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Front Cover: Close-up view of a patch-reef coral head in Grahams Harbor, north of Dump Reef. As shown here, Caribbean shallow-water reefs have declined since the mid-1980s and are now largely overgrown by fleshy green macroalgae and a variety of encrusting organisms. See Curran et al., "Shallow-water reefs in transition," this volume, p. 13. Photograph by Ron Lewis.

Back Cover: Dr. A. Conrad Neumann, University of North Carolina, Chapel Hill, NC, Keynote Speaker for the 11th Symposium and author of "Cement loading: A carbonate retrospective," this volume, p. xii. Photograph by Mark Boardman.

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HOLOCENE HISTORY OF SPITTAL POND, BERMUDA: IMPLICATIONS FOR SEA LEVEL CHANGE

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ABSTRACT

Spittal Pond, a 3.24 hectacre inter-dune lowland pond, is located in Smith's Parish, Bermuda. The pond is composed of three independent basins that since have joined to form the present geomorphic feature. Thirteen vibracores, ranging from one-to-five meters in length, and three piston cores, all limited by lithified Pleistocene eolianites at their bases, have been recovered and used to reconstruct the Holocene sedimentological record. The core suite revealed several distinct sediment types: basal clay, hemic (fibrous) peat, sapric (amorphous) peat with intercalated bioclasts composed primarily of gastropod and ostracod shells, and fine-to-medium bioclastic sand. Two types of sediment-accumulation cycles have been recognized. The first consists of intervals of hemic and then sapric peat accumulation; the second exists within the latter intervals wherein sapric peat alternates with concentrated shell accumulations.

Inasmuch as the pond consists of three independent basins, three independent sedimentological sequences have been identified. The southwestern basin is best characterized by couplets of hemic and sapric peat (with interbedded bioclastic sand consisting of gastropod and ostracod shells) with a basal ^{14}C date of 4,320 ± 40 yr BP. The central basin contains not only the peats and bioclastic sand, but also includes 100 cm of basal clay that does not appear elsewhere in the record. The first peat in the central basin has a ^{14}C age of 3,760 ± 40 yr BP. Interbedded sapric peat and the ostracod/gastropod sand dominate the northwestern basin that has a basal ^{14}C date of 3,640 ± 40 yr BP.

Over its more than 5,000-year history, Spittal Pond can be characterized as operating within two primary depositional regimes. One supported the accumulation of thick deposits of hemic peat, while the other favored development of sapric peat. The presence of gastropod and ostracod sand exclusively within the sapric peat is interpreted to represent environmental perturbations within the pond that exceeded the tolerance of these invertebrate communities.

INTRODUCTION

The Bermuda archipelago consists of five islands located roughly 1,000 km due east of Cape Hatteras, North Carolina (Figure 1). The islands are near the southern edge of a 650 km^2 platform that lies upon a completely buried Oligocene volcanic seamount (Vacher et al., 1995). Bermuda is composed of 90% bioclastic dune rocks or eolianite first characterized by Sayles (1931), formed as linear ridges by lateral coalescence of coastal dunes (Vacher et al., 1995). The eolianite is interbedded with paleosols, which indicates the episodic transitional development of the island. These paleosols tend to be red to brown in color and are thought to have formed from deposits of atmospheric dust (Bricker and Mackenzie, 1970), derived from the Sahara (Muhs et al., 1990; Herwitz et al., 1996).

While study of the eolian material provides clues into the Pleistocene history of Bermuda, it does not provide much information for the Holocene deposits of the island. The well documented "yo-yo" nature of sea level during the Pleistocene transitioned into a gradual steady rise during the Holocene (Meischner et al., 1995). Sea level stabilization terminated further eolian development and a number of terrestrial ponds developed with rainwater filling depressions and interdunal lowlands created in the Pleistocene. Limited sedimentological analyses have been conducted on coastal ponds in the archipelago to characterize the Holocene (Jenks, 1970; Lister, 1971; Thomas and Wassmann, 1992; Rueger and von Wallmenich, 1996; Rueger et al., 1998; Hamzi and Rueger, 1998; Rueger, 2000).

This paper will detail the complex sedimentary history of a unique pond – Spittal Pond. Previous work was limited to analyses of single sediment cores taken from the southwestern basin. Herein the sedimentary character of the entire pond is reported based on the vibracores collected along a transect across the pond. Hence, a comprehensive understanding of the processes responsible for the Holocene history of the pond can be derived.

PHYSIOGRAPHIC FEATURES

Spittal Pond, located in Smith's Parish, covers a total area of 3.24-hectares within a nature preserve and bird sanctuary developed between 1954 and 1976 (Thomas and Wassmann, 1992), on the south shore of the island (Jenks, 1970). Its volume is estimated to be 12,200 m^3 with a mean present water depth of 38 cm and a maximum depth of 95 cm in the southern basin where dredging has taken place along the western and southern margins (Thomas and Logan, 1992). Salinity ranges from 6.5 to 42.5‰, with extremes thought to be the result of fresh water filling of the pond during wet weather, and salt water incursions during storms, very high tides, or episodes of evaporation (Thomas and Logan, 1992). Temperature, documented to range between extremes of 16.1° C to 37.5° C, is thought to be controlled as a result of higher rates of solar insolation on the shallow pond depths during low recharge periods. Additionally, dissolved oxygen varies spatially across an extreme range (surficial waters – 8.8 ppm; 0.5 m depth – 0.00; 10 June 2000). Thomas and Logan (1992) report that when biomass is at a maximum in late summer, periods of anoxia exceeding 24 hours in duration result in mass mortality events.

SITE DESCRIPTION

Spittal Pond lies between two parallel sets of Pleistocene dune ridges, which occur in the form of three small hills separating the pond from the Atlantic Ocean. Low-lying areas between these hills mark the northern and southern boundaries of the pond. During major storms and hurricanes, these lowlands are breached allowing infiltration of fully marine waters (Department of Agriculture and Fisheries, 1969). The pond is composed of three basins that are separated by shallow sills (Jenks, 1970; Figure 1).

Figure 1. Location map of Spittal Pond , Bermuda, with location of vibracores noted. Vibracores are labeled by locality (SP - Spittal Pond), collection year (00 or 01), and core number (1). Three sub-basins have been identified in the pond and are labeled.

PREVIOUS INVESTIGATIONS

There have been a limited number of investigations focused on Spittal Pond. Jenks (1970) provided a general description of the pond and the surrounding area, including an inventory of the modern flora and fauna, in addition to characterizing one subsurface piston core extracted from the southern basin. Two peat types were described from the core: (1) a fibrous peat consisting of plant material (mostly *Paspalum* that is found presently along the edge of the water and along mudflats) intermixed with finely divided organic material, and (2) a sedimentary peat consisting of finely divided organic particles forming a "dense amorphous mass." Jenks (1970) believed the amorphous peat was of algal origin, having formed in deep water beyond the limit of marsh or swamp vegetation. Three subsurface sediment types also were described – a "lower ostracod sand," an "upper ostracod sand," and "gastropod sands." The "lower ostracod sand" at -5.5 to -6.5 ft depth consisted of 40-50% ostracod shells and 50-60% reworked Pleistocene debris suspended in a gelatinous organic material. The "upper ostracod sand," above a depth of -5.5 ft, was composed of 100% ostracod shells with little to no organic or reworked Pleistocene material. "Gastropod sands," found interbedded with both sedimentary peat and the "upper ostracod sand," consisted of 20-30% *Hydrobia* shells, 40-50% ostracod shells, and 10-15% reworked Pleistocene debris with some organic matter.

Jenks (1970) concluded that the flora and fauna of the modern pond reflect volatile environmental conditions within the pond itself, imposed by fluctuations in salinity, temperature, and water depth. Cyclicity observed in the sediment types was thought to be due to a combination of changes in water depth, climatic regime, salinity, dissolved oxygen, and possibly the effect of hurricanes, storms, and high tides that would introduce sea water to the pond.

Lister (1971) investigated one core, taken by Neumann (1971), but details on the coring location were not provided. The ostracod *Cyprideis tomentosa* was reported as an abundant component of the benthic fauna and within the core. *Cyprideis*, common to other brackish water ponds in Bermuda, was abundant throughout the core and was associated with the aquatic gastropod *Hydrobia bermudensis*. Lister (1971) concluded that the low microfaunal diversity observed was characteristic of an immature ecosystem that had been maintained since the formation of the pond between 4,000 and 5,000 yr BP. Extreme variations in salinity were thought to restrict Spittal Pond from developing into a more mature ecosystem.

More recent work has focused not the pond's origin but, instead, on its current ecological state. Spittal Pond is one of a limited number of ponds on the island that is salt-water influenced. Thomas and Wassmann (1992) documented the biotic and physical characteristics of Spittal Pond, and, rather than focusing on the sedimentological characteristics, they conducted extensive geochemical analyses to characterize the waters and their suitability for migratory fowl. Since then, a number of studies have been conducted on Bermuda's terrestrial ponds (Rueger and von Wallmenich, 1996; Rueger et al., 1998, Hamzi and Rueger, 1998; Rueger, 2000; Severs et al., 2001), particularly Spittal Pond (Tackaberry et al., 2000).

MATERIALS AND METHODS

Vibracores of varying lengths were recovered along an axial transect from the Southwest to the Northeast (Figure 1, Table 1). Coring was conducted from an 8x8-ft pontoon platform constructed on site with the assistance of colleagues from the Bermuda Aquarium (Rueger et al., 2004); vibracoring techniques followed standard practices (Hoyt and Demarest, 1981). The maximum length of three-inch aluminum pipe used was 5 m, allowing for recovery of bedrock eolianite in most instances. Extracted cores were cut into one-meter lengths, capped, and transported to the Bermuda Aquarium where they were spit, photographed, logged, sampled, and archived. The degree of sediment compression during the coring process was calculated based on the distance between the surface of the pond and the sediment water level within the core pipe. Decompaction calculations were used to expand the cores back to their approximate original length for stratigraphic analysis.

Ten peat samples were sent to Geochron Laboratories (Cambridge, MA) for ^{14}C AMS dating. Samples were taken from bedrock/hemic peat contacts and the base of hemic peat layers in other cores where bedrock was not encountered. This sampling strategy was chosen to develop a time line that would allow for an interpretation of the development of the basin. Additionally, these dates were used as an aid to calculate sedimentation rates.

To assist in the determination of organic-matter contribution, carbon and nitrogen analyses were conducted at Colby College using an Exeter Analytical CHN 440 Analyzer. Representative samples from each peat within all cores were placed in 50 ml beakers and 10% HCl added to dissolve any carbonate fraction. This procedure was repeated to insure complete dissolution. Subsequently, samples were rinsed with distilled water, oven dried for 72 hours at 85° C, and powdered using a mortar and pestle. Each of the 71 samples from the cores taken in 2000 was analyzed in triplicate on the CHN analyzer.

Vibracore	GPS	Length	Eolianite/ Clay	Facies
SP001	N32 18 636 W64 43	4.0 m	Eolianite	H, S, Uncon.
SP002	N32 18 616 W64 43	2.31 m		H,S
SP003	N32 18 683 W64 43	2.85 m	Eolianite	H, S, Uncon.
SP004	N32 18 679 W64 43	2.58 m	Eolianite	H, S, Sa, Un-
SP005	N32 18 743 W64 43	3.62 m	Eolianite	RC, GC, H, S, Sa
SP006	N32 18 766 W6443 454	1.0 m	Eolianite	GC, H
SP007	N32 18 766 W64 43	2.25 m		H, S, Sa Uncon.
SP008	N32 18 749 W64 43	1.54 m	Eolianite	H, S, Sa
SP0101	N32 18 225 W64 43	1.48 m		H, S
SP0102	N32 18 466 W64 43	1.62 m	Eolianite	H, S, Uncon.
SP0103	N32 18 466 W64 43	2.47 m	Eolianite	GC, H, Sa, S
SP0104	N32 18 446 W64 43	3.47 m	Organic clay	GC, H, Sa, S
SP0105	N32 18 445 W64 43	2.66 m	Organic clay	GC, H, S

Table 1. Location of vibracores, recovered vibracore length, basal lithology or sediment, and Facies encountered (H – hemic peat, S – sapric peat, Sa – subangular sand, RC – red clay, GC – gray clay, Uncon – unconsolidated recent sediment)

Two clay samples were processed for XRD analysis: one gray clay sample and one red clay sample (SP005, Figure 1). Five grams of each sample were centrifuged at 1,000 rpms for 10 minutes to separate the fraction > 1µm. The supernatant was then centrifuged at 8,000 rpms for 15 minutes to separate the 0.1 –1 µm fraction. The remaining supernatant (the fraction < 0.1 µm) was used to prepare four slides of each sample following Pollastro (1982). Three different preparation techniques were used for each clay type and size fraction: one slide was untouched and used as a control, a second slide was glycolated over night, a third was heated to 300° C, and a fourth was heated to 550° C. Samples were then analyzed on a Rigaku DMAX II-B XRD at Colby College.

RESULTS

Sediment Types

Field and lab analysis of the cores resulted in the description of seven different sediment types – Pleistocene eolianite, red and gray clay, hemic peat, sapric peat, bioclastic sand and fine-to-medium sand (Table 1). The unconsolidated and saturated organic-rich sediments at the top of each core are equivalent to immature sapric peat found beneath these stratigraphic intervals.

Capping the Bermuda volcanic pedestal and composing nearly 100% of the exposed bedrock on Bermuda is a sequence of five formations dominated by eolian calcarenites and beach deposits that accumulated during the Pleistocene (Vacher et al., 1995). Amino acid racemization (AAR), ages are thought to correspond to oxygen isotope stages 13 (Walsingham Fm.), 11 (lower member, Town Hill Fm.), 9 (upper member, Town Hill Fm.), 7 Belmont Fm.), 5e (Rocky Bay Fm.) and 5a-c (Southampton Fm.) (Vacher et al., 1995). Deposition of the eolian calcarenites was principally as retention ridges (Vacher, 1973; Vacher et al., 1995) that formed by the coalescence of large scale, lobate, coastal dunes during sea level fall (Vacher and Rowe, 1997). Development of the dunes and enlargement of Bermuda was principally by lateral accretion (Vacher et al., 1995). The calcarenites are separated by paleosols of white (immature) or red (mature) color (Rowe, 1998). Marshes and ponds developed in the interdune lowlands and collapsed sinks in response to late Holocene sea level rise and climate change. In seven vibracores, the eolian sandstone was penetrated up to a depth of more than 0.5 m, the penetration depth may be the result of dissolution of cement by groundwater (Figure 2). In the cores the eolianites occur as fine grained, lithified, pale yellow brown (10 YR 8/2) calcareous sand.

Basal clays have been encountered in several vibracores – SP005, SP006, SP0103, SP0104, and SP0105 – but red clays are restricted to the central basin (SP005). An interval of 43 cm of red clay (5 YR 3/4), composed primarily of vermiculite (XRD analyses) and interspersed with organic material, overlies a basal sandy mud which is the product of dissolution of the underlying eolianite. The clay to organic ratio is approximately 50:50. The gray (N4) to dark grayish brown (10 YR 3/2) clay, found in all clay-bearing cores, is composed primarily of kaolinite (XRD analysis). One authigenic irregular nodule has been recovered from SP0104. Vertical rooting structures commonly are preserved, as well as dispersed organics (Figure 3), but the clay:organic ratio does not approach that in the red clay.

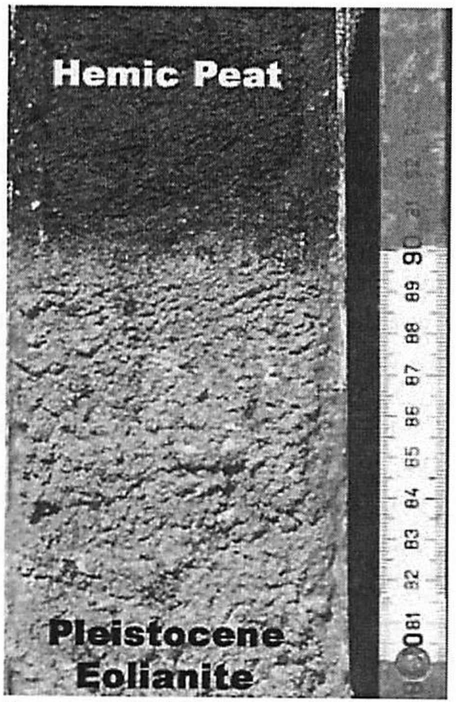

Figure 2. Core SP001 interval 78-100 cm from base of core illustrating Pleistocene eolianite bedrock overlain by hemic peat.

Hemic peat intervals are composed of tightly packed fibrous plant material which may be of terrestrial origin. This peat is characteristically black (5 YR 2/1 to 10 YR 2/1) in color. Some horizons include woody debris and rooting structures (Figures 2, 3), but no shell debris or carbonate sand fraction has been recovered from samples dissolved in 30% H_2O_2.

Intervals of sapric peat layers are more varied in their color and composition. Sapric peat intervals range from yellowish-brown (10 YR 5/4) to dark reddish brown (5 YR 3/2). They can be characterized as a more gelatinous or spongy accumulation, appearing to be composed of decayed aquatic plant and algal material, avian fecal matter (Severs et al., 2001), and gelified organics. Macroscopic detritus includes *Ruppia mearitima* seeds, dispersed shells of *Cyprideis tomentosa* and *Hydrobia bermudensis,* and interbeds of bioclastic accumulations of either *Cyprideis* or *Hydrobia* (Figure 4). The concentrated shell assemblages range between 1-5 cm in thickness, and are essentially sapric peat free, often only with angular mm-sized clasts of sapric peat found as intercalated matrix.

Several intervals are dominated by fine-to-medium grained carbonate sand in which both macroinvertebrate shells and sapric-peat angular clasts are encountered. This sand is yellow-brown (10 YR 5/4), consists of subangular to angular or well-rounded grains, and may be up to several centimeters in thickness. In general, the sand occurs at the base of fining-upward sequences where both organics and dispersed shells are encountered. Sand intervals have been found in the northern (SP007, SP008), central (SP005), and southern basins (SP004, SP0103, SP0104).

Basin Characteristics

Previous publications have divided Spittal pond into either two (Thomas and Wassmann, 1992) or three basins (Jenks, 1970) without regard to a bedrock profile. Using depth to bedrock, where bedrock was encountered in the bottom of ~60% of the cores, a rough basinal profile (Figure 5) indicates that the pond is composed of three small basins, herein termed the southern, central, and northern basins (Figure 1). These are separated by Pleistocene-eolianite highs that currently are submerged or have a limited areal exposure. Each of the three basins has its own unique sedimentological character.

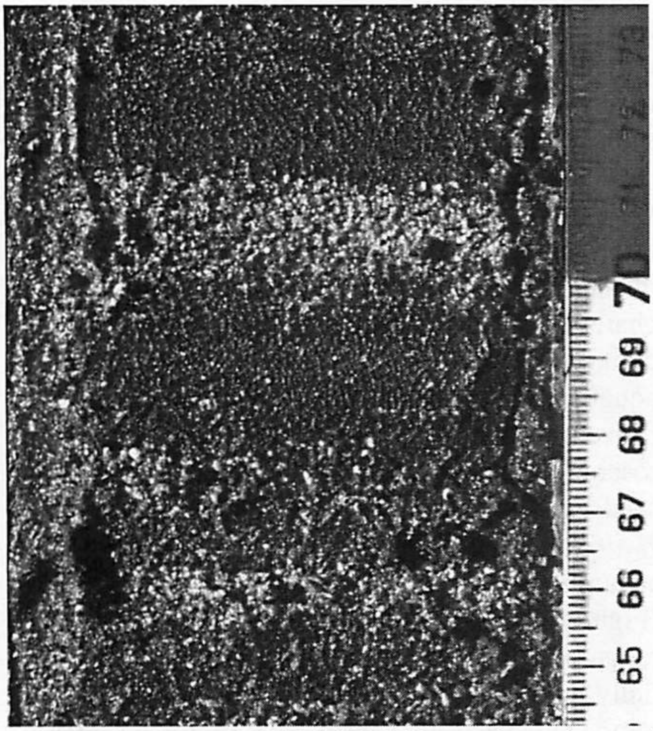

Figure 3. Core SP0104 75-100 cm from base of core illustrating rooted basal gray clay facies overlain by hemic peat.

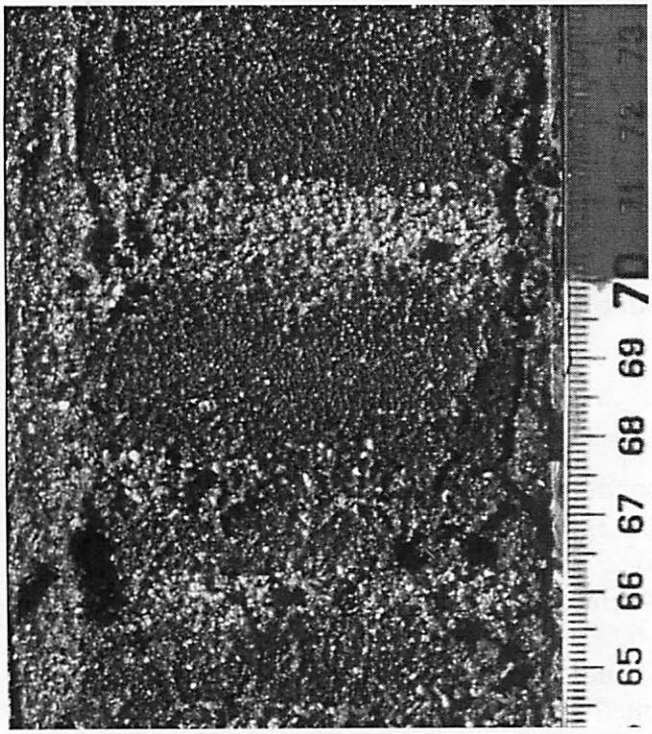

Figure 4. Core SP004 interval 162-175 cm from base of core illustrating concentrated shell beds of ostracods and gastropods overlain by sapric, gelatinous peat.

Southern basin

This depression is characterized by couplets of 50-to-100 cm intervals of hemic and sapric peat. Couplet number and thickness vary across this part of the pond, with a maximum of three cycles encountered in SP002 (Figure 5). The sapric peat intervals are characterized by episodic deposits of bioclasts described by Jenks (1970) as skeletal carbonate sand. These deposits range from 1-to-3 cm in thickness and appear to be monospecific in systematic composition. The transition from the southern basin to the northeast is through a section of narrows bounded by bedrock highs, where the depth to bedrock is approximately 1 m (Figure 1), and cores recovered from this area show a reduced number of peat cycles and a greater proportion of bioclastic sand. Intervals consisting of fine-to-medium subangular-to-angular sand have been found along the northwestern margin of the pond (SP0103, 0104).

Central basin

This area differs because there is no evidence for more than one cyclic peat couplet. The base of core SP005 also is unique because it consists of nearly 1.5m of clay (Figure 6) that can be subdivided into a basal red clay that is overlain by a gray clay. Both preserve dispersed organic matter, with woody rooting structures present in the upper gray clay (Figure 6). Hemic peat directly overlies these basal clays. Sapric peat with interbedded bioclastics, as found in other parts of the pond, makes up the remainder of the sediment core. A 50-cm thick interval of fining-upward yellow-brown sand occurs in the middle of the core, with dispersed gastropod shells and organics.

Northern basin

Like the central basin, this area is dominated by interbedded sapric peat and concentrated bioclastics. The basal sediments vary across the area, though, with either a thin (~ 50cm) gray clay (e.g., SP006;), or sapric peat with bioclasts directly above eolianite. In core SP007, the sapric peat/bioclastic interval is roughly 150 cm thick,

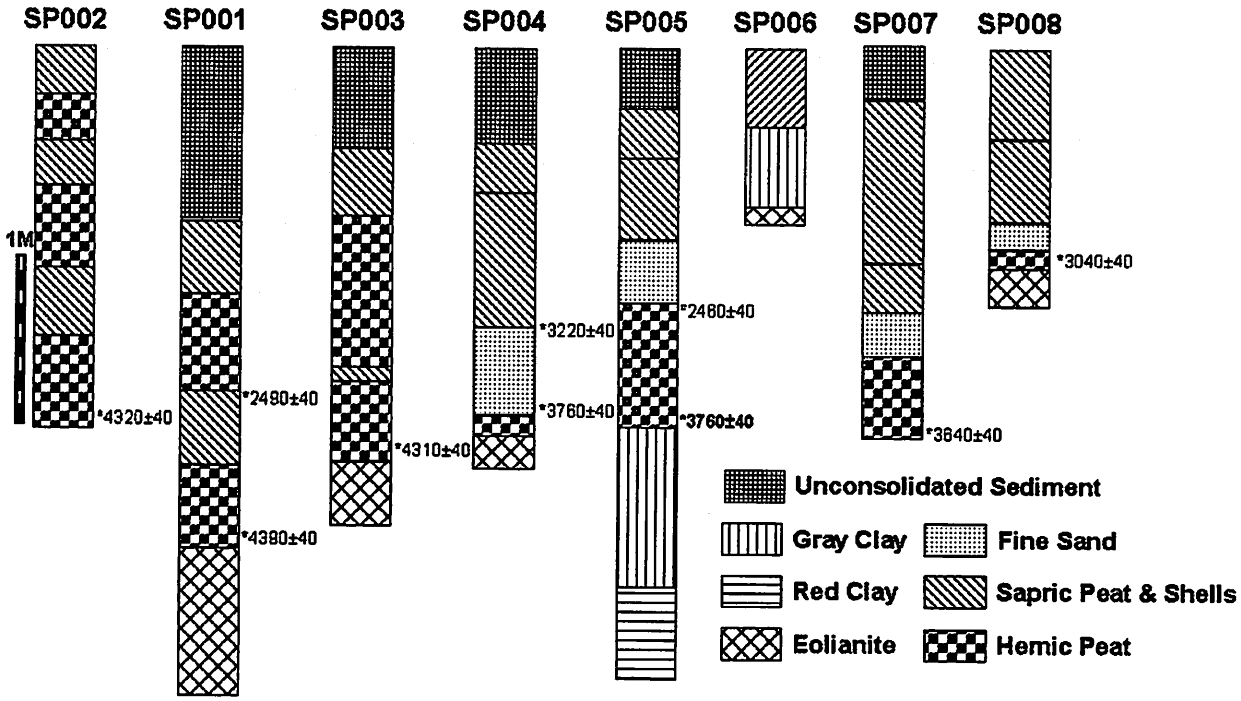

Figure 5. Vibracore transect across Spittal Pond depicting sediment facies distribution within cores and across the basin. Note that three different basins can be identified (southern, central, and northern) based on the depth to eolianite bedrock. AMS ^{14}C *dates for specified core samples are included. Scale in decimeters.*

while the basal hemic peat is only 55 cm thick. In core SP008, the hemic peat layer is only 20 cm thick, with the remainder of the core composed of the sapric peat/bioclastic sand layering (Figure 7). In addition, there are fining upward cycles that begin with fine to very fine sand (10 YR 5/4) that is overlain by dispersed organics and gastropod shells, overtopped by sapric peat with very fine sand and ostracods. At least 18 of these cycles have been identified in SP007.

^{14}C AMS Dates

AMS dating results of selected hemic peat samples are provided in Table 2 and graphically illustrated in Figure 5. The oldest basal date occurs in core SP001 (4,390 ± 40 yr BP) taken from the southern basin, while the youngest basal date occurs in core SP008 (3,040 ± 30 yr BP) taken from the northern basin. From these dates, it is possible to determine a general trend in the timing of organic matter beginning first within the southern basin, extending through the central and into the northern basins.

C/N Results

The C/N results for each facies indicate that the primary contributors to the hemic peat were vascular plants, the affinities of which are presently unknown (Table 3) and should be identified once palynological analyses are completed. C/N ratios obtained from the sapric peat indicate that it originated from a combination of vascular and algal material. Optical analyses are being conducted presently on this material to identify any resistant palynomorphs.

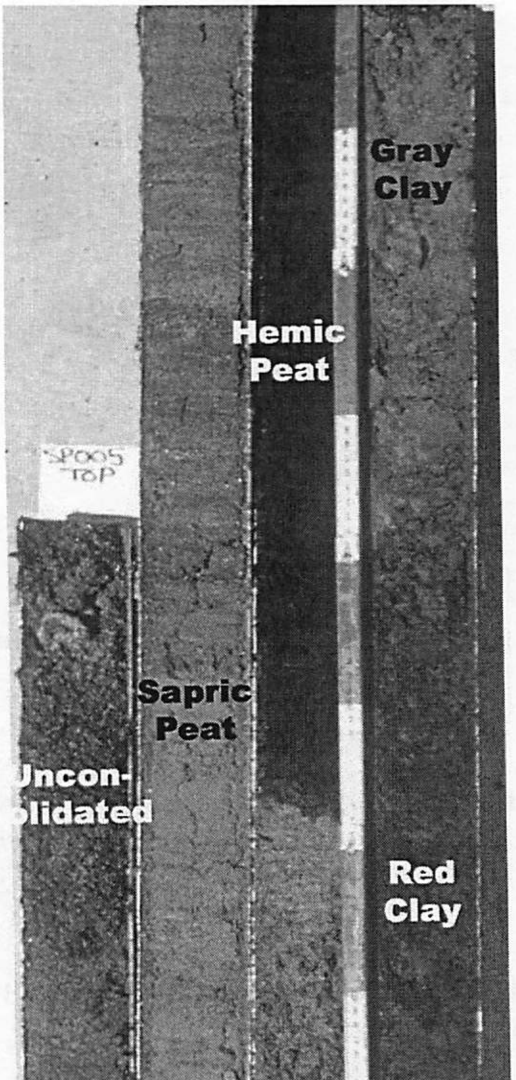

Figure 6. Vibracore SP005 from the central basin in which there are two basal clay layers (red clay 5-48 cm, gray clay 48-142 cm) overlain by hemic peat. See Figure 5 for details of vertical sediment-facies distribution. Scale in cm (dm also marked).

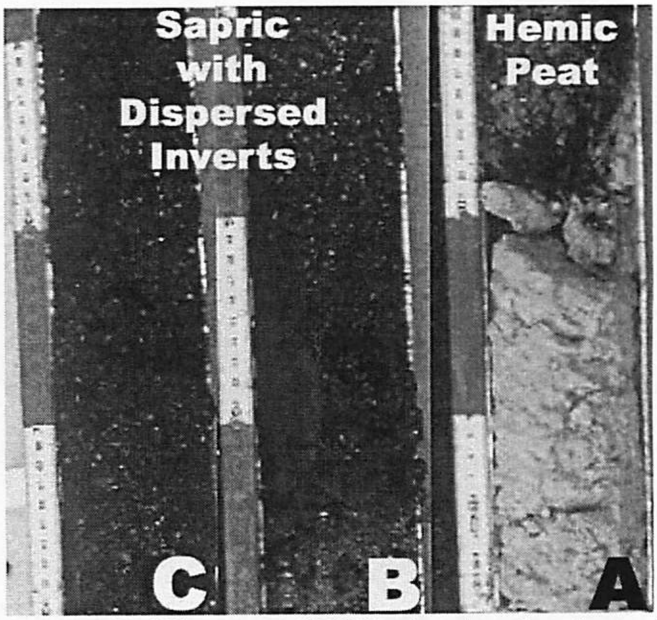

Figure 7. Vibracore SP008 showing hemic and sapric peat with dispersed shells overlying basal eolianite from the northern basin. (A) Basal 30 cm of core, (B) next 30-60 cm interval showing gradation between hemic and sapric facies, (C) next 60-90 cm of core showing that bedded gastropods and/or ostracod layers are absent. Compare with Figure 6. Scale in cm (dm also marked).

Sample Number	Facies	^{14}C date	δ^{13}C ‰
SP001:89	Hemic	4,390±40	-27.7
SP001:195	Hemic	2,490±40	-27.4
SP002:0	Hemic	4,320±40	-27.1
SP003:41	Hemic/Sapric	4,310±40	-28.5
SP004:43	Hemic	3,760±40	-27.9
SP004:90	Hemic	3,220±40	-26.8
SP005:142	Hemic	3,760±40	-29.2
SP005:198	Hemic	2,460±30	-26.3
SP007:0	Hemic	3,640±40	-28.3
SP008:20	Hemic	3,040±30	-27.9

Table 2. Samples analyzed by Geochron Laboratories, Cambridge, MA. Dates are in years Before Present (yr BP).

Facies (# Samples)	Minimum	Maximum	Average
Clay w/organics (8)	5.4	18.3	12.7
Fine Sand (4)	6.6	27.6	7.0
Hemic Peat (18)	12.8	36.0	20.4
Sapric Peat (19)	6.77	22.0	13.1

Table 3. Carbon:nitrogen ratios obtained for sediment facies analyzed using an Exeter 440 CHNO Analyzer.

DISCUSSION

Holocene Stratigraphy

No two Spittal Pond vibracores preserve the same stratigraphic sequence (Figure 5), although a generalized overall pattern can be discerned. Basal Pleistocene eolianite, assigned to the Belmont Formation (Vacher et al., 1995; Rowe, 1998), marks deposition during late isotope stage 7 (Hearty, 1991; Hearty et al., 1992), estimated to have accumulated ~200 Ka. Overlying this lithology are basal clays restricted to the central (red vermiculite-rich and gray kaolinite-rich) and northern (gray kaolinite-rich) basin, which are similar to those encountered in other Bermuda ponds (Rueger, 2002; Severs et al., 2001). Dating of a basal gray clay in Warwick Pond by ^{14}C AMS (Severs et al., 2001) results in an age of >9,000 yr BP; AMS dating of organics preserved within basal clays in Spittal Pond have not been obtained, but it is believed that at least the gray clay encountered in Spittal Pond is roughly the same age as that in Warwick Pond. In any case, there is a significant diastem between Pleistocene bedrock and the Holocene sequence.

Hemic peat accumulation was initiated at 4,390 ± 40 yr BP in the southern basin and progressively expanded northward through the central (3,760 ± 40) and northern (3,640 ± 40) basins over an interval of several hundred years. Initiation of peat is the result of the development of an impervious (clay-rich) interval, resulting in the stilting of the water table, amassment of biomass, and retention of degradation products in an organic-rich acid environment (Gastaldo and Staub, 1995). Under these conditions, sapric peat may accumulate initially (Staub and Esterle, 1994) due to high degradation rates, but the presence of a fibric hemic peat above the clay is more indicative of debris accumulating in an A-horizon of a water-logged aqueant soil (inceptisol) of low acidity.

The thick interval of hemic peat, in which vertical rooting structures are identified, can be traced across most of the recovered cores. Hence, this accumulation is more indicative of higher water tables, but not standing water as in the present pond. The change in organic-rich sediments, from hemic to sapric peat in which an ostracod and gastropod fauna is preserved, is indicative of deepening water and subsequent organic matter (OM) contribution from either the water column or the surrounding landscape. Again, the transition from the initial terrestrial peat to a limnic peat is time transgressive across the pond, with sapric OM beginning to accumulate near 3,220 ± 40 yr BP in the southern basin, and similar somewhat younger accumulations in the central (2,460 ± 40 yr BP) and northern (3,040 ± 40 yr BP) basins.

Previous interpretations of the pond's depositional history (Jenks, 1970; Lister, 1971) relied on the sea level curve published by Neumann (1971), which was based on ^{14}C ages from various sites within the archipelago (C. Neumann, 2002, pers. comm.). Jenks (1970) assigned a basal age of 3,800 yr BP to the pond sediments, assuming that the water level in the pond was contiguous with that of the groundwater lens developed on the island. It is known that the groundwater lens moves in response to sea level; hence, intuitively, the water level within the pond also should respond to changes in sea level (Jenks, 1970). The base of Jenks' (1970) core was 13 feet below present sea level; sea level had been estimated to have been 13 feet below its present level 3,800 yr BP (Neumann, 1969). The addition of ^{14}C dates in the present study provides higher chronostratigraphic resolution for basinal development, with results that differ slightly from Jenks' (1970) interpretations. The recognized transition from hemic to sapric peat marks a small, but dramatic change in base level that resulted in standing stagnant waters in which a brackish fauna was established. This change can be traced across the pond after approximately a millennium of hemic peat accumulation and associated ecosystem stability.

While the dating of peat in Spittal Pond may settle questions concerning the timing of sedimentation within the basin, it also raises questions concerning the timing of transitions from one site to another. There is an obvious discrepancy in the accumulation rates of peat when cores SP004 (southern basin) and SP005 (central basin) are compared. Here, basal hemic peat in each core is represented by a decompacted thickness of 65 cm. Both cores have identical basal hemic peat ages (3,760 ± 40 yr BP); however, the upper bounding ^{14}C dates differ by 760 years. The top of the hemic peat in SP004 (-1.94 m from the sediment/water interface) has an upper date of 3,220 ± 40 yr BP, whereas the same peat body in SP005 (-1.86 m depth) has an upper date of only 2,460 ± 40 yr BP. A similar condition is found in SP001 where the base of a peat at -2.56 m depth returned a radiocarbon age of 2,490 ± 40 yr BP which correlates well with a peat date from SP005 (-1.86 m depth). However, it does not correlate well with a 3,220 ± 40 yr BP date from SP004 (-2.59 m depth). Calculated accumulation rates in these cores differ by nearly two-fold within the same correlative facies, with extremes of 0.5 mm/yr (SP005) and 1.22 mm/yr (SP004). These differences may be due to vegetational contribution, water table fluctuations, accommodation space, or some combination of factors. Detailed peat analyses have not been conducted to determine microfacies changes during accumulation, which may reveal intervals that experienced higher rates of degradation or lower rates of accumulation within each sub-basin.

Carbon and nitrogen ratios have been used in Holocene studies to evaluate the proportion of terrestrial, aquatic, and algal components within organic rich sediments (Brown et al., 1998). In northern temperate lakes, Brown et al. (1998) have shown that C/N ratios ranging between 4 and 10 are indicative that algae are the primary contributors, whereas ratios >20 indicate that organic matter is derived from vascular plants. Ratios between 10 and 20 are indicative of a mixed contribution between algae and vascular plants.

Given the fact that there are cyclical intervals composed of hemic and sapric peat, it appears the pond has fluctuated between two distinct peat-accumulating environments. Hemic peat samples display either high (>20) or mixed (14-20) C/N ratios, with mixed signatures encountered near the center of the core transect. Sapric peat, on the other hand, possesses C/N ratios indicative of either algal (<10) or mixed origin, with values generally equal to or lower than the mixed signature hemic samples (Table 3). These data support the hypothesis that hemic peat accumulated in a predominantly fresh water environment, with samples more centrally located in the pond reflecting the initiation of standing deeper water in a topographically higher area. C/N ratios documented for sapric peat samples are more indicative of a brackish-to-saline environment (also reflected in the preserved macrofauna), with some contribution from terrestrial plants or *Ruppia* (Widgeon Grass), a member of the Zannichelliaceae, a family of aquatic angiosperms that are rhizomatous perennials (Radford et al., 1968) and thrives in brackish to high salinity waters. This is similar to what Hatcher et al. (1982) reported for peat recovered from Mangrove Lake, Bermuda. There, the basal peat, with a radiocarbon age of 9,000 yr BP, is composed of fern, palm, myrtle, and sawgrass (Hatcher et al., 1982). At approximately 4,000 yr BP, there is a transition from this hemic peat to a mangrove peat, suggestive of a brackish or saline environment (Hatcher et al., 1982).

Comparison with other Bermuda Ponds

Both Spittal Pond and Mangrove Lake record a transition from hemic peat to sapric peat accumulation in the basal part of the section, but only one such transition is recorded in the cores recovered from Mangrove Lake. Sediments from the southern basin in Spittal Pond record three such fluctuations from hemic-to-sapric peat, although all of these are not reflected across the entire basin. C/N ratios obtained from Spittal Pond sapric peat indicate that it is a mixture of both vascular plant and algal material, which may be explained by the presence of phytoplankton and *Ruppia* in the water column, as well as contribution from standing vegetation surrounding the pond in addition to avian fecal matter (Severs et al., 2001). Hatcher et al. (1982) reported the Mangrove Lake "gelatinous ooze," which they lumped within the sapric material, had three distinct biological sources based on geochemical analyses: an algal source, a higher plant source (mangrove, fern, etc.), and a microbial source, although later analyses have ascribed the organic matter to primarily to phytoplankton (Hatcher et al., 1983; Orem et al., 1986). Additionally, they observed a stratigraphic change in macrofauna with respect to two ostracod genera: *Potamocypris* (limited exclusively to freshwater) and *Cyprideis* (tolerant of both fresh and brackish water; Hatcher et al., 1982). They interpreted an environmental transition within the lake from a mixed population of the two ostracods low in the section to a population exclusively composed of *Cyprideis* higher in the core, reflecting a change in water chemistry from freshwater to brackish water. Hatcher et al. (1982) place a date of 4,000 yr BP for the initiation of freshwater sapropel based on Neumann (1969), although no ^{14}C dates have been published for this material.

Only one species of ostracod – *Cyprideis tomentosa* – has been recovered from Spittal Pond and is restricted to the sapric peat facies either within concentrated beds or dispersed within the matrix; it is absent from the hemic peat (Lister, 1971). Hence, the taxon reflects fresh-to-brackish conditions within the pond, but the exclusively freshwater system was not limnic, but more of a mire, probably similar to peat found in Devonshire Marsh elsewhere on the island (Rueger, 2002). Currently, palynological analyses are being conducted, the data from which will help to clarify the plant source(s) for both peat facies.

The Record of Bioclastic Sand

Superimposed on the accumulation of the intervals of sapric peat is a cyclicity of concentrated beds of bioclastics, referred to by Jenks (1970) as "ostracod sand" or "gastropod sand." Bioclasts also are found dispersed within the sapric peat matrix but are most conspicuous in these beds, similar to what has been documented in other Bermuda ponds (Severs et al., 2001). Currently, there is no direct evidence that would indicate which process or processes are responsible for concentrating these shells, but three hypotheses to account for their origin are (1) washover events from Atlantic hurricanes causing salinity spikes in the pond, (2) vegetational takeover of the pond by the aquatic angiosperm – *Ruppia* – resulting in anoxia and decimation of the biological populations, and (3) selective settling of the shells associated with storm-induced erosion and resuspension of peat.

Spittal Pond is located between 50 and 100 m from the Atlantic Ocean with low topographies at both the northern and southern ends of the interdune depression (Figure 1). Proximity to the ocean and presence of two low-lying conduits results in periodic washover into the pond during highly turbulent storm events (R. Hollis, 2000, pers. comm.). The incursion of fully marine waters would raise the salinity levels in the pond, which could exceed the tolerance of the gastropods and ostracods, resulting in a mass die-off and a shell concentration at the sediment-water interface. Thomas and Logan (1992) offered a similar explanation, suggesting storms or very high tides as the mechanism responsible for observed extreme salinity ranges in Spittal Pond (6.5 to 42.5‰). Although there is little published ecological data on *Cyperideis,* the genus is believed to be restricted to brackish and fresh water conditions (Sanger and Teeter, 1982) and able to tolerate hypoxia and increased sulfide concentrations (Gamenick et al., 1996). *Hydrobia*, on the other hand, is acknowledged to be able to tolerate wide fluctuations in salinity, although this taxon is subject to mass mortalities when there is an extreme change in temperature (Jensen and Mouritsen, 1992).

Although video has been taken recently of washover events in Spittal Pond (e.g., during Hurricane Fabian), evidence for these events consists of intervals of fine-to-medium sand and erosional contacts within the vibracores. Bioclastic sand encountered in the northern, central, and western part of the southern basin consists of subangular to angular shell fragments, similar to sand found along the margin of the island. Fining upwards sequences, as found in SP007 in which fine-grained sand is overlain by a mixture of whole shells and peat, records the presence of turbulence in the basin and the introduction of extrabasinal sediment. Episodes of high energy and erosion are especially characteristic of core SP0105 (Figure

8) where angular erosional surfaces within the sapric peat interval are overlain by concentrated assemblages of either *Cyperideis* or *Hydrobia*, or both taxa. Hence, although it is probable that washover events are the cause of some concentrated bioclastic beds, this process, alone, cannot explain the assemblages. Turbulence generated during a washover event would resuspend the degraded organic matter and dispersed shell material at and below the sediment-water interface, concentrating the shells from suspension load above the ero sional contact. This would differ from a single event responsible for the death of the macrofauna, which would then have to settle to the sediment-water interface followed by the rain of degraded organic matter, resulting in only mixed beds of ostracods and gastropods.

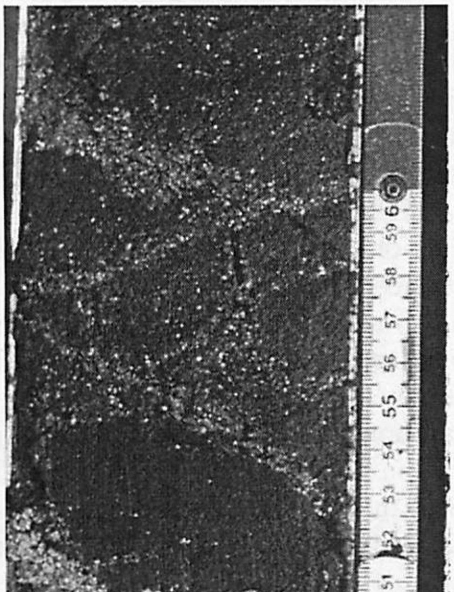

Figure 8. Vibracore SP0105 in which erosional contacts can be seen overlain by concentrated beds of macro-invertebrates. Scale in cm.

An alternative explanation is the development of anoxic conditions during periods of little to no meteoric recharge that result in mass die off, coupled with increased water temperature. During both field seasons, a mat of *Ruppia* up to 5 cm thick covered the surface of the pond. This angiosperm supports colonies of both *Hydrobia* and *Cyprideis* in oxygenated waters (8.8 ppm, 10 June 00); only a few cm beneath the air-water interface, the pond waters were anoxic (0.0 ppm, 10 June 00; Shosa et al., 2004). Hence, it is probable that as *Ruppia* overtakes the pond, increasing biomass production and organic detritus contribution to the water column, the oxygen levels within the pond drop in response to the decay processes. As anoxia spreads to the surface waters when rainfall is low during the summer months, the drop in oxygen levels would affect large numbers of gastropods and ostracods at and just below the water's surface. Anoxia coupled with increased water temperatures (reported to be as high as 37.5° C; Thomas and Wassmann, 1992) would add significant additional stress to these populations, that would result in increased individual deaths. Following such a mass die off, the shell material would settle to the bottom of the pond following decay of soft body tissues and, subsequently, be covered by decayed material originating from both the aquatic mat and water column. Kantrud (1991) notes that decay of *Ruppia* can coincide with an increase in sulfur-reducing bacteria both on the submerged parts of the plants and in the substrate; Thomas and Wassmann (1992) characterize Spittal Pond as a "polluted" water body mainly due to its odor.

A third possibility has been proposed by Severs et al. (2001) for similar assemblages in Warwick Pond, Bermuda. In this interior pond, a basal hemic peat is overlain by several intervals of banded peat that are characterized by well preserved sedimentary cycles. Each cycle consists of a basal, ostracod sand overlain by dark sapric peat. A sharp upper contact exists between this sediment and the overlying cycle, which begins with the next ostracod sand. Severs et al. (2001) proposed that such cycles are the result of a physical process, such as major storm-generated mixing within the pond, resulting in sediment resuspension and concentration of the sand, followed by background suspension-load deposition of the sapric organics. A similar mechanism probably is responsible for some of the same type of cycles found in Spittal Pond. Storms of hurricane intensity have been relatively infrequent across Bermuda during historical time, with storm frequency ranging from 0 to 6 hurricanes per decade since colonization in 1609, with an average of approximately 1 to 3 per decade (Tucker, 1995). Such storms generate waves across the surface of the pond and lower wave base to the sediment-water interface. A lowered wave base would disturb pond sediments, providing a mechanism to account for the graded bedding. Evidence exists for erosional contacts in several cores, but this third mechanism does not require coincident washover from the Atlantic and development of high salinities. Higher salinities may develop as the result of high evaporation rates.

Implications for Sea Level Rise

Neumann's (1971) sea level curve for Bermuda projected that sea level was 7 m lower than present approximately 5,000 yr BP. The curve implies that sea level rose gradually since then to its present position. Recently, evidence has been presented indicating that Holocene sea level has risen in punctuated events (e.g., Clark et al., 2002; Blanchon et al., 2002). For example, the global meltwater pulse IA (MWP-IA) at about 14,000 yr BP is recorded in Barbados corals (Bard et al., 1990) and elsewhere, indicating an average 20-m rise in less than 1,000 years (Clark et al., 2002). This was followed by sea-level stability that lasted several millennia wherein coral reefs flourished. Blanchon et al. (2002) interpreted younger relic reefs on Grand Cayman, Barbados, St. Croix, St. Thomas, and northern Florida to have stopped accreting within 160 years of each other, while modern reefs re-established at depths 4-9 m higher upslope within 100 years of the former's demise (if the older radiocarbon dates, uncorrected for metabolic fractionation, are accurate). This change in elevation is explained by a rapid sea-level rise of at least 6 m approximately 7,500 PB. Hence, evidence exists for a circum-Caribbean back-stepping response on a century-scale. A similar scenario, although on a smaller scale, can be envisioned for Bermuda.

Recognition that there is cyclicity in accumulation of hemic and sapric peat in the southern basin of Spittal Pond would imply long-term (millennial-scale) stability of two different peat-accumulating systems. Hemic peat accumulates within basins where there is considerable terrestrial plant input and, most often, is associated with mire development. Although the water table in mires is high, it rarely covers the histosol, allowing for development of the ecosystem and the geopedal penetration of rooting structures. On the other hand, sapric peat represents accumulation of highly degraded organic matter which may be a function of climate depending upon the mire type (Moore, 1987, 1995). In the case of Spittal Pond, the sapric intervals represent accumulation of organic matter that originated in a standing body of water, and represents settling from the water column to the sediment-water interface. This is evidenced both by the C:N ratio of the organic matter as well as the preserved fauna and flora.

Hemic peat began to accumulate between 4,390 ± 40 and 4,310 ± 40 yr BP in the southern basin, and these dates mark the hemic peat/bedrock interface (SP001, SP002, and SP003). Fibrous debris probably accumulated under peatland conditions until ~3,760 ± 40 yr BP (SP004) until the water level was raised in the basin, and the depression was altered to a lake setting. Standing water was maintained until at least 2,490 ± 40 yr BP when sapric peat accumulation ceased (SP001) and hemic peat accumulation was reinitiated. The absence of additional ^{14}C dates from the cores precludes documentation of the more recent timing of hemic-sapric peat transitions. But, the re-initiation of hemic peat accumulation signals another change in water level, with the development of another peatland.

Changes in water level and quality in-and-around Spittal Pond are controlled by both the position of the freshwater lens within the island and the position of the ocean adjacent to the shoreline. Intervals of hemic peat generally are indicative of accumulation under freshwater conditions (Devonshire Marsh – Rueger, 2002), and ground-water lenses are controlled by the lateral variation in conductivity in the saturated zone (Vacher, 1978). The bases of these lenses mark the elevational position of the freshwater table at any point in time; the presence of hemic peat, therefore, would be a proxy for these geochemical conditions in the pond. Conversely, sapric peat in Bermuda accumulates in brackish to saline ponds (e.g., Mangrove Lake – Hatcher et al., 1982; Warwick Pond

– Severs et al., 2001), with salinity controlled by either proximity of base level to the ocean (e.g., Mangrove Lake) or evapo-transpiration rates (Warwick Pond). Hence, the presence of sapric peat within the Spittal Pond cores can be used as a proxy for the position of sea level adjacent to the pond, resulting in standing brackish water conditions. Using these relationships, then, it is possible to hypothesize that three cycles of freshwater-to-brackish water conditions, mediated by changes in the groundwater lens and the relative position of sea level, are recorded in Spittal Pond. As such, these cycles can be interpreted to represent three short-term jumps in sea level, all occurring over the past 4,400 years. ^{14}C AMS dates from below and above the contacts of each cycle could provide for a well-constrained timing of each pulse. To date, though, such data are not available.

CONCLUSIONS

Spittal Pond preserves an unique sedimentological record on Bermuda, encompassing the past 4,500 years. Two types of sedimentary cycles have been identified above either basal Pleistocene eolianite attributed to late isotope stage 7 (Hearty, 1991; Hearty et al., 1992), estimated to have accumulated ~200 Ka, or vermiculite- and kaolinite-rich clay of an undetermined age. Millennial-scale cycles of hemic and sapric peat have accumulated across the basin, with the most complete record encountered in the southern basin. Hemic peat intervals mark times when freshwater prevailed within the pond, allowing for peatland/mire development, whereas intervals of sapric peat mark times when standing brackish water conditions predominated. The timing of changes in peat-type accumulation allows for the development of a hypothesis that there were at least three short-term, meter-scale jumps in sea level beginning some 4,500 yr BP. These are not recorded in the marine record.

In addition, shorter-term cycles (decade to century) are recorded within the sapric peat record. These cycles consist of a basal bed of concentrated ostracod and/or gastropod shells directly overlain by gelatinous and/or sapric peat; this sediment type grades upwards into a sapric peat in which dispersed shell material is preserved. One or a combination of processes may be responsible for this record including (1) changes in pond salinity, in response to washover events or evaporation, that exceeded the tolerance of the invertebrates, causing mass mortality and settling to the bottom of the pond; (2) anoxia of the entire water column in response to aquatic plant takeover by *Ruppia*, wherein the biological populations were decimated, with shells concentrating at the sediment-water interface; and/or (3) selective settling of the shells associated with storm-induced erosion and resuspension of bottom sediments. Evidence exists in cores to support this last process as having affected Spittal Pond, but the other two mechanisms can not be ruled out as the cause of other graded intervals.

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