores collected from Triangle Pond in 2009.

physically pushed into the bottom sediment and low pressure was created by the downward push of the corer and the upward movement of the piston, allowing for the sediment to be recovered. At two locations, this process was repeated in order to obtain longer cores using extension rods. Five cores were collected in all (Table 1). This study focuses on TP3, which was recovered in two pushes, a combined 170 cm, 16 m from shore (Table 1, Figure 3).

The core was split and described based on the classification of lacustrine sediments outlined by Schnurrenberger et al. (2003). The units of the core were distinguished either by color changes or by changes in composition and texture of the sediment (Figure 4). Macrofossils were collected from all units and cleaned with hydrogen peroxide before identification (Lawson, 1993). Sediment

Core	Core Depth	Recovered	Percent Recovered	Distance from TP3
TP3	220 cm	170 cm	77%	0
TP2	144 cm	130 cm	90%	10 m (to the E)
TP1	66 cm	58 cm	88%	20 m (to the E)
TP4	125 cm	74 cm	59%	55 m (to the NE)
TP5	123 cm	78 cm	63%	97 m (NNE)

Table 1. Record of core recovery for five sediment cores retrieved from Triangle Pond in 2009.

size and composition were verified by microscopic examination using smear slides (unconsolidated material sealed under a coverslip in Norland Optical Adhesive 61).

The Loss-on-ignition (LOI) technique (Dean, 1974) was used to determine dry bulk density (DBD), organic matter content (OM), and inorganic carbon content (IOC) (Figure 4). For this analysis, one cubic cm of sample was

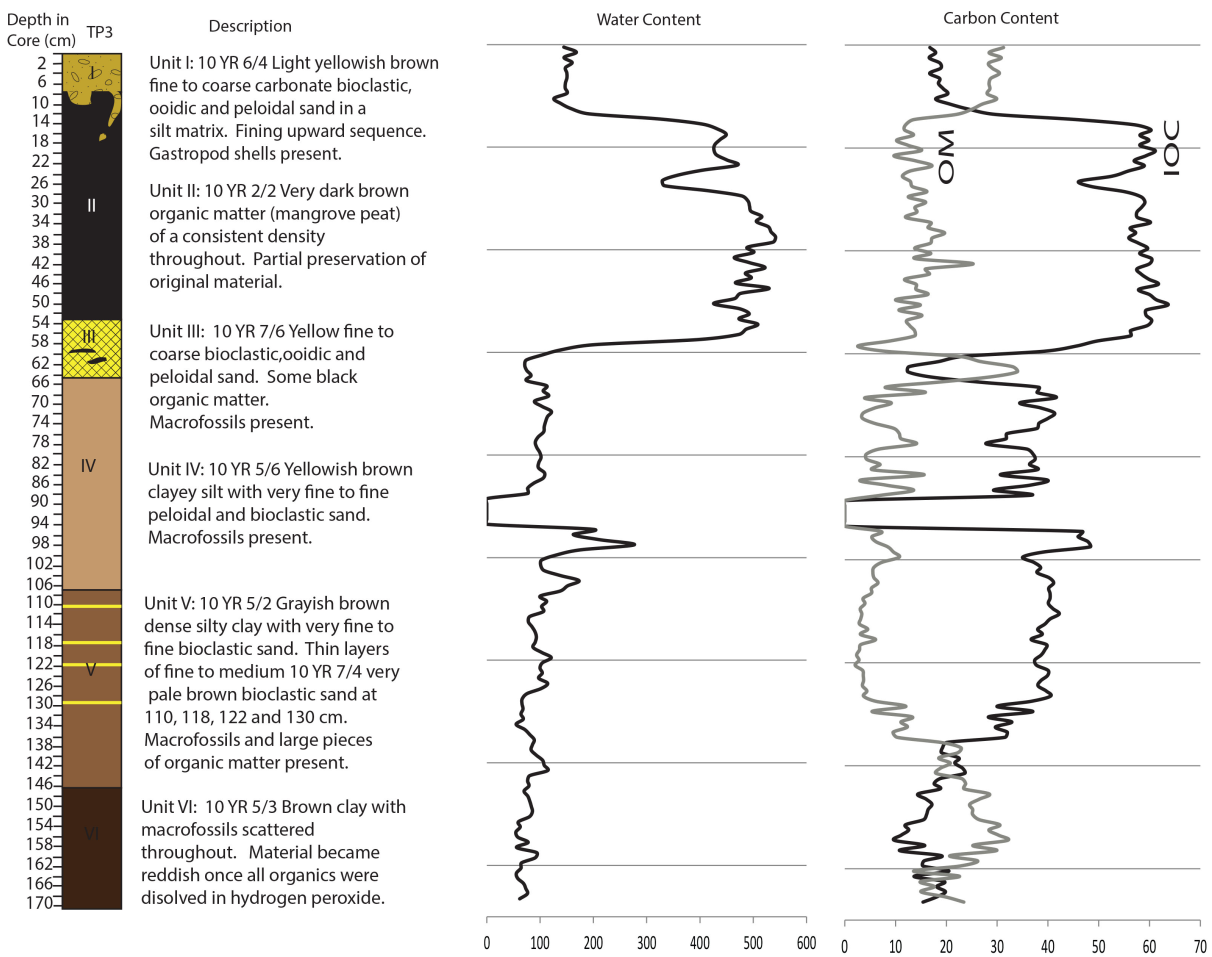

Figure 4. Core TP3 displayed six different depositional units which were differentiated by sediment composition, texture, organic/inorganic content, and macrofossils.

removed at every cm of the core. The DBD, OM, and IOC of sediment can assist in the determination of the depositional environment. For example, IOC is a good indicator for the amount of carbonate sand present.

A Varian UltraMass 600 Inductively Coupled Plasma Mass Spectrometry (ICPMS) was used to determine elemental content of the sediment on one cubic cm samples collected from the core at one-cm intervals (Figures 5 and 6). Samples were first dried in an oven at 105°C to remove excess water. From each sample, 0.05 g was weighed out and placed in an individual bottle where it was titrated with 2 ml of nitric acid and left overnight to dissolve. The samples were then filtered to remove any solids and the remaining solution was diluted with deionized water to 100 g. The liquid samples were then analyzed following the procedure described in Worley and Kvech (2000).

Peat samples were collected at 15 cm and 60 cm, and a sample of wood was collected at 160 cm. The samples were sent to the University of Georgia for radiocarbon analyses (Table 2).

Core	UGAMS Number	Depth in Core	Material	Unit	^{14}C Date
BA09TP3A	6553	15 cm	Peat (bottom of bioturbation)	II	1,350 ± 25 YBP
BA09TP3A	6554	60 cm	Peat (bottom of unit)	II	2,290 ± 30 YBP
BA09TP3B	6555	5 cm	Peat (loose, top of core)	V	2,220 ± 25 YBP
BA09TP3B	6556	67 cm	Wood (middle of unit)	VI	3,380 ± 30 YBP

Table 2. Results from radiocarbon dates extracted from TP3. The core was taken in two sections and information is displayed based on the two separate sections rather than cumulative depth, which was altered due to dehydration of the sediment.

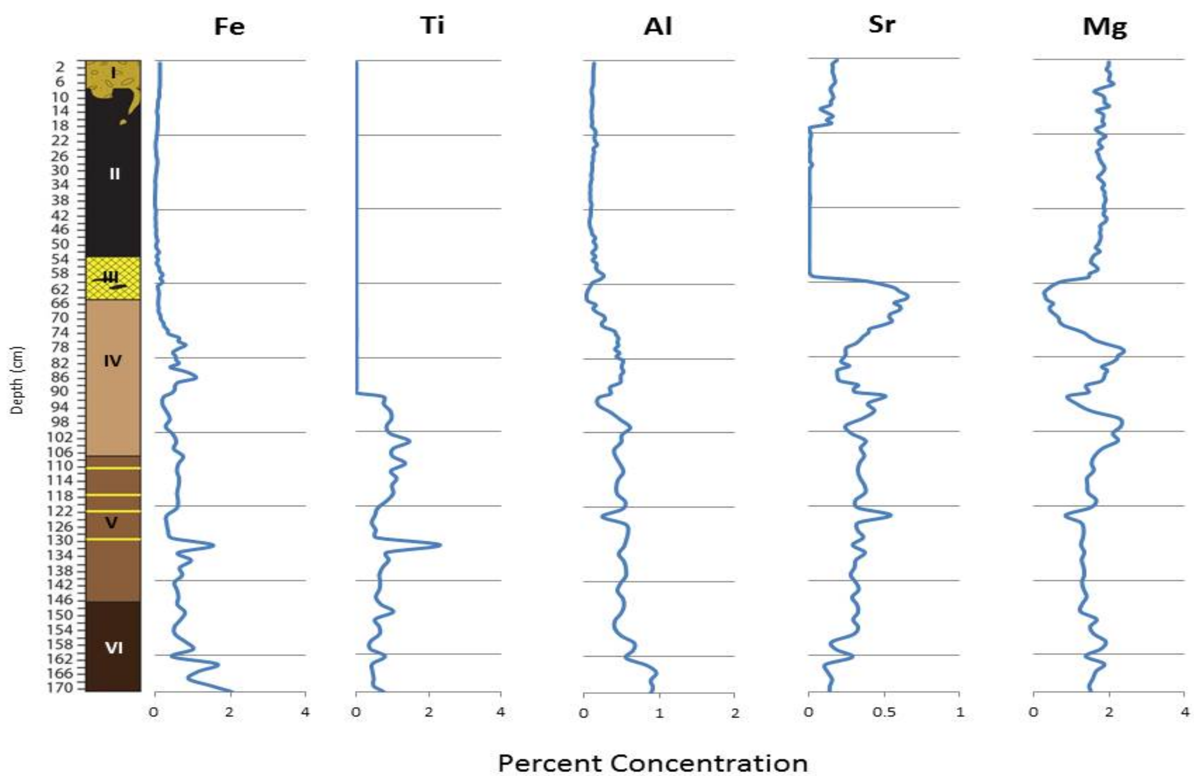

Figure 5. Five minor elements were determined using ICPMS. Iron, titanium and aluminum are indicators for terrestrial runoff. Strontium and magnesium are elements used to determine salinity, where strontium is used to indicate a marine influence.

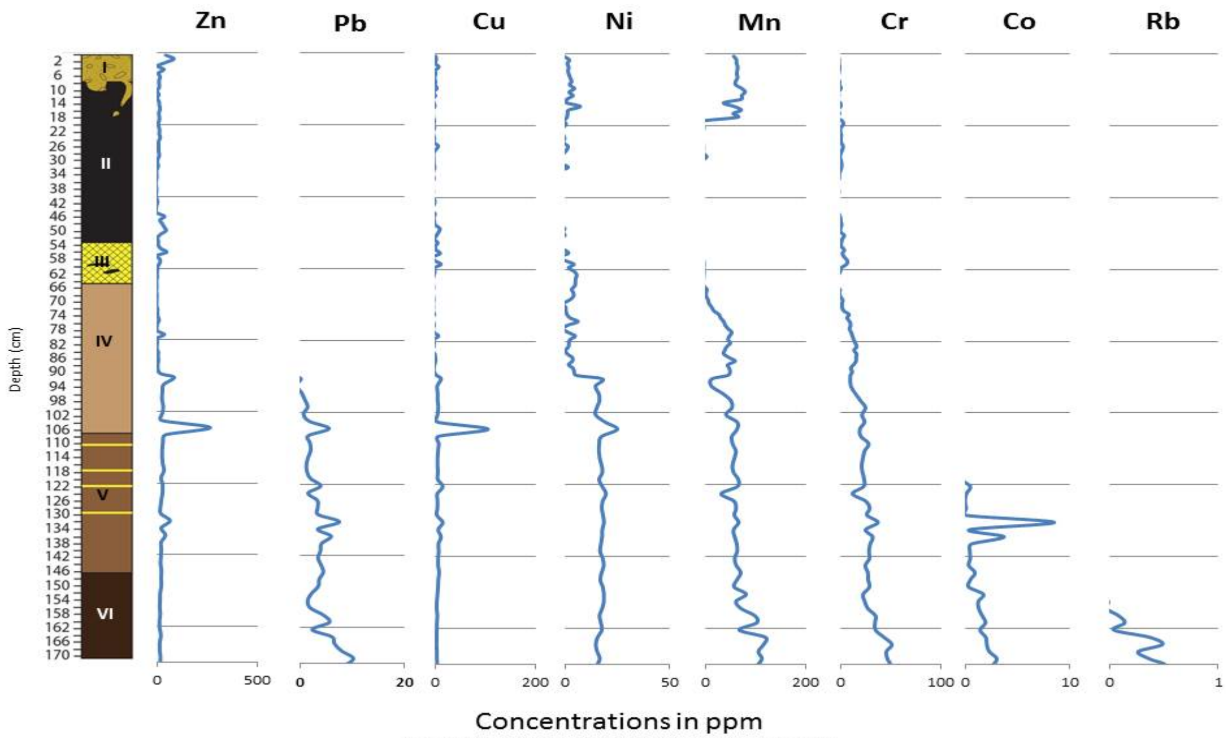

Figure 6. Concentrations of eight trace elements were determined using ICPMS. The higher amounts of these elements in the lower 3 units of the core correspond to elevated levels of Fe, Al, and Ti concentrations, which indicates a terrestrially dominated depositional environment.

RESULTS

Sedimentary Units

Unit I. The top 8 cm of the core consists of a fine- to medium-sized bioclastic, oolitic and peloidal carbonate sand in a carbonate mud matrix. Under microscopic examination, both ostracods and marine foraminifera are present. The sediment also shows a decrease in size towards the upper portions of the unit. *Cerithidea costada*, mollusks typical of mudflats and mangroves, shells are present within the layer (Lawson, 1993). This layer contains organic material either from the overlaying layer (not collected in sediment core) or as a disturbance from the peat layer below. LOI indicates that this layer has a relatively lower water content percentage and a lower (16-19%) organic matter content while having higher inorganic carbon content (28-32%) (Figure 4).

Unit II. This unit, 8 to 53 cm, is primarily of a dark brown peat layer. The top 18 cm is bioturbated by a root system which has been back filled by the overlaying layer. One *Cerithidea costada* gastropod shell was found at 15 cm within the sand layer. LOI indicates that this layer has very high water content as well as a high percentage of organic matter (20-60%), but has low inorganic carbon content (2-28%) (Figure 4). The large variance in IOC is most likely caused by the sand contained within the bioturbated section and selective sampling during lab work. The bottom of the bioturbation, 15 cm depth, dates to 1,350 ± 25 yr BP (Table 2). The bottom of the layer, at 60 cm depth, dates to 2,290 yr BP (Table 2). It is important to note that the original thickness of the peat layer when wet was 60 cm. It shrunk approximately 7 cm between the original sampling in 2009 and the core description in 2013. The shrinkage would have no effect on the overall dating of the layer.

Unit III. This unit measures from 53 to 65 cm. It is a fine to coarse, bioclastic and ooidic yellow sand. The unit contains some organic clasts. Two *Cerithium certith* gastropod shells, common to shallow marine waters, were found within this layer (Lawson, 1993). LOI indicated that this layer has lower water content than the overlying units. There is a large spike in IOC at 61-65 cm correlating with a decreased amount of organic matter (Figure 4).

Unit IV. From 65 to 107 cm, the core is dominated by a yellowish brown carbonate mud with peloidal and bioclastic very fine to fine sand. A few large organic clasts are present towards the top of the unit. LOI indicates that the unit composition is dominated by high organic content with an occasional spike in IOC (Figure 4).

Unit V. This unit, 107 cm to 145 cm, is dominated by a grayish brown dense carbonate mud. Within the carbonate mud matrix, very fine bioclastic, subrounded sands are present. At 111, 118, 122, and 129.5 cm, there are distinct thin beds of pale brown sand layers that coordinate with peaks in IOC (Figure 4). Towards the bottom of this layer, IOC starts to dominate the matrix. A wide variety of shells were found throughout this layer with three *Vexillum henderson*i, three *Anomalocardia brasiliana*, nine *Cerithidea costada*, two *Cerithium ebureum,* and one *Melampus coffeis* with the majority of these mollusk types found primarily within mudflats.

Unit VI. The bottom 24 cm of the core is dominated by brown carbonate mud with a few pieces of organic material found throughout. The mud has a reddish tint when all organic material is removed. Similar to the overlaying layer, many mollusk shells were found with the dominate species being *Cerithida costada* at 11 shells. There was one shell of each: *Cerithium eburneum, Crithium litteratum* and *Cerithium certith*. This layer has an increased amount of IOC with a few peaks of OM (Figure 4). A piece of wood collected at 160 cm was radiocarbon dated to 3,380 ± 30 yr BP (Table 2).

Elemental Analysis

The ICPMS analyses indicate trends in five minor elements (Figure 5) and eight trace elements (Figure 6). The minor elements were aluminum, iron, magnesium, strontium, and titanium while the trace elements were cobalt, copper, manganese, nickel, lead, zinc, chromium, and rubidium. The elements show similar trends throughout the length of the core. The only exception to the trends is strontium. Strontium shows an inverse relationship to the other elements.

In general, the concentrations of the elements were high in the lower units of the core. Magnesium stayed the most dominant element throughout all units except for a marked decrease at the bottom of unit 3. In the lower three units, the minor elements have high concentrations with maximum peaks correlating with increases in inorganic carbon. This is most obvious in units IV and V. The peat layer of unit II has low concentrations of most elements until a depth of 18 cm where there is a slight increase in all trace and minor elements (Figures 5 and 6).

DISCUSSION

Stratigraphic and geochemical analyses of Triangle Pond indicate that there were six different depositional environments since its formation around 3,400 years ago (Figure 4). Each of these depositional environments can be defined not only by sediment composition and texture, but also by macrofossils, microfossils, elemental content, and inorganic/organic carbon content. Variations in the depositional units give insight to the lake's development and anthropogenic activity.

The oldest unit is a clay-like carbonate mud, Unit VI, high in minor and trace elements. It is specifically higher in the elements of iron, titanium and aluminum (Figures 5 and 6). These elements have been used in previous works to indicate an increase in terrestrial input (Niemi et al., 2008). The theory behind the use of these elements as a terrestrial input markers rests on the fact that the carbonate environment of the Bahamas lacks any significant amount of insoluble residues, and therefore, the input of these elements into a lacustrine environment must be due either to runoff of the land or dust deposits during intense dry periods (Muhs et al., 2007). The layer was also deposited with little influence from marine waters indicated by the low levels of strontium. Strontium is incorporated into biogenic carbonate crystal lattice structures during formation, and marine levels of strontium are higher than those found in freshwater (Reinhardt et al., 1998). Therefore, levels of strontium can be used to determine the presence of a marine influence. The bottom of the core dates to approximately 3,400 yr BP, which coincides with a known dry period in Caribbean history (Tedesco and Thunell, 2003; Park, 2012). Triangle Pond was most likely a sub-aerial depression that received little marine input and an occasional inundation from minor precipitation or major storm events.

As depth in the core decreases, the marine influence on the sediment increases. Units V, IV and III show increasing amounts of strontium entering the system (Figure 5). These sediments also are increasing in grain size and inorganic carbon content, showing a more direct input of carbonate sediment (Figure 4). The increasing of marine influence within Triangle Pond coincides well with an increasing sea-level during the late Holocene, where sea-level rose to approximately 1 m higher than present levels (Bourrouilh-Le Jan, 2007). These layers also show signs of terrestrial input, indicated by large peaks in both zinc and titanium at specific horizons (Figure 6). These massive spikes may be indications of major storm events as they are also marked by increases in grain sizes (the sand layers described in the results section). Large storms often deposit carbonate sand packages in coastal lacustrine environments (Park, 2012). The sediment composition along with the geochemistry of these three units indicates that Triangle Pond became increasingly opened to the ocean, with it becoming a deep tidal inlet by approximately 2,500 yr BP.

The end of this opened tidal inlet is defined by the beginning of unit II. This unit is a dark brown peat layer formed by the presence of a mangrove forest and coastal marsh (Figure 4). On San Salvador Island, this environment is found in tidal creeks and along the coasts. Mangroves can withstand a variety of environmental conditions and are specifically good at adapting to changes in salinity and constant inundations from the sea, and as such, the peats from these plants are often used as proxy for sea level (e.g., Monacci et al., 2011). The mangrove forest began approximately 2,300 yr BP, as indicted by radiocarbon dating (Table 2). The mangroves found in Triangle Pond grew during a period where the lake was a tidal inlet, as indicated by the layers deposited in this unit, and thrived as the tidal inlet became increasingly protected.

A radiocarbon date of 1,350 ± 25 yr. BP was obtained from unit II at a core depth of 15 cm (Table 2). This location is at the bottom of a bioturbation of mangrove root systems and 7 cm below the termination of the peat accumulation (Figure 4). There is a peak in trace and minor elements at this position in the core (Figures 5 and 6). Zinc, iron, aluminum, and nickel all increase at this point while they were not present in any appreciable quantity through the rest of the unit. The cause of this increase is most likely the arrival of the Lucayans and their slash and burn agriculture, which would have cleared some of the stabilizing biota of the island and caused an increase in terrestrial runoff (e.g., Oldfield et al., 2003; Niemi et al., 2008).

The youngest unit shows the most diverse sedimentary composition. It contains bioclastic, oolitic and peloidal sand as well as marine foraminifera (Figure 4). The unit also shows signs of a fining upward sequence. This unit also has an increased amount of minor and trace elements, the most obvious increase being in manganese with a peak in zinc towards the top of the unit indicating mixed marine and terrestrial sources (Reinhardt et al., 1998; Muhs et al., 2007; Niemi et al., 2008) (Figures 5 and 6). The sediment from this unit fills in the bioturbation created by the root system of the underlying layer. This feature may indicate that unit I was deposited quickly in a single event which uprooted the existing mangroves and deposited a thick layer of sand in the voids created. Further research is required to support this theory. It is clear that this unit represents a change in the insular environment of Triangle Pond. Unit I is located directly under the uncollected organic matter which represents the current conditions of the lake and directly above the peat layer which indicates a mangrove forest (Figure 4). If it is shown that a singular event deposited this unit, then the change in environment may indicate an abrupt closing of the tidal inlet.

The sediment core TP3 collected from Triangle Ponds shows a changing coastal environment over the last 3,400 years. The alterations within the insular environment indicated by six depositional units recorded early aridity in the region, an increase in sea level, and the development of a mangrove swamp. The study also shows that during Lucayan occupation of the Minnis-Ward and Palmetto Grove prehistoric sites, the lake was an open tidal inlet dominated by a mangrove forest. This environment coincides with the known Lucayan settlement patterns. An event occurring post Lucayan settlement may have been identified within the core. The event deposited a large package of carbonate sand within the mangrove swamp and most likely closed the tidal inlet. The closure of the tidal inlet created a hypersaline lake. This quick alteration of the environment may explain why, unlike other Lucayan sites on the island, these two sites were unoccupied when Europeans arrived in 1492. Further studies on cores from Triangle Pond will allow for a more precise reconstruction of paleoenvironment, and with the inclusion of the water/sediment interface, also give insight to effects on the environment created by the Loyalist period (late 18th and early 19th century).

CONCLUSION

Through examination of a core taken from one of the deepest and most central portions of Triangle Pond, San Salvador Island, the Bahamas, it can be observed that changes in the surrounding environment, climate and anthropogenic activity can be recorded in the sediment of the lake. The different stratigraphic units and variations in elemental content throughout the six sedimentary units identified in the core show that the depositional environment of Triangle Pond has changed since its formation and that these changes shed light not only on local and regional climate changes, but also provide information on the settlements along its shores. The lower units of the sediment core indicate that an arid environment, ca. 3,400 yr BP, allowed for the dominance of terrestrial input. As sea level rose during the late Holocene, Triangle Pond became increasingly marine influenced, and at one time, was an open tidal creek. The tidal creek was replaced by a mangrove forest. The mangrove forest would have provided marine resources the Lucayans needed in order to settle both at Minnis-Ward and Palmetto Grove. This intertidal environment changed with the closing of the lake basin from a large input of marine water and sediment leading to the hypersaline pond found there currently.

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