Marine saline ponds as sedimentary archives of late Holocene climate and sea-level variation along a carbonate platform margin: Lee Stocking Island, Bahamas

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Abstract

A 1500-year, late Holocene history of coastal and lacustrine carbonate sedimentation is preserved in shallow ponds on Lee Stocking Island, Exuma Cays, Bahamas. Details of environmental change have been extracted by integrating lithostratigraphy, biostratigraphy (macrobiota, foraminifers, ostracodes), and chemical stratigraphy (C, O isotopes of foraminiferal and molluscan skeletal carbonate; MgO wt% of ostracode calcite) with a well defined 14 C AMS radiocarbon chronology. Carbonate deposition began within physically restricted, euryhaline coastal embayments, with several pronounced changes in salinity defined by biotic and calculated salinity variation (from MgO wt% in shells of Cyprideis americana). By about 700–740 yr B.P., embayment closure occurred possibly related to changed longshore deposition associated with sea level rise and/or regional change in climate (previously documented). With closure, the initial euryhaline foraminifer assemblage was replaced by a predominant hypersaline biofacies (e.g., Triloculina sp.); with progressive basin fill, ostracode assemblages, calculated salinities, and variation in abundance of the gastropod Cerithidea sp. may resolve higher-order (and some extreme) salinity fluctuations throughout the remaining history of saline pond development. Foraminiferal isotope stratigraphy is compatible with that expected for hydrologically closed lake basins. Carbonate accumulation was effectively shut-down <200 years ago, replaced by stromatolitic growth. Present-day salinities vary according to water balance governed by rainfall and evaporation. A centuries-scale (300–400 year) flux of abraded (reworked), marine-derived bioclasts, admixed with skeletal remains of indigenous biota, is also preserved in these ponds. Allochthonous sediment was transported by hurricane storm surges or related to abrupt transgressive events superimposed on an overall gradual rise in global sea level. We discuss evidence for both as controls on sedimentation. Our study illustrates that saline ponds on Bahamian islands are excellent sedimentary archives of local, regional, and possibly global paleoclimatic events of late Holocene age. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Bahamas; Holocene; lacustrine sedimentation; stratigraphy; changes of level
1. Introduction

Little is known about sedimentary dynamics of marine saline lakes and ponds (Mackenzie et al., 1995) when compared to continental saline lakes (e.g., Renaut and Last, 1994). Yet, marine-lake basins are likely excellent sedimentary archives of high-frequency patterns of Holocene paleoclimate (Burnett et al., 1989, p. 778; Teeter and Quick, 1990). Located at or very near sea level, their water balance and chemistry often responds quickly to even subtle changes in sea level or local climate (Burnett et al., 1989; Mackenzie et al., 1995). These lakes also form relatively protected sites of deposition juxtaposed to often more energetic, open-marine settings. Thus, evidence of elevated sea level related to storm surges (e.g., Liu and Fearn, 1993) or other regional to global controls (Revelle, 1990) may be preserved.

In the Bahamas, shallow lakes and ponds occur on many low-lying islands, with water often “choked with an odorous red mud” (Craton and Saunders, 1992, p. 6). The proximity of many of these islands to deep-water seaways (Fig. 1) increases the potential that marine-lake stratigraphies might preserve a high-resolution record of changes in late Holocene climate, sea level, and oceanography not recognized or preserved in adjacent shallow-water or island geological records. Our paper documents a ~1500-year record of late Holocene sedimentation from two ponds on Lee Stocking Island (LSI), Exuma Sound, Bahamas (Figs. 1 and 2). Patterns of environmental change are defined by integrating lithostratigraphy, biostratigraphy, and chemostratigraphy with $^{14}$C AMS radiocarbon chronology. Ponds formed by closure of euryhaline embayments. A centuries-scale change in sea level related to either storm surge or eustatic variation is superimposed on this history; we discuss evidence for both. Bahamian lakes offer an improved resolution of paleoclimatic variation, one that complements existing island and marine shelf geology (Carew and Mylroie, 1995; Kindler, 1995).

2. Geologic setting: Lee Stocking Island

Lee Stocking Island (LSI) is underlain by Quaternary carbonate rock units (Fig. 3; Kindler, 1995). The island forms a windward, bank-margin barrier that separates a narrow, high-energy, shallow shelf from a relatively protected, shallow bank-interior (Dill et al., 1986). As such, the eastern side of the island has sustained substantial erosion, with sedimentation restricted to pocket embayments (Fig. 2; Kindler and Hearty, 1996). High-energy subtidal facies (ooid shoals, stromatolite mounds; Dill et al., 1986) extend into the platform interior only from inter-island, bank-margin channels (Fig. 2).

Two natural ponds occur on LSI. Beach Cottage Pond (BCP) occupies a very small, rounded basin within a low-relief, vegetated landscape (Fig. 4A). Pond sediment onlaps a paleokarst developed on Pleistocene bedrock, and overlies part of the Holocene (~0.45–3.8 kyr B.P.) Perry Peak limestone (Kindler, 1995). We estimate the pond’s surface to be <1 m above mean sea level; a breach (entrance) through the basin rim is partially barred by a vegetated (mangrove) sand ridge, and opens above the present beach storm terrace. Dune Pass Bay Pond (DPBP) is an elongate pond between two vegetated ridges (Fig. 2). The windward (eastern) ridge is underlain by the Holocene (ca. 5.2 kyr B.P.) Dune Pass Bay limestone (Fig. 3; Kindler, 1995). A lower (~4 m) leeward ridge (Fig. 4B) is underlain at least in part by Pleistocene rocks (Fig. 2; P. Kindler, written commun., 1998). It remains unclear if the narrowed southern part of the valley (Fig. 2) was once connected to the windward coastline. The basin appears to broaden toward the island’s leeward margin (Fig. 2). Elevation of the DPBP surface is ~1+ m above mean sea level.
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Fig. 2. On the left, an oblique airphotograph (courtesy of the Caribbean Marine Research Centre) showing Lee Stocking Island (foreground), Dune Pass Bay Pond (lower large arrow) and Beach Cottage Pond (upper large arrow). White areas are sand shoals and beaches, and the black arrow (top) indicates a prominent ooid shoal complex associated with the interior extension of an inter-island tidal channel. Scale bar is 2 km for the lower part of the photograph. On the right, topography (in feet) in the vicinity of Dune Pass Bay Pond based on Lands and Surveys Department (1968). Areas A and B define Pleistocene bedrock leeward of the pond basin.

Fig. 3. Local and regional Quaternary stratigraphy of Bahamian islands; from Kindler (1992, 1995) and Carew and Mylroie (1995).

3. Methodology

A core from each pond was obtained by vibrating PVC pipe using compressed (SCUBA) air (Fig. 4A). Samples represent 2- to 3-cm-thick sedimentary intervals taken at irregular intervals accommodating downcore changes in lithology. One gram of bulk sediment was used for carbonate content analysis using a carbonate bomb (Müller and Gastner, 1971) whereas remaining sediment was wet sieved to separate gravel, sand and mud fractions (σ = 5%). Composition of size fractions was based on binocular, petrographic, and scanning electron microscopy (SEM). Macroskeletal carbonate was identified to genus level where possible. Carbonate mineralogy and mineral weight percentages were estimated by
X-ray diffractometry (Milliman, 1974). Additional qualitative assessment of chemical composition of mud-size sediment used energy dispersive spectrometry (EDS) associated with SEM.

The DPBP core, with its longer stratigraphic record (Figs. 5 and 6), was used to define foraminifer and ostracode distributions using 2- to 3-cm sampling intervals. Counts of foraminifer tests per sam-
4. LSI Pond stratigraphy

4.1. Lithostratigraphy and sediment composition

The BCP and DPBP cores each contain the entire sediment cover to bedrock in each pond. Cur- sory sediment probing revealed no other sites with greater thickness. Each core contains a thin laminar stromatolite (Unit 1; Fig. 7A) that caps carbonate-rich (>97% by weight) sediment. The stromatolite at DPBP is relatively compacted, with local enterolithic folding, and contains coccolith and large filamentous cyanobacteria (J. Thompson, oral commun., 1996). The change from carbonate to organic deposition may have been grossly gradational, as represented by interbeds of these lithologies (Fig. 7A). Rhythmic variation in thickness of organic lamination characterizes stromatolitic stratification (Fig. 7B). Laminae to lenses of inorganic detritus are locally distributed toward the upper and lower margins of thicker organic laminae (Fig. 7B). Non-organic detritus consists of lithoclasts of surrounding bedrock (micritized to prist- tine ooids, skeletal grains, and ooid and skeletal grain-
stone), in situ to fragmented foraminifer tests as well as ostracode and gastropod (*Cerithidea* sp.) shells, and detrital as well as in situ corroded crystals of gypsum. At BCP, a compact stromatolite is only 2 cm thick, yet overlies about 7 cm of purplish-brown, soupy, organic-rich (30–40%) carbonate mud. This latter material may be an equivalent facies to the stromatolite at DPBP. At the time of our field work, the DPBP basin contained about 15 cm of brackish water. The partially submerged stromatolite was polygo-

nally cracked with crusts of corroded microcrystalline gypsum (Fig. 7C). The DPBP basin had been dry a few days earlier (P. Copper, oral commun., 1995), prior to a heavy rainfall. The same amount of water occupied the BCP basin but desiccation features and surficial gypsum were absent.

Units 1 through 5 are common to each core (Figs. 5 and 6). The basal sand at BCP is lithologically and chronologically equivalent with Unit 7c at DPBP (see below). Units 9 through 6, excluding Unit 7, are re-
Fig. 7. Laminar stromatolite, Dune Pass Bay Pond. (A) Stromatolite (dark) overlies carbonate-rich sediment (light) with alternating bedding (arrow) that defines the base of Unit 1; scale bar = 2 cm. (B) Rhythmic variation of thin and thick (arrow) stromatolitic laminae. White objects are carbonate sediment and gypsum crystals. Scale bar = 0.5 cm. (C) Partially submerged stromatolitic mat showing polygonal desiccation cracks, crusts of microcrystalline gypsum (white), and leaves. The mat in the upper right of the photograph is under water. Rectangular scale (bottom) is 15 cm in length.
stricted to the DPBP basin. Abraded, marine-derived sediments (M1 to M4; Fig. 6) occur in the DPBP core, and likely comprise part of the basal sand in the BCP core (Fig. 5; see below). None of the clasts contain attached, remnant marine or meteoric carbonate cements, and are similar in texture as loose sediment found in present-day shallow marine and beach environments on LSI. Disconformities occur in each core (Figs. 5 and 6), and are defined by erosion of sedimentary structures along planar or inclined surfaces, as well as by burrows that extend beneath horizontal surfaces and are filled by overlying sediment. M1, M2 and M4 in the DPBP core (Fig. 6), and the marine-derived sediment at BCP (Fig. 5), overlie disconformities. Whereas M4 sits with apparent conformity on Unit 5 in the DPBP core (Fig. 6), it is disconformable with respect to Unit 5 in the BCP core (Fig. 5). The base and top contacts of sediment containing M3 are not obviously abrupt, nor erosive.

Overall, downcore lithologic changes are subtle variations among carbonate lithologies of muddy sand, sandy mud, and gravel-bearing muddy sand (Figs. 5 and 6). This is partly due to local variation in intensity of biomottled fabric related to infaunal bivalves (tellinids), with a few prominent intervals of biomixing (Figs. 5 and 6). Discrete burrows of unknown affinity occur in Unit 5 in the DPBP core (Fig. 6), it is disconformable with respect to Unit 5 in the BCP core (Fig. 5). The base and top contacts of sediment containing M3 are not obviously abrupt, nor erosive.

4.2. Biological remains and biostratigraphy

Of the many macrobiota represented in each core (Table 1), in situ accumulations of the gastropod Cerithidea costata, tellinid bivalves, and oogonia of macrophytic algae are prominent. (The term in situ is used here to define accumulation with little or no transport.) Increased abundance of Cerithiidae sp., beginning by Unit 7a, displays a peak in Unit 3 (Fig. 9). There is no obvious distinction in stratigraphy of whole versus disarticulated tellinid shells, although both are very much reduced in abundance in Unit 1. Tellinid species remain unidentified; they possess a significantly reduced pallial sinus when compared to examples documented by Abbott (1974) that may represent local environmental factors. Oogonia occur in relative abundance only in Unit 9 (Fig. 9). Specimens are Chara fibrosa and possibly Nitella flexella (L.) Agardh (P. Hamilton, Canadian Museum of Nature, written commun., 1995).

Abraded, and less common pristine, marine-derived sediment (M1 to M4) is generally coarser grained (Fig. 8C), less muddy, and often more aragonitic than the other sediment in the cores. According to Abbott (1974), Milliman (1974), Rose and Lidz (1977), Wray (1977), and Taylor (1978), these skeletal fragments identify a relatively normal marine assemblage that includes (Table 1): calcareous algae (Halimeda sp., indeterminate calcareous red algae); gastropods (Caecum sp., Margarites sp., tiny olives, Epitonium sp., Odostomia sp.); indeterminate stick-like corals; a strongly plicated bivalve (possibly Americardia sp.); and foraminifers (Peneroplis sp., Homotrema rubra, and Archais sp.).

SEM illustrates that spherical and ovoid carbonate bodies, <100 nm in diameter (Fig. 8D), make up to 50% of the mud fraction in many samples, and are similar to some bacterially induced precipitates (e.g., Folk, 1993; Buczynski and Chafetz, 1993). Otherwise, the mud fraction in both cores consists of angular to rounded, detrital calcite and aragonite crystals admixed with euhedral to broken elongate crystals of aragonite.

We have concentrated on the DPBP core to define assemblages and distribution of foraminifers and ostracodes. An in situ foraminiferal assemblage is well developed in both cores. There is low diversity but considerable stratigraphic variation in abundance (Plate I, Fig. 10; see Appendix A). With exception of the uppermost 2 cm, the two dominant species, Ammonia beccarii and Triloculina oblonga, display
Fig. 8. Sediment; Dune Pass Bay Pond. (A) Detrital gypsum; thin section, plane light; scale bar = 150 μm. (B) Angular lithoclast of ooid grainstone with arrow pointing to edge of an ooid surrounded by calcite spar; thin section, plane light; scale bar = 1 mm. (C) Sand- and gravel-size fraction of Unit 7c showing well rounded, abraded marine-derived particles; reflected light, scale bar = 2 mm. (D) SEM photomicrograph of spherical bodies that are probably calcitized nannobacteria (overview, left; scale bar = 1 μm; close-up image, right; scale bar = 200 nm).

an antithetic stratigraphic variation in relative abundance (Fig. 10). Q-mode cluster analysis (Fig. 11; Fishbein and Patterson, 1993) resolves three groupings interpreted to reflect gross biofacies (Figs. 10 and 11). Each is described below.

*Ammonia beccarii* dominates the assemblage below 1010 mm. This is a species common throughout the Caribbean region in shallow embayments of restricted circulation and along shore regions where the seasonal influx of freshwater results in highly variable salinities (Bandy, 1964; Rose and Lidz, 1977; Poag, 1978, 1981; Sen Gupta and Schafer, 1973). The presence of this species identifies a stressed eco-tone environment. Our assemblage is overwhelmingly dominated (95.3–100%) by the euryhaline strain *parkinsoniana* (Schnitker, 1974), which Poag (1978) identified as characterizing lower salinity regimes in San Antonio Bay, Texas. From 960 to 680 mm, the Mixed Species Biofacies (Fig. 11) records a stratigraphic ‘cross-over’ in abundance of
### Table 1
Abundance and type of biota recovered from sediment samples in cores from Dune Pass Bay Pond and Beach Cottage Pond, Lee Stocking Island

<table>
<thead>
<tr>
<th>Fauna</th>
<th>Biota abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dune Pass Bay Pond core (depth, mm)</td>
</tr>
<tr>
<td><strong>Preservation</strong> a</td>
<td>Biota abundance b</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------</td>
</tr>
<tr>
<td><strong>Fauna</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Gastropods</strong></td>
<td></td>
</tr>
<tr>
<td>Cerithidea sp.</td>
<td>E, F</td>
</tr>
<tr>
<td>Odostoma sp.</td>
<td>E</td>
</tr>
<tr>
<td>Margarites sp.</td>
<td>E</td>
</tr>
<tr>
<td>Batallaria sp.</td>
<td>E</td>
</tr>
<tr>
<td>Truncateellidae bahamensis</td>
<td>E, Ab</td>
</tr>
<tr>
<td>Acteocina sp.</td>
<td>Ab</td>
</tr>
<tr>
<td>Coecum pulchellum</td>
<td>E, F</td>
</tr>
<tr>
<td>Coecum imbricatum</td>
<td>E</td>
</tr>
<tr>
<td>Caecum sp.</td>
<td>Ab</td>
</tr>
<tr>
<td>Epitonium sp.</td>
<td>Ab</td>
</tr>
<tr>
<td>Pyramidella crenulata</td>
<td>Ab</td>
</tr>
<tr>
<td><strong>Indeterminate abraded genera:</strong></td>
<td></td>
</tr>
<tr>
<td>periwinkle shell</td>
<td>Ab</td>
</tr>
<tr>
<td>olive shell</td>
<td>Ab</td>
</tr>
<tr>
<td>heavily abraded welk</td>
<td>Ab</td>
</tr>
<tr>
<td>high-spired turreted</td>
<td>Ab</td>
</tr>
<tr>
<td>top shell</td>
<td>Ab</td>
</tr>
<tr>
<td><strong>Bivalves (mostly tellinids)</strong></td>
<td></td>
</tr>
<tr>
<td>shell halves</td>
<td>E</td>
</tr>
<tr>
<td>shell fragments</td>
<td>E</td>
</tr>
<tr>
<td>Americardia sp. (?)</td>
<td>Ab</td>
</tr>
<tr>
<td><strong>Coral</strong></td>
<td></td>
</tr>
<tr>
<td>stick-like fragments with small coxalae</td>
<td>Ab, F</td>
</tr>
<tr>
<td><strong>Crustaceans</strong></td>
<td></td>
</tr>
<tr>
<td>crab body fragments</td>
<td>Ab, F</td>
</tr>
<tr>
<td><strong>Abrided Foraminifera</strong></td>
<td></td>
</tr>
<tr>
<td>Archaias sp.</td>
<td>Ab, F</td>
</tr>
<tr>
<td>Homotrema rubra</td>
<td>Ab, F</td>
</tr>
<tr>
<td><strong>Flora</strong></td>
<td></td>
</tr>
<tr>
<td>Charaphaecia</td>
<td></td>
</tr>
<tr>
<td>Nitella furcata</td>
<td>E</td>
</tr>
<tr>
<td>Chara fribosa</td>
<td>E</td>
</tr>
<tr>
<td><strong>Calcareous Algae</strong></td>
<td></td>
</tr>
<tr>
<td>indeterminate calcareous red algae; local Halimeda sp.</td>
<td>Ab, F</td>
</tr>
<tr>
<td><strong>Ovoid seed pods</strong></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>C</td>
</tr>
</tbody>
</table>

a E = excellent; F = some fragmentation; Ab = abraded, bleached.
b Range for number of specimens in each category: vR (very rare), 1; R (rare), <5; C (common), <20; A (abundant), <70; vA (very abundant), >70; empty space indicates none found.
the two dominant species while registering a slightly more diverse assemblage (Fig. 10). The appearance of *Cribroelphidium gunteri* (Cole) and *Triloculina oblonga* (Montagu) indicate increased salinity. A decrease in abundances of *C. gunteri* across the Unit 7–8 boundary is partly replaced by a more diverse, normal-marine assemblage: *Rosalina*, *Peneroplis*, *Archaes*, and *Asterigerina* (Rose and Lidz, 1977). Peaks in abundance of more saline fauna in Unit 7c and 7a (Fig. 10) seem to coincide with marine-derived bioclasts that define M2 and M3 (Fig. 6). Cluster analysis places our sample at 730 mm within the overlying *Triloculina* Biofacies (Fig. 11). This may indicate there were short-term shifts to more extreme saline conditions (see below).

The *Triloculina* Biofacies is represented by a genus often found in hypersaline lagoons (Brasier, 1975); a minor increase in abundance of *Triloculina* cf. *fittele* begins in the upper part of Unit 6 (Fig. 10). The continued, albeit much reduced presence of *A. beccarii* may indicate some fluctuations in salinity. Total foraminiferal abundance passes through a maximum in the lower part of Unit 4, then decreases sharply to the base of Unit 1. Species variation is erratic within the upper 1–2 cm of the stromatolite (Fig. 10), with an apparent sympathetic increase in *T. oblonga*, *A. beccarii*, and *A. angulatus*, species of contrasting biofacies (see above) that may indicate wildly fluctuating salinities.

Ostracode diversity is low (Fig. 12), and resembles the assemblage recovered from Reckley Hill Pond, San Salvador Island (Fig. 1; Sanger and Teeter, 1982; Luginbill, 1983). Both pitted- and smooth-shelled varieties of *Cyprideis americana* are found within the same levels of the core. Biofacies boundaries are defined here by relative change in abundance of prominent species, and are less distinct than those for foraminifer distribution. Our interpretation of biofacies is based on environmental data in Sanger and Teeter (1982) and Teeter and Quick (1990), and references therein. The *Auria* Biofacies, extending from core base to the top of Unit 7, contains fluctuations in the abundance of its nominate species (Fig. 12); one most often associated with normal saline settings. However, the presence of hypersaline (*Dolerocypria* sp.) and brackish water (*P. bicelliforma*) indicators may define a euryhaline environment. *Perissocytheridea bicelliforma* increases in abundance upsection, offsetting a decrease in *A. floridana* between 600 and 320 mm (Fig. 12). This change may indicate a net shift to more brackishwater conditions. The *Dolerocypris* Biofacies, from 320 to about 150 mm, may denote a return to above normal marine salinities especially with a decrease in abundance of *P. bicelliforma*. This change overlaps the peak abundance in foraminifers and the gastropod *Ceriithidae* sp. (Figs. 9 and 10). The uppermost ostracode biofacies is defined by the most prominent re-occurrence of the euryhaline ostracode *Cyprideis americana* relative to Unit 9 (Fig. 12).

5. Chemostratigraphy

C- and O-isotope values of the foraminifer *Ammonia beccarii* define a general sympathetic decrease upsection from Unit 9 to about the base of Unit 5 (Fig. 13). Above this depth, there is no further significant change in δ18O. In contrast, a spike (∼5‰)
Fig. 10. Foraminiferal biostratigraphy, Dune Pass Bay Pond. Relative fractional abundance of in situ foraminifers, total population, biofacies distribution, and percentage of sample examined are shown relative to lithostratigraphy. See Fig. 6 for explanation of symbols.

in $\delta^{13}C$ occurs within Unit 5. Above a depth of 40 mm, $\delta^{13}C$ values display a possible slight increase upsection, then an abrupt decrease across the base of the stromatolite (Unit 1). $\delta^{13}C$ values of gastropod aragonite increase abruptly across the Unit 7–8 boundary, and define a maximum ($\sim -3$ to $-4\%o$) within Unit 7. Above this unit, values first decrease, then illustrate a similar, yet more exaggerated upsection trend when compared to change in foraminiferal $\delta^{13}C$ (Fig. 13). $\delta^{18}O$ values for gastropod aragonite describe a broadly similar upsection trend as defined by foraminiferal calcite, with values varying between 0 and $-2\%o$.

Mg/Ca ratios in ostracode calcite (Fig. 13) are generally low (compare with Chivas et al., 1986) with exception of indigenous shells taken from marine-derived sediment (M2 and M4) as well as clay-size sediment in Unit 5 and locally in Unit 8 (Fig. 13). Calculated salinities based on MgO wt% in C. americana illustrate several prominent shifts moving upsection. Up to the middle of Unit 7, two shifts to very hypersaline values are present (Fig. 13). Gypsum and pyrite occur in sediment containing the lower hypersalinity peak, beneath 1100 mm (Figs. 6 and 13), whereas the second shift coincides with a more saline, diverse foraminiferal assemblage and increased abundance of T. oblonga (Fig. 10). Above

PLATE I
Representative examples of the in situ foraminifer assemblage in core from Dune Pass Bay Pond.
1. Triloculina oblonga (Montagu).
2. Apertural view. ×300.
3. Triloculina cf. fiterrei Acosta.
5. Quinqueloculina poeyana D’Orbigny.
6. Apertural view. ×400.
7. Ammonia beccarii strain ‘parkinsoniana’ (D’Orbigny).
8. Umbilical view. ×100.
10. Side view. ×270.
11. Peneroplis proteus D’Orbigny.
13. Edge view. ×250.
Fig. 11. Q-mode dendrogram based on Wards Method and Euclidean Distance measure for Dune Pass Bay Pond core. The 28 most populous samples (listed vertically as depth in cm) are divided into distinct assemblages (dashed lines). Clusters of samples with correlation coefficients greater than a selected level were considered biofacies.

Unit 7, low salinity values are centred about Unit 5. The brackish-water ostracode *P. bicelliforma* is also more abundant within these sediments (Fig. 12). Between 750 and 250 mm, calculated salinities suggest there may have been abrupt and substantial fluctuations (Fig. 13). Values increase within the lower part of Unit 4, and may continue to increase and peak in Unit 3 (Fig. 13). This increase coincides with appearance of marine-derived bioclasts (M1; Fig. 6), increased abundance of foraminifers and *Cerithidae* sp. through to Unit 3 (Figs. 9 and 10), and distribution of the hypersaline *Dolerocypria* Biofacies (Fig. 12). Salinities appear to decrease above Unit 3.

6. Radiocarbon chronology

6.1. Age–depth distribution

$^{14}$C AMS radiocarbon dates for the DPBP core (Table 2) define a linear age–depth trend beneath Unit 1 (Fig. 14). This confirms little to no compaction of carbonate sediment by coring or during burial. The gastropod in Unit 1 is modern (Table 2); elevated ($\sim 108.5\%$) $^{14}$C activity may indicate shell growth within influence of seawater or sea spray, and oceanic waters at a similar latitude contain excess activity ($<160\%$; Stuiver and O’Stlund, 1980). The basal sand at BCP is chronologically equivalent to Unit 7c at DPBP (Table 2; Fig. 14) whereas the
Fig. 12. Stratigraphic distribution of ostracode species, abundances, and biofacies distribution relative to lithostratigraphy for the Dune Pass Bay Pond. See Fig. 6 for explanation of symbols.

Fig. 13. Chemostratigraphy, Dune Pass Bay Pond. Central columns show downhole changes in specific sample means (circles) and mean trend (dashed line) for Mg/Ca and MgO wt% in shell calcite of Cyprideis americana. Calculated salinity ranges (black bars) accommodate 95% confidence limits set by Teeter and Quick (1990). The right hand column shows downhole distribution of δ¹³C and δ¹⁸O values for foraminiferal (A. beccarii) calcite (circles) and gastropod (Cerithidea sp.) aragonite (squares).
Table 2
Radiocarbon and carbon isotope data for samples from Dune Pass Bay Pond and Beach Cottage Pond on Lee Stocking Island, with interpreted age correction relative to reservoir effect

<table>
<thead>
<tr>
<th>Location and Lab identifier</th>
<th>Core depth (mm)</th>
<th>$^{14}$C age, yr B.P. (± error)</th>
<th>$\delta^{13}$C (% PDB)</th>
<th>Sample type</th>
<th>$^{14}$C age, yr B.P. corrected for reservoir effect $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dune Pass Bay Pond</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GX-20612-AMS</td>
<td>30–35</td>
<td>100</td>
<td>−10.1</td>
<td>gastropod $^a$</td>
<td>100</td>
</tr>
<tr>
<td>TO-4590</td>
<td>190–200</td>
<td>1880 (70)</td>
<td></td>
<td>gastropod</td>
<td>212</td>
</tr>
<tr>
<td>GX-20613-AMS</td>
<td>560–570</td>
<td>2176 (55)</td>
<td>−4.8</td>
<td>gastropod</td>
<td>615</td>
</tr>
<tr>
<td>GX-20614-AMS</td>
<td>830–840</td>
<td>2642 (55)</td>
<td>−4.0</td>
<td>gastropod</td>
<td>908</td>
</tr>
<tr>
<td>TO-4591</td>
<td>1330–1340</td>
<td>3080 (70)</td>
<td></td>
<td>gastropod</td>
<td>1452</td>
</tr>
<tr>
<td><strong>Beach Cottage Pond</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GX-20615-AMS</td>
<td>190–200</td>
<td>751 (55)</td>
<td>−4.7</td>
<td>gastropod $^c$</td>
<td></td>
</tr>
<tr>
<td>GX-20616-AMS</td>
<td>440–450</td>
<td>2676 (55)</td>
<td>1.3</td>
<td>gastropod</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Hand-picked, whole shell, Cerithidea sp.
$^b$ Based on linear age–depth plot and offset with modern date (Fig. 14).
$^c$ See text for discussion.

upper sample is younger than predicted assuming an interpreted lithostratigraphic correlation with Unit 2 at DPBP (Table 2; Fig. 14).

6.2. Reservoir effect

Reservoir effect is the age offset related to change in the $^{14}$C activity of lake and marine water relative to that of the atmosphere (Stuiver and Polach, 1977). It can be substantial in lacustrine and peritidal environments because of reduced $^{14}$C activity associated with bicarbonate contributed by waters involved in meteoric diagenesis of underlying or adjacent bedrock. The linear age–depth plot for DPBP implies there was a relatively stable pre-Unit 1 basin hydrology; hence, a likely constant reservoir effect (Fontes et al., 1996). Extending the age–depth line to the top of Unit 1 produces an age of ~1653 yr B.P. for the present lake floor (Fig. 13). This contradicts the modern age of the gastropod interred within the mat (Table 2) and active cyanobacterial growth. There is no obvious erosional unconformity separating the stromatolite from carbonate, and gastropods in Unit 3 and above display no obvious diagenetic alteration. The anomalous age likely represents the magnitude of the reservoir effect (see also Fontes et al., 1996). This is geologically reasonable: the DPBP basin is surrounded by Quaternary bedrock (Fig. 3; Kindler, 1995); lithoclastic particles occur within all sedimentary units; and, pond water is fed by surface and groundwater that has likely reacted...
with the surrounding bedrock. If BCP has been influenced by the same reservoir effect, the two samples from this basin should lie to one side of the DPBP line (Fig. 14). Instead, the younger than predicted age for the shallower sample (Fig. 14) may represent a ‘resetting’ of the magnitude of the reservoir effect. Stratigraphically, this change may have occurred as a result of modification of the basin’s hydrology during or following the formation of the disconformity that caps Unit 5 (Fig. 14).

7. Discussion

7.1. Chronology and character of pond development, Lee Stocking Island

Formation of both ponds on LSI is considered to be a result of closure of coastal embayments by longshore transport, with increased basin isolation from marine influence due to progressive basin-fill. We describe this history using two phases of development as illustrated by a ‘model’ island north of LSI (Fig. 15). Deposition in both DPBP and BCP basins overlapped the later period of peritidal accumulation of skeletal shoals that now comprise the Perry Peak limestone (Kindler, 1995).

7.1.1. Coastal embayment

The DPBP basin lay between two ridges, and likely opened to the lee of the island (Fig. 2). The embayment was physically restricted, narrow, and relatively protected, somewhat similar to our ‘model’ example (Fig. 15). Initial deposition records a period of elevated sea level that allowed transport and mixture of marine-derived sediment (M1) with indigenous euryhaline biota. The presence of charophytes suggest that embayment salinity was no greater than about 2/3 of normal seawater (Wood and Imahori, 1964). To the top of Unit 8, a changing balance among evaporation, rainfall, and marine influences likely lead to large changes in salinity (Fig. 13), in-

Fig. 15. An island north of LSI showing two phases of pond development. A physically restricted embayment (arrow) will be closed by longshore deposition creating a saline pond basin (to the right of the embayment). Horizontal view is ~1 km.
ducing ecological stress. This is supported by low in situ faunal diversity that is dominated by an essentially monospecific foraminiferal assemblage. Calculated salinities (Fig. 13) and changing abundances of ostracode species (Fig. 12 record higher order change. The very rare occurrence of *Chara* oogonia above Unit 9 suggests that salinity variation became inimical for this alga. Detrital gypsum in Unit 8 may denote reworking of possible crusts along the embayment margin, similar to gypsum found today on the stromatolite (Fig. 7C). Burrows connected to apparent paraconformities in Unit 8 may reflect short-term changes in salinity that allowed for specific infaunal activity.

The embayment became more saline or stabilized to normal and slightly hypersaline conditions thereby allowing establishment of the Mixed Species Biofacies (Fig. 10). This change is cryptic lithologically, marked only by a possible root structure, which may represent establishment of a minor mangrove community, and increased abundance of framboidal pyrite (Fig. 6). Thus, although M2 clearly defines an episodic incursion of normal marine conditions, this high-energy event post-dates the initial change to more saline conditions. Deposition of M2 defines the first phase of deposition in the BCP basin (Fig. 5). This suggests that either the BCP basin is more elevated than that at DPBP or a paleotopographic sill was finally breached.

7.1.2. Evolution of a marine saline pond

Sedimentation in the DPBP basin changed irreversibly after deposition of M2. Closure of the embayment may have occurred at this time due to formation of a sand bar, a seaward extension of M2. Transposition of foraminifer biofacies, from mostly euryhaline to mostly hypersaline species, is complete near the top of Unit 7 (Fig. 10). Large, abrupt fluctuations in abundances of hypersaline and euryhaline foraminifer species within Unit 7 (Fig. 10) may indicate either a poorly developed barrier that allowed episodic mixing with normal marine waters or episodic freshening of the salinity behind a very good barrier due to changing rainfall and evaporation patterns. M3 sediment is muddier than M1 or M2 sediment (Fig. 6), and may indicate deposition within a more protected, lower energy setting. From our age–depth plot (Fig. 14), closure of the embayment occurred by ca. 740–700 yr B.P. Change in coastal sedimentation patterns may have been linked with an interpreted change in regional Bahamian paleoclimate, as recorded on Andros Island (Kjellmark, 1996) where, by ca. 740 yr B.P., tropical hardwood vegetation was replaced by pine woodland vegetation. This occurred with increased precipitation in the northern Bahamas (Kjellmark, 1996). Changed weather patterns, including wind and wave regimes, may have influenced coastal sedimentation patterns helping to close off DPBP and BCP embayments.

A saline pond should record tremendous change in water chemistry according to meteoric input, evaporation, seepage across a coastal barrier, and flux of marine waters during elevated sea level (e.g., marine-derived sediment of M4). Increased meteoric input in the LSI vicinity may explain the appearance of the brackish-water *Perissocytheridea* biofacies in Units 6 and 5 (Fig. 12). Greater rainfall would certainly increase rates of surface erosion and basin-filling, further isolating the saline pond from marine influence. A shift toward more negative δ¹³C values for gastropod aragonite above 700 mm (Fig. 13) supports the presence of increasing brackish-water conditions (e.g., Keith and Parker, 1965). Given the paleotopographic setting (Fig. 2), and basin closure, sympathetic negative trends in foraminiferal δ¹³C and δ¹⁸O up to the base of Unit 5 (Fig. 13) are expected given that the basin was becoming hydrologically closed (Talbot, 1990). Depletion in δ¹³C in skeletal carbonate may identify increased fraction of soil-derived bicarbonate from surface runoff; a sharp decrease in δ¹³C values across the base of Unit 1 (Fig. 13) may illustrate uptake of bicarbonate depleted in δ¹³C due to organic diagenesis or productivity within a water mass variably diluted by meteoric water (as found today).

The increasing dominance of foraminifer *T. oblonga* implies a shift toward hypersaline conditions (see above). Yet, δ¹⁸O values for skeletal carbonate (Fig. 13) are not characteristic of highly saline water. Absolute values and an overall negative shift in foraminiferal δ¹⁸O may identify greater thermal influence on O-isotope fractionation because of likely increased influence of solar-heating of pond water. As our foraminiferal isotope data are based on *A. beccarri* alone, however, the O-isotopic record may reflect this species’ productivity related to periods
of lesser hypersalinity created during or immediately following rainfall.

Elevated calculated salinities in the lower part of Unit 6 correspond with relatively abundant gastropods (Figs. 9 and 13). Much reduced numbers in overlying sediment, coincident with a possible abrupt shift to hypersaline conditions (Scott and Cass, 1977). A maximum in the abundance of these gastropods occurs in Unit 3 (Fig. 9), which displays a possible maximum in calculated salinity as inferred by bounding data (Fig. 13). Units 3 and 4 also contain the hypersaline *Dolerocypria* biofacies and maximum population of the hypersaline foraminifer *T. oblonga*. A second massive killing of gastropods at DPBP may have been contemporaneous with a similar die-off at BCP (Fig. 5). This parallel stratigraphy suggests that there has been a common environmental control despite the distance between the two basins.

Very quiet water accumulation of clay (1–2 μm) size sediment characterizes Unit 5. Elevated Mg/Ca ratios in ostracode shell carbonate (Fig. 13), along with the marked positive shift in foraminiferal δ13C, may record bacterially induced precipitation of carbonate related to ‘blooms’ of nannobacteria, their fossil remains (Fig. 8D) relatively abundant in this unit. Ca2+ would be removed preferentially, relative to Mg2+; biological utilization of 12C would increase δ13C of remaining bicarbonate within this hydrologically closed system. Elevated Mg/Ca ratios within ostracodes from M2 and M4, and also distributed within Unit 8 (Fig. 13), may have similar origins. However, elevated ratios associated with these sediments may also indicate growth within the presence of more saline water.

7.1.3. Pond eutrophication

The most dramatic, recent change in pond development is shut-down of carbonate accumulation and start-up of organic (stromatolitic) production. When compared to the calibration of Stuiver and Pearson (1986), this occurred in the last 200 years. Today, high-frequency variation in pond salinity, as recorded by foraminifer populations, presence of corroded gypsum, and desiccation cracks, seems to reflect a balance among rainfall, evaporation, and basin drainage. Modern lacustrine stromatolites are documented on San Salvador Island (Dakoski and Bain, 1984; Neumann et al., 1988), and a similar redish colour in other lakes noted by Craton and Saunderson (1992) may be indicative of more widespread distribution of lacustrine stromatolite. This evokes influence of an extrinsic factor. While the role of anthropogenesis, beginning in the 19th century (Craton and Saunders, 1992), has been interpreted to have influenced other attributes of insular sedimentation (Mitchel et al., 1988; Kjellmark, 1996), other factors helping to trigger elevated organic productivity may be related to changes in groundwater chemistry, hydrology, and nutrient supply affected by rise in sea level.

7.2. Sea level change: storm surge versus eustasy

Admixture of marine-derived sediment (M1 through M4) with indigenous biota (see above) defines an apparent centuries-scale (300–400 year) flux of sediment and marine waters into, first, embayments, then pond basins. Texture and composition of the marine-derived sediments, when compared to the lithoclasts (with evidence of meteoric cement) forming background pond sediment, suggests these marine-derived allochems were not eroded from adjacent semi- to lithified dunes. Given the tectonic stability of the Bahamian platform in recent times (Myroie and Carew, 1995), change in sea level is related to either storm surges or high-order eustatic variation. A future regional stratigraphic network among lacustrine basins might help to resolve these alternatives. Here we discuss possible evidence for both.

Some Holocene sea level curves for the Bahamas–Caribbean region (e.g., Droxler, 1985; Fairbanks, 1989; Boardman et al., 1989; Pirazzoli, 1991) do not interpret high-order eustatic variation. Instead, given that many are ‘best-fit’ curves, they define a general rise in sea level since platform-flooding, which occurred by ca. 5–6 kyr B.P. in the Bahamas region (e.g., Droxler, 1985). If higher order, eustatic variation can be excluded, the study region can certainly accommodate storm-surges as explanation for the M1 through M4 deposits. At least 30 hurricanes over the last 100 years have passed over and near the vicinity of LSI (Cry, 1965). Most have followed a
northwesterly track along Exuma Sound while a few have passed to the northeast over the bank-interior (Cry, 1965). This estimate translates into at least 450 hurricanes over the last 1500 years or <2000 of these storm events since platform flooding. Hine (1983), using a decadal average, estimated <5000 hurricanes in the northern Bahamas in the last 6000 years. Thus, storm effects on sea-level and sedimentation have been likely significant. Windward storm ramps are exposed in Dune Pass Bay limestone (ca. 5.2 kyr B.P.; Kindler, 1995) near Dune Pass Bay on LSI (White and Curran, 1993). The open, narrow shelf offers little protection (Kindler and Hearty, 1996) against westerly or northwesterly storm waves. Although storm surges can be substantial (Dunn and Miller, 1964), they would need to be extraordinary to pass over the Holocene ridge east of the DPBP basin (Fig. 2). Instead, however, hurricane tracks located inboard of the Exuma Sound margin (Cry, 1965) may have reworked platform-interior sediment in order to generate the marine-derived deposits. From stratigraphy of coastal lake basins along the Gulf of Mexico, Liu and Fearn (1993) suggested that category 4 and 5 (>211 km/h) hurricanes have occurred once every 600 years over the last 3000 years. This frequency is of similar magnitude as our centuries-scale stratigraphy of marine-derived sediment.

Evidence for high-order eustatic events such as stillstands and rapid, episodic changes in rates of sea-level rise is accumulating for the late Holocene interval in the Gulf of Mexico and Florida–Bahamas region (e.g., Anderson and Thomas, 1991; Kindler, 1992; Kindler and Bain, 1993; Goodbred et al., 1998). We compare several depositional events in the Bahamas region with Ters (1987) proposed high-order eustasy curve to illustrate potential higher-order events (Fig. 16). First, the phase of euryhaline deposition at DPBP may coincide with one of Ters’ (1987) lowstands (Fig. 16). Available geochronology suggests that increased flux of meteoric water and progradation of inner-shelf facies occurred on San Salvador Island at about the same time (Fig. 16; Lind, 1969; Anderson and Boardman, 1988; Teeter and Quick, 1990; Kindler and Bain, 1993; Teeter, 1995). Second, the ages of M1, M2 and M4 may fit with parts of various highstands (Fig. 16). M3 stands separate from these, yet corresponds to interpreted phase of climate change in the Bahamas (Kjellmark, 1996) that may have affected coastal sedimentation patterns (see above). Of greatest interest is the appearance of the Mixed Species Biofacies, indicating increased salinity, prior to more obvious lithologic evidence of marine incursion in the form of M2 sediment (Figs. 6 and 10). This succession may represent a low, then high-energy phase of rapid marine transgression, ca. 1000 yr B.P. Alternatively, storm deposition (=M2) is superimposed on a more cryptic sea level rise. Rapid, steplike rises in sea level may characterize the later Holocene history of post-glacial sea level change (Anderson and Thomas, 1991), as has been described across marsh deposits along the low-energy west Florida coastal region, ca. 1800 yr B.P. (Goodbred et al., 1998). Marine-derived deposits in the DPBP may be records of such rapid, step-like transgressions. However, a regional stratigraphic framework is needed to exclude ‘local’ (storm) effects. Finally, several seemingly independent depositional features developed along the Exuma Sound margin ca. 400–500 yr B.P. These features may be interlinked with regional changes in coastal and oceanographic dynamics, and include: (1) termination of Perry Peak limestone accumulation (Kindler, 1995); (2) increased isolation and facies restriction in the DPBP and BCP ponds (this study); (3) deposition of M4; and (4) appearance of subtidal stromatolites as fringing shelf reefs and within inter-island channels (Dill et al., 1989; Macintyre et al., 1996). Whether these biological and sedimentological features are responses to a common, extrinsic control, such as sea-level change, awaits future analysis.

8. Conclusions

A high resolution record of lithostratigraphy, micro- and macrobiostratigraphy, and detailed radiocarbon chronology in short (<1.4 m) cores from saline ponds on Lee Stocking Island, Bahamas, reveal two patterns of late Holocene (<1500 yr B.P.) paleoenvironmental change:

(1) Sediments initially accumulated in euryhaline, semi-protected coastal embayments that were closed by ca. 740–700 yr B.P. possibly due to changing coastal oceanographic and depositional patterns re-
Fig. 16. Chronology of pond development at Lee Stocking Island relative to apparent chronologies of other depositional events in the Bahamas region, and proposed eustatic sea level curve for the late Holocene (Ters, 1987). See text for explanation.

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Appendix A

Foraminiferal synonymies for the in situ assemblage recovered from the Dune Pass Bay Pond core. Sources are provided in the References list.

Ammonia beccarii strain `parkinsoniana'
Rosalina parkinsoniana d’Orbigny, 1839, p. 99, pl. 4, figs. 25–27.

Rotalia beccarii (Linné) var. parkinsoniana (d’Orbigny)
Phleger and Parker, 1951, p. 23, pl. 12, figs. 6a, b.

Ammonia parkinsoniana (d’Orbigny) forma `typica'
d’Orbigny Poag, 1978, p. 397, pl. 1, figs. 5–9, 13–16.

Archaias angulatus (Fichtel and Moll)
Nautilus angulatus Fichtel and Moll, 1798, p. 113, pl. 22, figs. a–e.

Archaias angulatus (Fichtel and Moll) Cushman, 1930, p. 46, pl. 16, figs. 1–3; pl. 17, figs. 3–5.

Archaias angulatus (Fichtel and Moll) Rögl and Hansen, 1984, p. 69, pl. 27, figs. 3, 4; pl. 28, figs. 2–6.

Asterigerina carinata d’Orbigny
Asterigerina carinata d’Orbigny in De la Sagra, 1839 p. 118, pl. 5, fig. 23; pl. 6, figs. 1, 2.

Asterigerina carinata d’Orbigny Poag, 1981, p. 42, pl. 47, fig. 1; pl. 48, fig. 1a, b.

Cribroelphidium gunteri (Cole)
Elphidium gunteri Cole, 1931, p. 34, pl. 4, figs. 9, 10.

Peneroplis proteus d’Orbigny
Peneroplis proteus d’Orbigny in De la Sagra, 1839, p. 60, pl. 7, figs. 7–11.

Peneroplis proteus d’Orbigny Poag, 1981, p. 74, pl. 47, fig. 3; pl. 48, fig. 3a–c.

Quinqueloculina poeyana d’Orbigny
Quinqueloculina poeyana d’Orbigny in De la Sagra, 1839, p. 191, pl. 11, figs. 25–27.

Quinqueloculina poeyana d’Orbigny Cushman, 1929, p. 31, pl. 5 figs. 2a–c.

Rosalina floridana (Cushman)
Discorbis floridana Cushman, 1922, pl. 39, pl. 5, figs. 11, 12
Rosalina floridana (Cushman) Todd, 1965, p. 10, pl. 3, figs. 1, 3; pl. 4, fig. 5.

Triloculina cf. fitleri Acosta, 1940
Triloculina fitleri Acosta, 1940, p. 25 pl. 4, figs. 6–8.

Triloculina oblonga (Montagu)
Verniculam oblongum Montagu, 1803, p. 533, pl. 14, fig. 9.

Triloculina oblonga (Montagu) Todd and Bronnimann, 1957, p. 27, pl. 5, figs. 15, 16.

References


Acosta, J.T., 1940. Nuevos foraminíferos de la costa sur de Cuba, 3, Torreia, La Habana, Cuba.


Cushman, J.A., 1929. The Foraminifera of the Atlantic Ocean


Lands and Surveys Department, 1968. Exuma Group Map Sheet 12, scale 1:25,000, Nassau, Bahamas.


Montagu, G., 1803. Testacea Britannica, or Natural history of British shells, marine, land, and fresh-water, including the most minute. Hollis, Romsey, England, 606 pp.

