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

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

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SEA LEVEL AND THE PALEOENVIRONMENTAL INTERPRETATION OF THE MIDDLE TO UPPER HOLOCENE HANNA BAY LIMESTONE, SAN SALVADOR, BAHAMAS: A HIGH FORESHORE SETTING WITHOUT A HIGHER-THAN-PRESENT EUSTATIC HIGHSTAND

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ABSTRACT

The Hanna Bay Member (belonging to the middle to upper Holocene Rice Bay Fm.) crops out along the periphery of San Salvador Island and has been interpreted, in part, as a nearshore deposit. Outcrops of suspect intertidal facies rest as much as 2 m above current mean sea level, suggesting the existence of a sea-level highstand higher than current sea level. This hypothesis was tested through study of the sedimentology, petrology, and ichnology of the limestones. Numerous outcrops were investigated with two extraordinary exposures studied in greater detail. Additionally the sedimentology of modern lee- and windward beaches on San Salvador was characterized for comparison. Whole rock, standard counting radiocarbon dating of the two sections yields different ages (Cal BP 3260 – 4070 at Hanna Bay; Cal BP 780 – 1230 at Grotto Beach). Ages taken at different heights within the same section are stratigraphically disordered. This variability may be explained by the confounding effects of averaging the age of various allochems and cements within the same rock. Nonetheless, the difference in age range between the two sections suggests they represent diachronous intervals. Sedimentary structures are consistent with a foreshore origin and include fenestrae, rill marks, and swash marks. Limestones are composed of tabular thin beds that dip seaward between 4-8°, also consistent with a foreshore interpretation. Grain size distributions and allochem types are comparable to those from modern fore- and backshore settings. Mean grain size of the beds varies between medium to very coarse sand, indicating these nearshore deposits were not exclusively deposited during storms. The trace fossils and vegemorphs present, however, are consistent with a backshore to dune environment. Marine cements are conspicuously absent; blocky isopachous and meniscus cements are common, supporting a phreatic and vadose freshwater cementation. We propose these sediments were deposited in a foreshore setting during a short-duration highest tide interval and then quickly restored to a backshore position once the tide subsided. This interpretation is not consistent with a eustatic sea-level highstand. A mechanism is still needed to explain a short-lived interval of high tides without storm conditions. Preliminary research on Eleuthera and the Exuma Islands demonstrates that similar scenarios exist for Hanna Bay rocks elsewhere in the Bahamas.

INTRODUCTION

The existence of iterative short-duration sea-level highstands during the last 5000 years of the Holocene has been debated over recent years (e.g., Blum et al., 2001, 2003; Otvos, 2004; Törnqvist et al., 2004). Evidence for highstands as high as 2 meters above current mean sea level has been presented for numerous regions across the planet (examples include: Gulf Coast, U.S.: Blum et al., 2003, Balsillie and Donoghue, 2004; Brazil: Angulo and Lessa, 1997; Maldives: Kench et al., 2009; Red Sea: Siddall et al., 2003; Singapore: Bird et al., 2010; Japan: Hongo and Kayanne, 2010; Western and Eastern Australia: Twiggs and Collins, 2010, Baker and Haworth, 1997; Tunisia: Jedoui et al., 1998; Hawaii: Calhoun and Fletcher, 1996, Fletcher and Jones, 1996; equatorial Pacific: Grossman et al., 1998;

South China: Davis et al., 2000). Some of these depend upon sea-level indicators that require the persistence of high sea level for significant periods of time (e.g., reef development, peat formation, erosional notches, phreatic cave development, etc.), rather than short-term ephemeral processes indicative of local oceanographic phenomena that influence sea-level height locally. Less ephemeral sea-level highstand indicators, though genuinely reflecting a persistent highstand, might be due to local phenomena of tectonics or subsidence and not eustatic, global phenomena. Nonetheless, the evidence is prolific and compelling, and regional sea-level curves have been generated and published suggesting eustatic highstands may have existed over recent history.

The implications of short-term sea-level highstands during the middle to late Holocene are significant for the anticipatory effects of our current global climate change. Abrupt rises in eustatic sea level of less than 10 m amplitude during the recent past are best explained by ice sheet collapse in Antarctica or Greenland (Zwally et al., 2005; Vaughan, 2008; Nicholls et al., 2008; Long, 2009; Hillenbrand et al., 2009). Abrupt, step-wise eustatic rises have been documented for the latest Pleistocene and early Holocene due to sheet collapse (Blanchon and Shaw, 1995; Locker et al., 1996; Bird et al., 2010) and for the former MIS 5e interglacial (Hearty and Neumann, 2001; O'Leary et al., 2008; Blanchon et al., 2009). If also true for the middle Holocene, this establishes precedent for abrupt and potentially catastrophic sea-level rise in the near future in response to planet warming. More difficult to explain, however, is a mechanism causing equally abrupt sea-level reductions. It is not clear if ice-sheet expansion can rival the rate of ice-sheet collapse.

Because the societal implications of rapid eustatic rise are great, geoscientists should commit a more significant research effort on testing this hypothesis of middle to late Holocene eustatic sea-level highstands. Three fundamental questions for every highstand claim should be addressed. (1) Has the sea-level indicator been correctly interpreted? The deposit representing ocean-height position must genuinely represent an intertidal or near-intertidal position. (2) Does the intertidal deposit represent a significant temporal duration to be consistent with a eustatic phenomenon? A higher-than-normal intertidal deposit that was produced by a short-term sedimentologic or oceanographic phenomenon (i.e., one lasting a few hours, days, or months) cannot be explained parsimoniously by a longer-term eustatic process. (3) Assuming the first two criteria are satisfied, can the intertidal deposit be explained by some local process that affected regional sea level? Here too the burden of proof is great; parsimony would dictate a local phenomenon would be more likely. Lastly, those case studies that withstand these criteria tests should then be integrated in an attempt to temporally correlate highstands. Knowing the number, duration, and timing of Holocene highstands requires such an analysis.

Middle to late Holocene highstands have been proposed for regions proximal to the Bahamas: the Gulf Coast of the United States, and Southwest and South Florida (Missimer, 1973; Stapor et al., 1991; Walker et al., 1995; Froede, 2002; Balsillie and Donoghue, 2004). Still other studies have suggested that the middle to late Holocene transgression proceeded gradually without periods of higher-than-present sea-level positions, following the sea-level curve reported by Toscano and Macintyre (2003), Mazzullo (2006), and Savarese et al. (2010) (Figure 1). One or more Holocene highstands have been proposed for the Bahamas based upon three lines of evidence, though all are circumspect. Backshore deposits sitting as high as 7 m above modern sea level have been described from the windward side of Lee Stocking Island, Exuma Cays (White and Curran, 1993). A 7 m-high backshore suggests a higher-than-present sea level. Backshore deposits, however, could reside this high during storm conditions, particularly on the exposed western edge of Exuma Sound. Subtidal muds of approximately 3000 years of age have been described from Andros Island and sit 1.5 – 2 m above current sea level (Bourrouilh-Le Jan, 2007). These sediments, however, were formerly

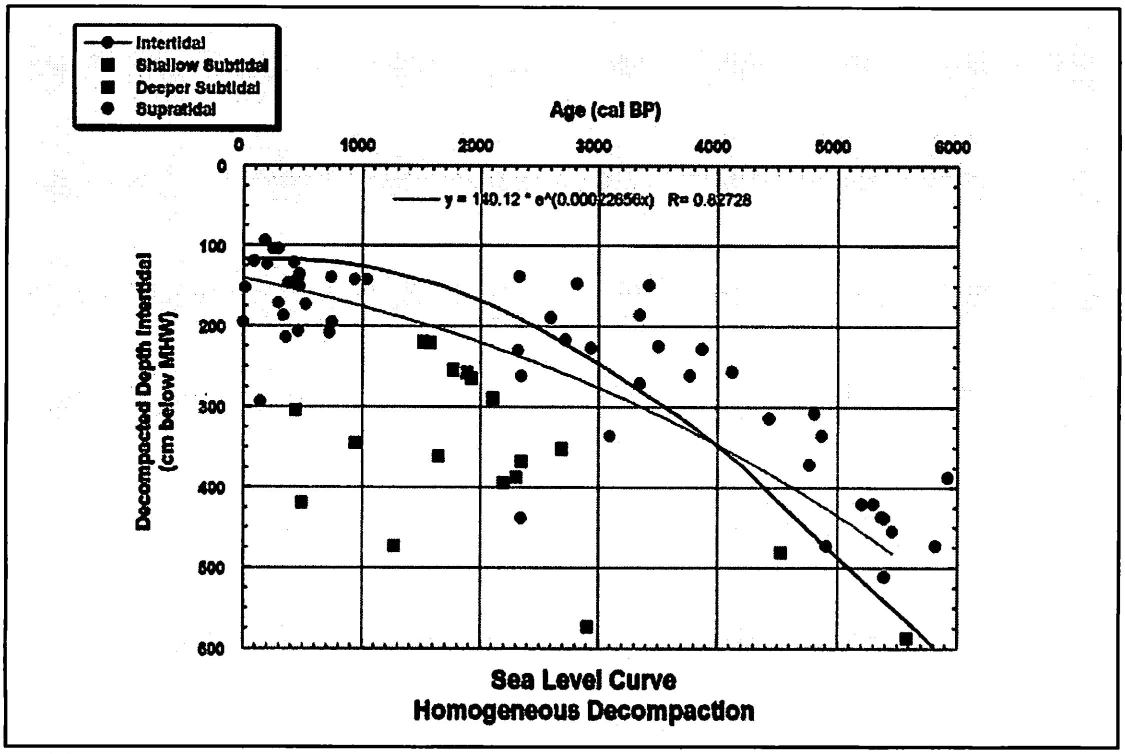

Figure 1. Middle to late Holocene sea-level curve for Southwest Florida. Data from Holocene cores taken throughout coastal environments in Collier and Lee Counties, Southwest Florida, by Savarese. Water depth plotted relative to Mean High Water (MHW), taken as the depth below the height of the lowest growing red mangrove leaves. Depths are adjusted by homogeneously decompacting the core lengths. Both an exponential best fit (thin) and a hand-drawn best fit curve (thick) are shown. Sedimentary facies are interpreted as either: supratidal, intertidal, shallow subtidal, or deeper subtidal. Best fit curves are placed through intertidal points, below supratidal points, and above subtidal points.

interpreted as storm-related deposits, rather than products of a highstand. Finally, Godefroid et al. (2010) interpret a middle Holocene calcrete from Eleuthera as having a marine algal-microbial mat, rather than a pedogenic origin, that sits approximately 2 m above modern sea level. In addition to these investigations, rocks belonging to the Hanna Bay Member of the Rice Bay Formation, a prolific lithostratigraphic unit found throughout the Bahamas (Carew and Mylroie, 1985, 1987, 1989, 1995; Hearty and Kindler, 1993a; Kindler et al., 2011), contain a facies that appears to be intertidal that currently sits as much as 2 meters above modern mean sea level (MSL). These rocks may be the best candidates for testing a highstand hypothesis for the Bahamas.

This study tests the middle to late Holocene highstand hypothesis for the Hanna Bay Member limestones exposed on the Bahamian Island of San Salvador. Two sub-hypotheses are considered, in logical order: (1) Portions of the Hanna Bay Member, sitting as much as 2 m above modern MSL, represent foreshore deposits, and therefore serve as valid sea-level indicators. (2) Elevated sea level persisted long enough to represent a eustatic phenomenon, rather than some ephemeral, local perturbation. Results from this project support the first sub-hypothesis: one lithofacies of the Hanna Bay Member clearly contains multiple lines of sedimentologic and stratigraphic evidence supporting a foreshore origin. However, diagenetic, paleontologic, and geochronologic evidence indicates these rocks, though formed in a beach setting, resided in this position for too short a period of time to indicate a eustatic global sea-level position.

Although proponents of a eustatic Holocene highstand may be disappointed with or find fault with this study, this work does not preclude the possibility for one or more eustatic highstands. Because the foreshore facies of the Hanna Bay Member ultimately does not meet the criteria for a valid eustatic sea-level indicator, its existence should not be invoked in support. Perhaps more significantly, this study illustrates the care required to adequately assess the applicability of evidence for the global position of sea level.

PHYSICAL STRATIGRAPHY AND STUDY AREA

Limestones from the middle to upper Holocene Hanna Bay Member belong to the Rice Bay Formation, and represent a regressive, progradational package deposited during time of decelerated sea-level rise (Carew and Mylroie, 1995, 1997, 2001; Mylroie, 2008). The type section is located along the shores of Hanna Bay on San Salvador Island (Figure 2), though the rocks are found prolifically around San Salvador's periphery. Hanna Bay strata are also described from many additional Bahamian Islands (Hearty and Kindler, 1993b; Kindler and Hearty, 1996). It is younger in age than the North Point Member, though a stratigraphic contact between these two members of the Rice Bay Formation is rarely observed (see however Kindler, 1992, 1995; and on Little Exuma, Savarese, unpublished data). Hanna Bay limestones typically sit unconformably on top the Pleistocene Grotto Beach Formation.

The most prolific facies represented in the Hanna Bay Member is an eolianite, deposited within dune and backshore environments. Rocks that appear to be foreshore in origin do occur, but are significantly less common. When facies successions are evident, the rocks purported as foreshore in origin sit basally and are overlain by backshore, followed by dune facies limestones. A subtidal facies has been described from North Bimini and Joulter Cays and it resides lowest within a section (Strasser and Davaud, 1986).

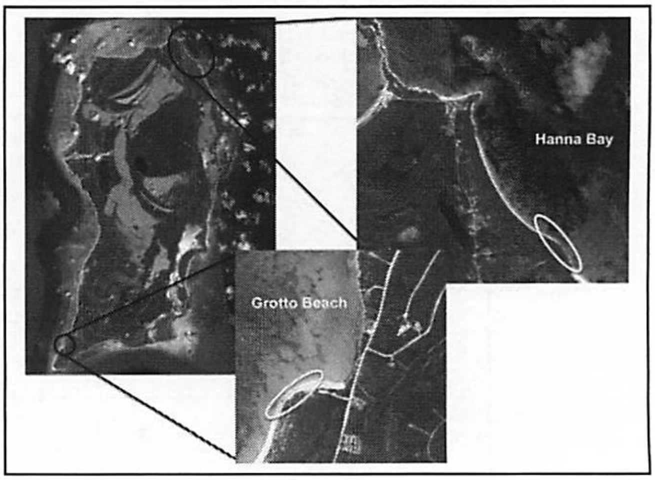

Figure 2. Locality maps showing San Salvador Island with insets for Hanna Bay and Grotto Beach. White ellipses mark the position of the outcrops used in this study.

METHODS

Modern Beach Environments

Hanna Bay Member limestone sedimentology was compared against modern beach sands from around San Salvador. Sands were collected from five localities from both the windward and leeward sides of the island. Foreshore, backshore, and dune sub-environments were included. Grain-size analysis was conducting using a Malvern Mastersizer 2000E particle size analyzer. In addition to existing currently active foreshore settings, an eroded berm of foreshore sands, sitting ~1.5 m above the active foreshore and presumably deposited during a recent storm or extreme high tide, was available at Grotto Beach. Two samples, each from a discrete lamination, were collected and analyzed similarly for further comparison. Grain slurries of all samples were delivered using a Hydro2000MU sample dispersion unit. From these grain size distributions, mean and standard deviation (i.e., sorting) were obtained using the Folk graphic method (Folk, 1974).

Hanna Bay Limestones

The Hanna Bay Limestone outcrops located at Hanna Bay and Grotto Beach (Figure 2) were described using standard practices of stratigraphy and sedimentology. Lithofacies were differentiated based upon sedimentologic characteristics and the presence of diagnostic sedimentary structures. Sedimentary structures within beds and on bedding surfaces were noted. One section exposing all facies in stratigraphic context from each locality was chosen as a reference section, and then measured and described in detail. Each facies within the reference section was lithologically sampled for later petrographic study. Trace fossils, body fossils, and vegetative traces (hereafter termed vegemorphs) were noted and identified from each facies.

In order to best infer lateral facies relationships, exposures of Hanna Bay Limestone oriented perpendicular to the modern shoreline were described and photographed. One exposure was available at Grotto Beach, though its lateral extent was only ~4.5 m. A more laterally extensive exposure was available at Hanna Bay, stretching approximately 10 m.

Thin sections were described using a Nikon Labophot-2 petrographic microscope. Each thin section was point counted; allochem type and maximum grain diameter were recorded. Grain populations were relatively

Table 1. Grain-size analysis data for modern foreshore, backshore, and dune sediments from beaches on San Salvador. Also included are data from two thin beds exposed within an eroded foreshore berm on Grotto Beach. Mean grain size and sorting were obtained using Folk's (1974) graphic method. All beaches, with one exception, are located on the western or northern leeward shores. Trash Beach is located on the eastern, windward shore.

Locality	Mean Phi	Mean Grain Size	Sorting Phi	Sorting Category
Foreshore berm				
Grotto Beach berm (09-30)	0.79	Coarse sand	0.61	Moderately well sorted
Grotto Beach berm (09-29)	-0.03	Very coarse sand	0.70	Moderately well sorted
Foreshore normal				
Grotto Beach (09-27)	1.13	Medium sand	0.46	Well sorted
Trash Beach (09-24)	1.86	Medium sand	0.58	Moderately well sorted
Long Bay, south (09-13)	2.35	Fine sand	0.47	Well sorted
Long Bay, north (09-06)	2.04	Fine sand	0.47	Well sorted
Fernandez Bay (09-08)	0.94	Coarse sand	0.40	Well sorted
Rocky Point (09-17)	1.47	Medium sand	0.45	Well sorted
Backshore				
Grotto Beach normal (09-28)	1.10	Medium sand	0.79	Moderately sorted
Grotto Beach berm (09-31)	0.68	Coarse sand	0.89	Moderately sorted
Long Bay, north (09-07)	2.23	Fine sand	0.46	Well sorted
Long Bay, south (09-14)	1.17	Medium sand	0.87	Moderately sorted
Fernandez Bay (09-09)	1.00	Coarse sand	0.45	Well sorted
Rocky Point (09-18)	0.46	Coarse sand	0.77	Moderately sorted
Dune				
Grotto Beach (09-25)	1.12	Medium sand	0.62	Moderately well sorted
Fernandez Bay (09-10)	0.91	Coarse sand	0.50	Well sorted
Rocky Point (09-19)	0.60	Coarse sand	0.92	Moderately sorted

Table 2. Grain-size distribution data from limestone thin-section point counts. Thin-section locations noted on Figures 5 and 6 for the outcrop at Hanna Bay (HB) and Grotto Beach (GB) respectively. Mean grain size and sorting values shown in phi units and in equivalent size and sorting categories.

Thin Section	Mean Phi	Mean Grain Size	Sorting Phi	Sorting Category
GB08-1	1.00	Coarse sand	0.84	Moderately sorted
GB08-2	1.75	Medium sand	0.48	Well sorted
GB08-5	-0.68	Very coarse sand	0.42	Well sorted
GB08-6 coarse lamination	-0.36	Very coarse sand	0.56	Moderately well sorted
GB08-6 fine lamination	0.74	Coarse sand	1.05	Poorly sorted
GB08-8	1.61	Medium sand	0.74	Moderately sorted
GB08-9	-0.38	Very coarse sand	0.93	Moderately sorted
HB08-1	1.30	Medium sand	0.58	Moderately well sorted

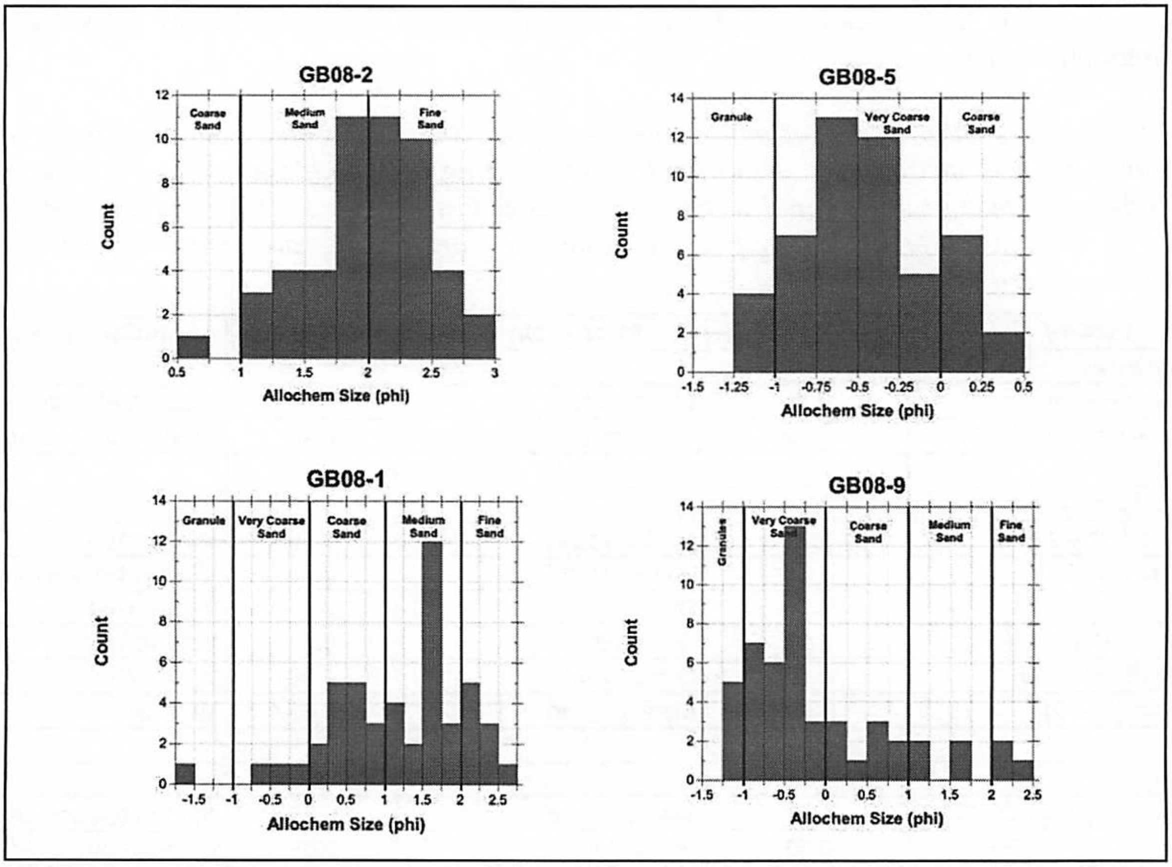

Figure 3. Sample grain-size distributions from thin-section point counts from Hanna Bay limestones exposed at Grotto Beach. Outcrop locations of the thin sections, based upon sample name (GB08-2, GB08-5, etc.), are shown on Figure 6. 50 grains per thin section were identified, as allochem type, and measured.

small due to the relatively large grain size of the rocks. Consequently grain distributions were based on 50-grain counts. These data were subjected to grain size analysis following Friedman (1958). This permitted direct comparison against results from the modern beach sands. Cement textures were described petrographically to infer diagenetic history. The presence of different cement types indicates the influence of fresh- versus marine water in either a vadose or phreatic zone.

Geochronology

Whole-rock radiocarbon dates were obtained for 7 samples, 3 from the Grotto Beach outcrop and 4 from the Hanna Bay outcrop. Clean rock was exposed at the outcrop and then sampled; if any weathered surfaces remained, these were trimmed away. Samples were shipped to Beta Analytic for standard counting radiocarbon analysis. Details of their pretreatment and analysis are available online (www.radiocarbon.com/analytic.htm). Dates are reported as both Conventional ^{14}C Ages (after applying ^{13}C/^{12}C corrections) and as Calibrated Radiocarbon Years Before Present, where "present" is AD 1950.

RESULTS

Grain-size analyses of leeward beach sands from San Salvador provide a basis for comparison with the grain-size descriptions from the Hanna Bay Limestone. Modern foreshore sediments have mean grain sizes that range from fine to coarse sand and are moderately well to well sorted. Backshore and dune sands have comparable grain sizes with more varied sorting values, ranging from moderately to well sorted (Table 1). Trash Beach, the only modern foreshore sediments from the windward east side of San Salvador, has a grain-size distribution comparable to those seen on the leeward sides of the island. The surf conditions at the time of sampling, however, were relatively calm. Lumps and bioclasts dominated allochems from all sediment samples.

At the time of sampling at Grotto Beach, an eroded berm sitting approximately 1.5 m above the active foreshore exposed thin bedded sands. These were composed of coarse to very coarse sands and were moderately well sorted (Table 1), distributions being not very different from the active foreshore sediments.

Thin-section point-count data are shown in Table 2 and Figure 3. Limestone allochems are composed of, in order from most to least abundant: lumps, bioclasts, and peloids. When grain populations from seven thin sections from Grotto Beach are pooled, lumps compose 41.8% of the grains, bioclasts 30.5%, and peloids 27.7%. Grain sizes vary from medium to very coarse sands, slightly larger when compared to the modern foreshore sands. Sorting is also more variable, ranging from poorly sorted (for only one thin section) to well sorted (Table 2).

Limestones are composed of tabular cross-laminated beds with shallow seaward dips. Dips vary from 5-10° with a mean of 7.0° at Hanna Bay (N=4, standard deviation = 2.2°) and from 5-11° with a mean of 7.6° at Grotto Beach (N=8, standard deviation = 2.0°). Some beds are graded with coarser basal laminations. Shallow angular unconformities can occur between beds. Fenestrae, swash lines, and rill lineations rarely occur on bedding planes (Figure 4).

Outcrops with faces that are oriented perpendicular to the beach offer glimpses of both lateral and vertical facies relationships. A 9.7 m long exposure at Hanna Bay (Figure 5) contains 3 facies. The lower two, facies A and B, are composed of tabular cross-laminated beds with seaward dips and bedding-plane fenestrae. Facies C sits above, truncates facies B, and is composed of steeply dipping trough cross-stratified bed sets with opposing dip directions. Laterally limestones from facies A transition from seaward-dipping tabular beds to bidirectional, steeply dipping trough cross-stratified beds (closer to the 0 m end of the outcrop transect). A much narrower outcrop face at Grotto Beach, spanning approximately 4.5 m, is composed of three tabular cross-stratified beds, facies A, B, and C, each separated by shallowly dipping angular unconformities (Figure 6). Bedding-plane surfaces within these facies are rich with fenestrae, with occasional rill laminations and swash lines. Facies D sits unconformably above and is composed of limestones with less ordered dip angles that nonetheless dip seaward. Just landward of this outcrop face (not viewable in Figure 6), facies D

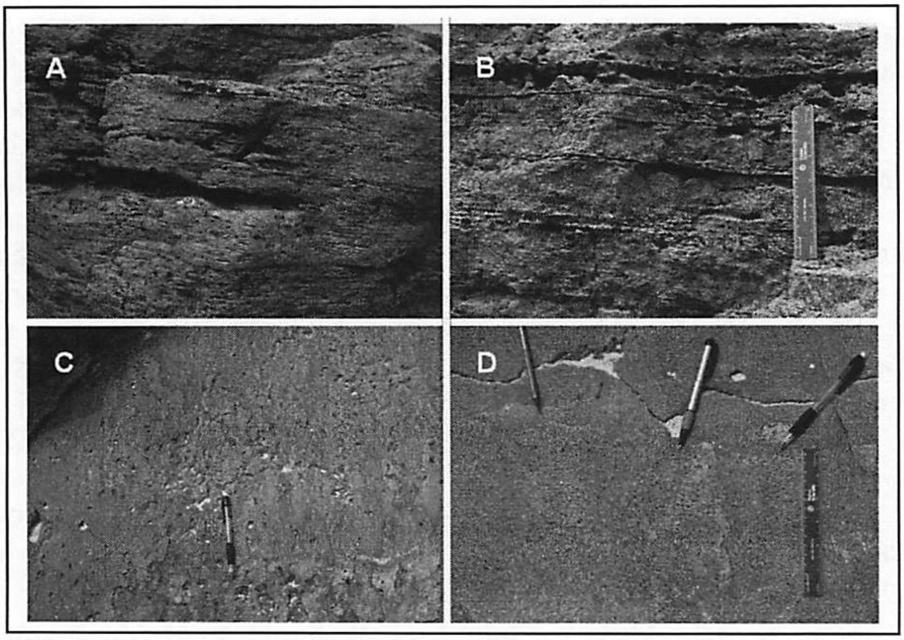

Figure 4. Sedimentary structures found within Hanna Bay limestones. A: Tabular or planar cross-laminated beds dipping shallowly seaward (toward right). B: Tabular cross-laminated beds with coarser basal laminae. C: Rill lineations seen on the upper surface of a tabular cross-stratified bed; pencil points in the down-dip, toward ocean, direction. D: Swash marks also found on upper surface of limestones. Pencils delineate the cuspate lobes and point in the down-dip, seaward direction; fenestrae can be seen only on the seaward side of the cusps.

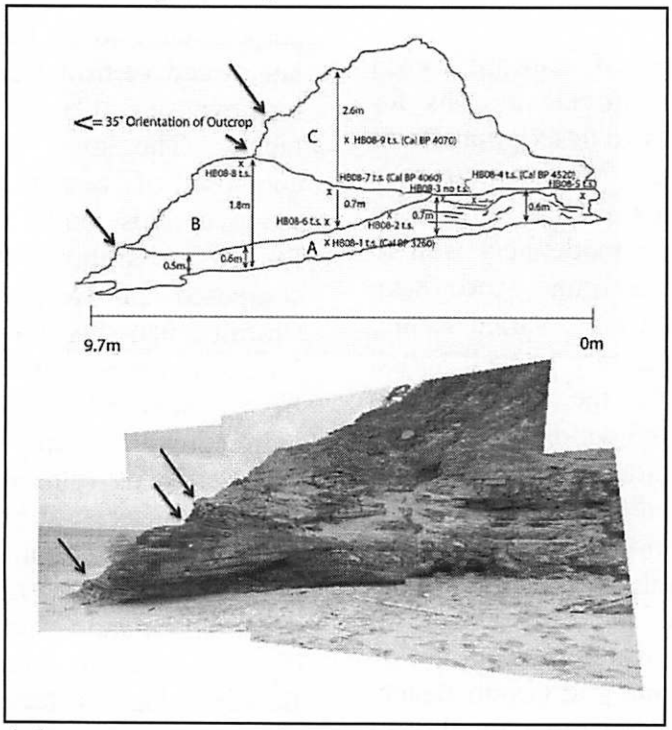

Figure 5. Photograph and diagrammatic overlay of an outcrop oriented perpendicular to the coast at Hanna Bay. Outcrop is 9.7 m long with an azimuth orientation of 35°. Bold arrows mark comparable spatial points for alignment of two images. Location of thin sections marked by an "X" and with a "t.s." designation; positions of the whole rock age-dated samples with their calibrate ages are noted.

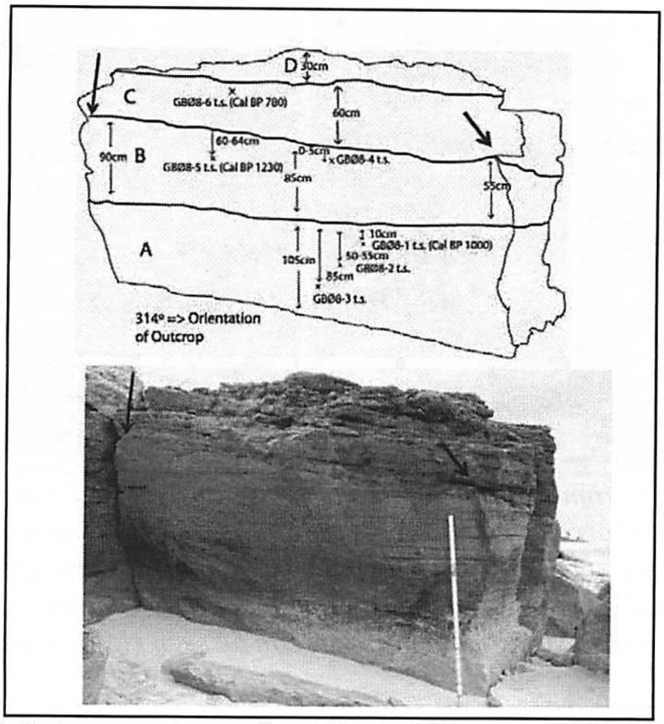

Figure 6. Photograph and diagrammatic overlay of an outcrop oriented perpendicular to the coast at Grotto Beach. Outcrop is approximately 4.5 m long with an azimuth orientation of 314°. Bold arrows mark comparable spatial points for alignment of two images. Location of thin sections marked by an "X" and with a "t.s." designation; positions of the whole rock age-dated samples with their calibrate ages are noted.

Figure 7. A second outcrop from Hanna Bay oriented perpendicular to the coast showing lateral facies relationships. Tabular cross-stratified beds transition to bidirectionally dipping beds in the left or landward direction.

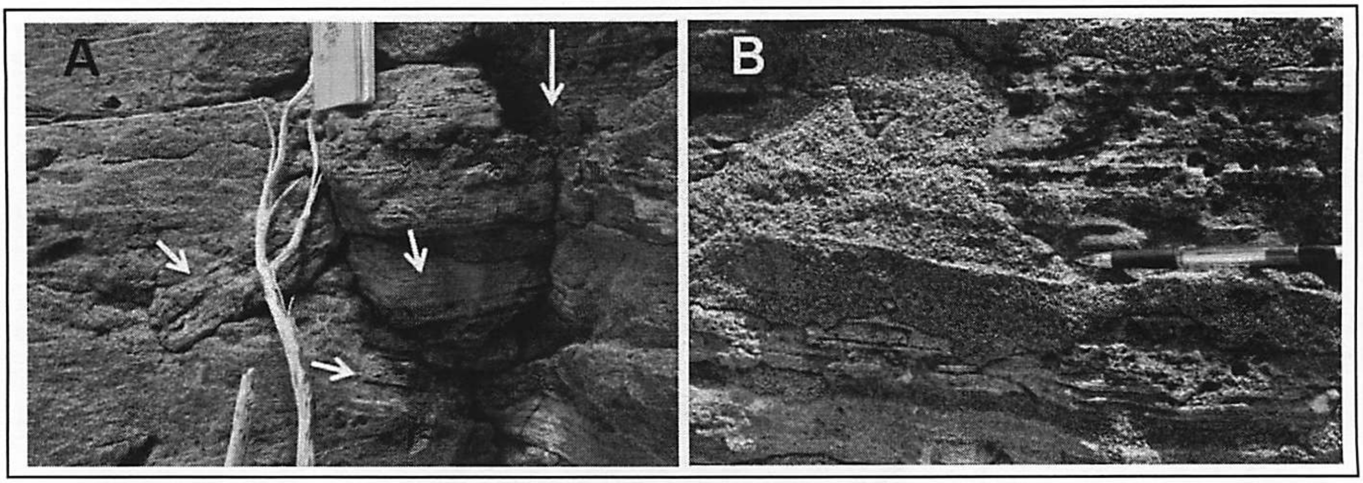

Figure 8. Outcrop photos from Grotto Beach. A: Outcrop oriented perpendicular to the coast with ocean toward the left. Short arrows point to breccia blocks. The long arrow marks the vertical fracture zone that runs parallel to the shore against which the breccia blocks are deposited. B: Outcrop oriented parallel to the coast; pencil denotes a coarse sand patina lightly cemented to the outcrop face; parallel laminations of the tabular cross-stratified limestones can be seen right of and below the patina.

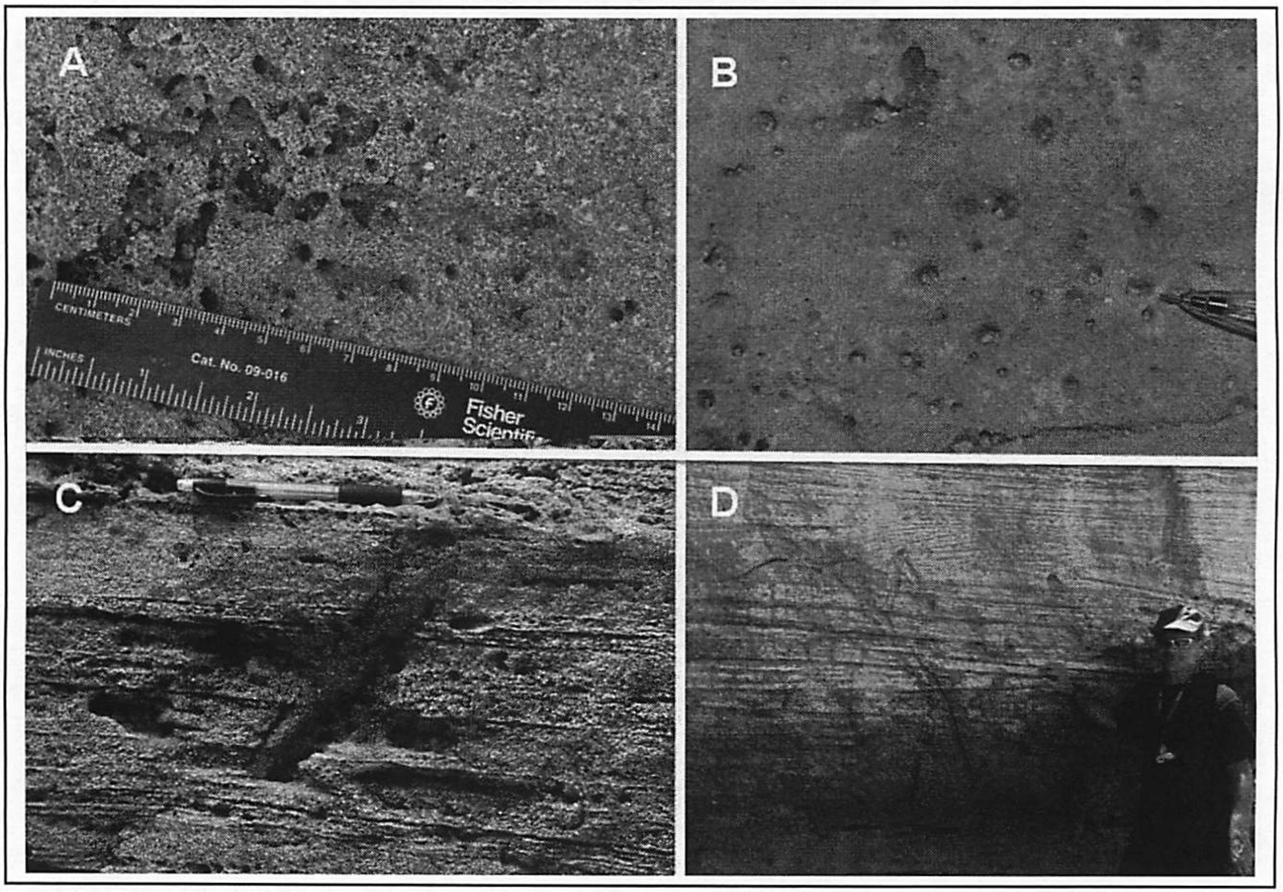

Figure 9. Trace fossils found within the tabular cross-stratified facies of the Hanna Bay Member. A & B: Bedding plane views of U-shaped burrows showing paired openings. C & D: Psilonichnus upsilon *burrows seen in cross section. C: Burrow penetrates the tabular cross-stratified limestone below pencil point, but is truncated by overlying bidirectional, trough cross-stratified facies above pencil. D: Y-shaped* Psilonichnus upsilon *burrows.*

transitions into steeply bidirectional-dipping trough cross-stratified beds. A third outcrop face, described only casually for this study, at Hanna Bay shows similar lateral facies relationships with tabular cross-stratified beds transitioning to bidirectional trough cross-stratified beds landward along the outcrop's strike (Figure 7).

At Grotto Beach other perpendicularly oriented outcrops exhibit brecciation, with blocks of tabular cross-stratified limestones misoriented and enveloped by carbonate sands of comparable grain size (Figure 8A). These brecciated zones are separated from the deeper portions of the outcrop by vertical fractures that run parallel to the beach. Finally outcrops parallel to the shore at Grotto Beach occasionally have coarse sand patinas cemented to the outcrop face. These drape the outcrop's graphic profile and thicken on exposed ledges; they are often shaped and positioned like small scale talus cones (Figure 8B).

Two ichnotaxa are found in the tabular cross-stratified facies. A burrow with paired openings on bedded surfaces occurs commonly (Figures 9A and 9B). This is presumably a U-shaped burrow, but the morphology in cross section has not been determined. The second trace fossil belongs to the ichnospecies *Psilonichnus upsilon*, manufactured by the ghost crab, *Ocypode quadrata* (Curran and White, 1991; Figures 9C and 9D). The former trace fossil has only been found in the tabular cross-stratified facies; *Psilonichnus upsilon*, however, occurs occasionally in the tabular cross-stratified facies, commonly in the trough cross-stratified facies, and rarely is found originating in the trough cross-stratified facies while penetrating the underlying tabular cross-stratified facies.

Vegemorphs are also present, commonly in the trough cross-stratified facies and rarely in the tabular cross-stratified facies. Two types of discrete vegemorphs of interest occur within the tabular cross-stratified facies at Grotto Beach. One resembles a root or rhizome that is inclined with respect to bedding with two shoots bifurcating from the main axis (Figure 10A). Only one specimen of this type has been observed. It is possible that this is not a vegemorph at all, but rather an unusual crab burrow. The second vegemorph (Figure 10B) has two occurrences at Grotto Beach and is also found at an undescribed Hanna Bay outcrop at Clear Beach on San Salvador. This vegemorph consists of a molded root or rhizome that runs parallel to bedding plane surfaces with numerous shoots issuing at right or near-right angles (Figure 10B). This form is also found within the bidirectional cross-stratified facies.

Petrographic study of the thin sections from Hanna Bay and Grotto Beach shows that intergrain cements most commonly have blocky isopachous or, less commonly, meniscus textures (Figures 11A and 11B). Limestones from the bidirectional trough cross-stratified facies uniformly have these intergrain cements, as do most of the limestones from the tabular cross-stratified facies. Those tabular cross-stratified limestones located close to current MSL (i.e., those exposed low in outcrop) do possess acicular aragonitic cements (Figure 11C). Intragrain pore spaces (within lumps or bioclasts) may contain acicular or blocky isopachous rim cements (Figure 11D).

The two stratigraphic sections yielded very different radiocarbon dates (Table 3). The section at Grotto Beach is younger with 3 calibrated dates ranging, from lower in the section to higher: 1000 yBP, 1230 yBP, and 780 yBP. The dates are disordered with the oldest date appearing at the middle height of the outcrop (see Figure 6 for stratigraphic positions). The section at Hanna Bay is considerably older, but also stratigraphically disordered with calibrated dates from lower in the section to higher: 3260 yBP, 4060 yBP, and 4070 yBP (see Figure 5 for outcrop locations). A fourth sample from the same stratigraphic height as the 4060 yBP-aged sample was dated from a lateral facies equivalent and yielded the much older date of 4520 yBP. These dates are generally consistent with those reported by Carew and Mylroie (1987), Hearty and Kindler (1993a), and Hearty and Kaufman (2009) for Hanna Bay Member rocks on San Salvador.

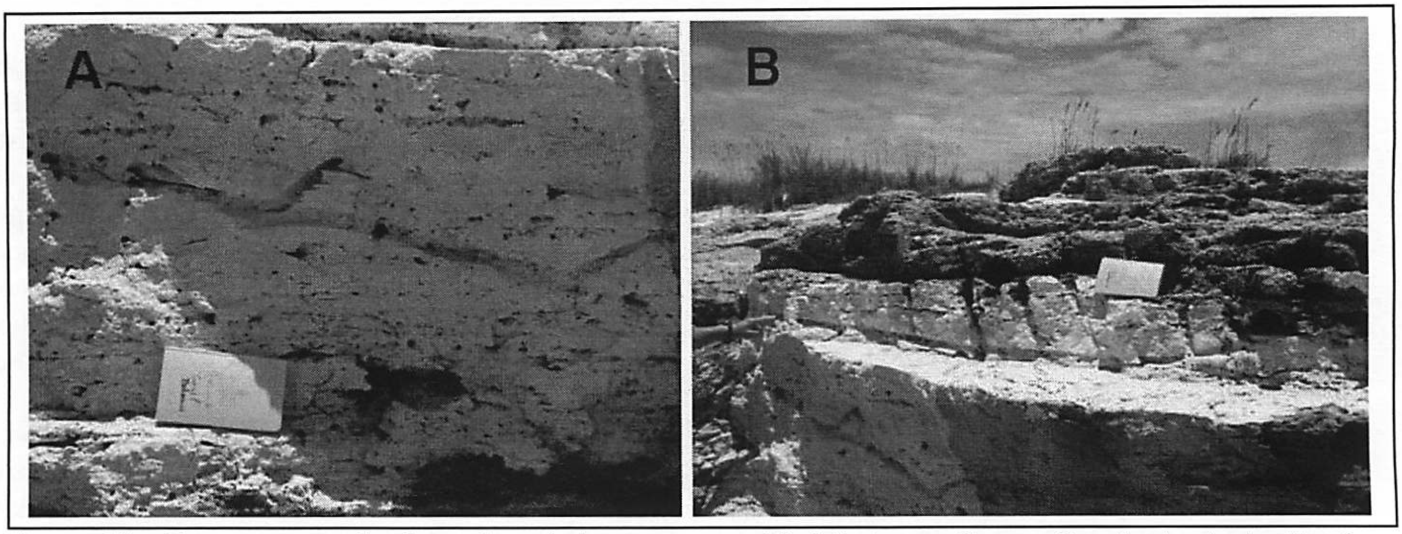

Figure 10. Two vegemorphs from the tabular cross-stratified facies at Grotto Beach. A: An inclined rhizome or root mold, only 2 shoots are shown, and the shoots emerge at a low angle. B: A similar rhizome or root mold following bedding with regularly spaced shoots oriented upward at a higher angle.

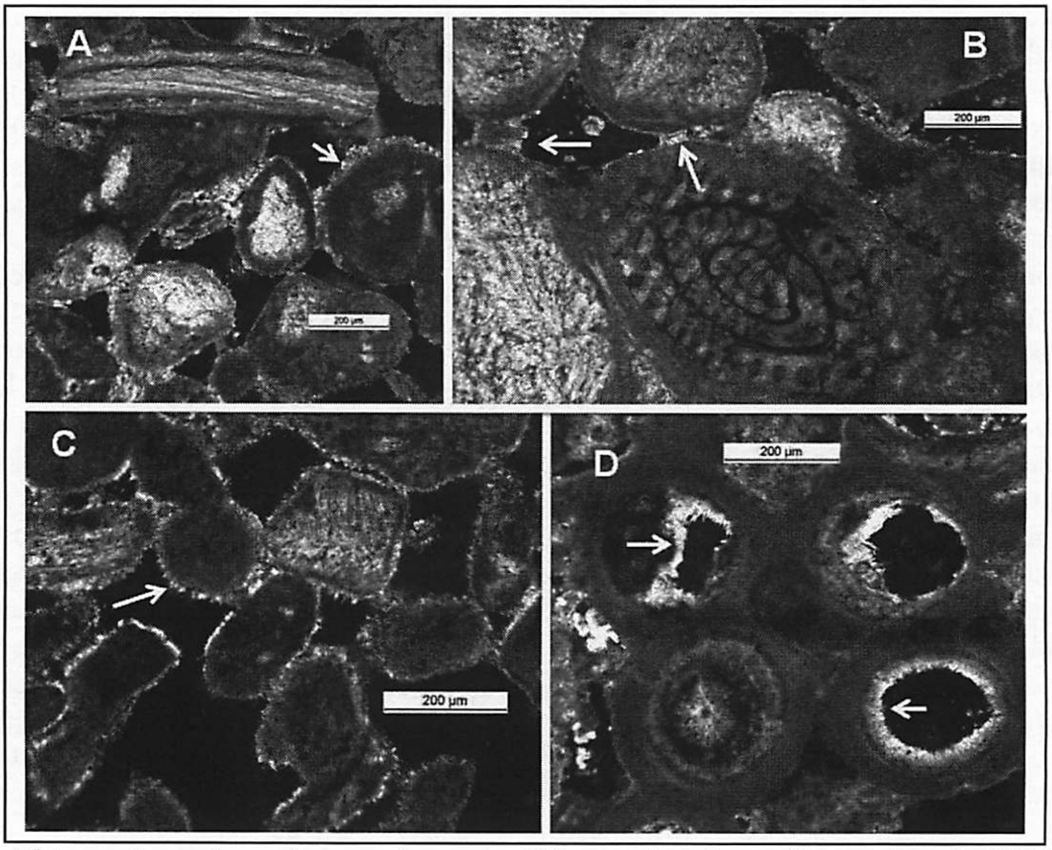

Figure 11. Thin-section photomicrographs. A: Thin section from Grotto Beach (GB08-8) with isopachous blocky cements. B: Same thin section (GB08-8) with meniscus cements. C: Thin section from very low in the outcrop at Hanna Bay (HB08-1), low enough to be affected by marine conditions during normal high tides. Acicular rim cements cover grains. D: Lump from a limestone at Grotto Beach (GB08-5) exhibiting acicular cements within intragrain pores.

Table 3. Standard counting radiocarbon age dates for 7 whole-rock samples of Hanna Bay limestones from Grotto Beach (GB) and Hanna Bay (HB). Conventional ages, intercept calibrated ages, and 1 sigma calibrated age ranges are reported, all in years before present (where "present" = AD 1950). Locations of the samples from the outcrops are shown on Figures 5 and 6.

Sample No.	Conventional Age	Intercept Calibrated Age	1 Sigma Calibrated Range
GB08-1	1450 +/- 50 BP	Cal BP 1000	Cal BP 1050 – 940
GB08-5	1640 +/- 50 BP	Cal BP 1230	Cal BP 1260 – 1170
GB08-6	1240 +/- 50 BP	Cal BP 780	Cal BP 870 – 730
HB08-1	3380 +/- 80 BP	Cal BP 3260	Cal BP 3350 – 3160
HB08-4	4380 +/- 60 BP	Cal BP 4520	Cal BP 4620 – 4440
HB08-7	4020 +/- 60 BP	Cal BP 4060	Cal BP 4140 – 3960
HB08-9	4030 +/- 50 BP	Cal BP 4070	Cal BP 4140 – 3980

DISCUSSION

The first hypothesis considered by this study – a foreshore origin for portions of the Hanna Bay Member – is well supported. Of the two facies described from the Grotto Beach and Hanna Bay outcrops (1: the shallowly dipping, tabular cross-stratified limestones; and 2: the bidirectional, steeply dipping trough cross-stratified limestones), the first exhibits numerous features consistent with a foreshore origin. It is these limestones, found basally within Hanna Bay Member outcrops up to 2 meters above modern MSL, that are potential indicators of middle to late Holocene sea-level eustatic highstands. The second facies, the bidirectional trough cross-stratified limestones, possesses features consistent with eolian transport and deposition within a backshore, foredune, to dune environmental setting, the environment immediately shoreward of the foreshore. These are the more typical rocks of the Hanna Bay Member that have received most attention in the literature. Their paleoenvironmental interpretation is well established (Carew and Mylroie, 1985, 1987, 1989, 1995; Hearty and Kindler, 1993a).

The sedimentology of the tabular cross-stratified limestone facies is consistent with a foreshore origin. Lumps are the most common allochem in both San Salvador's modern leeward foreshore deposits and these limestones. Lumps viewed in thin section show multiple generations of cementation, indicative of shallow-marine agitation and reworking. Bioclasts are the second most common allochems in both modern sediments and within the limestones. Extremely productive sea-grass beds, patch reefs, and barrier reefs are just offshore of the modern foreshore and presumably were also in the recent past; these environments are great producers of carbonate skeletal grains. Peloids are common in the thin-section point counts, but less obvious within populations of modern beach grains. Peloids within the limestones, however, may be misidentified and be micritized allochems of other origins.

The average grain size and sorting values of both the modern foreshore sands and limestones from the tabular cross-stratified facies are comparable, though the limestone sizes are on average slightly larger and the distributions have greater variance. Nonetheless, the limestones do not exceed in mean size or variance the distributions seen among modern foreshores. Interestingly the grain sizes of the modern eroded berm sands are among the coarsest, representing higher energy beach conditions that may have also resulted in the deposition of the tabular cross-stratified limestones.

The sedimentary structures found within this facies are also indicative of a foreshore environment. Beds dip shallowly in a seaward direction with similar magnitude and direction seen among San Salvador's modern foreshore sands. Foreshore sediments are deposited as thin planar sheets that follow the sloping contour of the beach. Through time the foreshore's slope shifts, changing the dip angle of the deposits while generating shallowly dipping angular unconformities between adjacent beds. Rill lineations and swash marks are characteristic of foreshores. Wave run-up leaves shallow cuspate ridges of sand at the wave's upslope terminus; and swash return can create down-dip rill lineations on the sediment surface. Both of these features have poor preservation potential; subsequent waves quickly destroy features produced by previous waves. Consequently, the preservation of these structures should be unusual and rarely noted.

Fenestrae are generated when air trapped within the sand's intergrain porosity by wave run-up escapes. The bubbles formed in the swash create the small circular holes within the foreshore surface (Dunham, 1970; Kindler and Hearty, 2000; but also see: Bain and Kindler, 1994). Fenestrae form most commonly in a 5-10 cm wide band just seaward of a wave's swash line. In the few occurrences of preserved swash lines within the Hanna Bay tabular cross-stratified facies, fenestrae are found just down dip of the swash lines (Figure 4D). Fenestral fabric can be pervasive within this facies and cover expanses of bedding plane surfaces without the preservation of swash lines.

The vertical and lateral facies relationships of the two facies further support a foreshore interpretation of the tabular cross-stratified limestones. When outcrops perpendicular to the shoreline are of great enough length, the tabular cross beds transition into trough cross-stratified limestones. In a few cases, the transition to dune forms can be seen (Figures 5 and 7). Vertically the trough cross-stratified limestone facies progrades over the tabular cross-stratified facies. The contact between foreshore and eolian sands shifts downward as one moves seaward across the perpendicularly oriented outcrops. This regressive nature of the Hanna Bay dune facies has been widely recognized in the past (Carew and Mylroie, 1995).

The paleontological data from the tabular cross-stratified limestones are contradictory. U-shaped burrows are diagnostic of shallow subtidal to intertidal ichnofacies (Seilacher, 1967; Curran and White, 1991; Nesbitt and Campbell, 2006). The remaining trace fossils and vegemorphs, however, are indicative of a subaerial environment. The ghost crab *Ocypode quadrata*, making *Psilonichnus upsilon* burrows, requires air- and not water-filled cavities for survival (Allen and Curran, 1974), though the crab does occasionally moisten its gills with salt water (Curran and White, 1987). These burrows must be within a vadose zone when created and occupied by the crabs; ghost crab burrows are principally formed today in backshore to foredune settings (Allen and Curran, 1974) and are constituents of a dunal ichnocoenosis (Frey and Pemberton, 1987; Curran and White, 2001; Nesbitt and Campbell, 2006). Modern ghost crabs have been noted in the upper foreshore and prefer backshore settings over dunes when the latter are heavily vegetated (Curran and White, 1987). Nonetheless, their propensity of occurrence in the modern is above the active foreshore. Finally, the very existence of vegemorphs also demands a subaerial paleoenvironmental interpretation. (Mangrove species could produce vegemorphs in intertidal settings, but the sedimentology and sedimentary structures are consistent with an open coast, fully marine setting where mangrove species are highly unlikely to occur.)

The cement petrography also provides contradictory evidence for a foreshore interpretation. The intergrain cements that occur within the tabular cross-stratified facies are indicative of a freshwater vadose to phreatic existence – grain contact and meniscus cements are most common, followed by blocky isopachous cements. Sands deposited within a foreshore environment are intermittently wetted with marine water; the foreshore alternates between a marine phreatic and a vadose zone at different portions of the tidal cycle. Nonetheless, the marine phreatic conditions typically persist long enough to generate the precipitation of acicular aragonitic rim cements. This can lead to quick cementation and the formation of beach rock within a foreshore setting (Gischler and Lomando, 1997). Isopachous acicular cements binding allochems within the tabular cross-stratified limestones are essentially absent, except within the lowest reaches of the outcrops. These lowest reaches currently sit within the intertidal zone and are therefore intermittently wetted with seawater; the acicular cements are therefore expected. A similar phenomenon has been described for North Point Member eolian limestones from San Salvador. Here dune sands located within influence of modern sea level are cemented by acicular isopachous aragonite (White, 1995). Interestingly no beachrock has been observed in the Hanna Bay Member above current MSL. Kindler and Bain (1993) described 965 yBP beachrock at French Bay, San Salvador, at 1 m below the modern low tide; these rocks were interpreted as forming supra- to intertidally, suggesting a short-term, high frequency sea-level lowstand. Acicular rim cements do occur occasionally within intragrain pores from the tabular cross-stratified facies. Regardless of where these allochems were ultimately deposited and cemented, the allochems originated subtidally and therefore had ample opportunity to acquire marine cements before final deposition. Lumps, the allochem type most commonly observed with acicular intragrain cements, are products of multi-generational marine cementation; acicular cements among a lump's constituent grains are predicted.

Finally, the geochronologic data are problematic, because they suggest the foreshores represented by the tabular cross-stratified limestones at Grotto Beach and Hanna Bay are of different ages, with Grotto Beach occurring approximately 1000 yBP and Hanna Bay occurring approximately 4000 yBP. The stratigraphic disordering seen at both localities can be explained by the problems associated with whole rock radiocarbon dating. Each sample represents the average of dates of origin of each allochem and cement crystal contained within the limestone. Allochems formed at some time before deposition, with some allochems having been reworked over great lengths of time; and cements can form soon after time of deposition or much later. Though the dates are unreliable, the difference in magnitude between the Grotto Beach and Hanna Bay sets indicates the two foreshores are not isochronous. They must represent two events.

How can these counter indications – sedimentologic and stratigraphic evidence supporting a foreshore interpretation and paleontologic and diagenetic evidence supporting a higher-than-foreshore position on the beach – be parsimoniously rectified? The explanation requires falsification of the second hypothesis – the foreshore setting did not persist long enough to represent a eustatic phenomenon and was ephemeral and short-lived. The contradictory paleontologic and diagenetic evidence suggests the foreshore environment was quickly displaced to a higher beach setting soon after deposition. Though deposited by foreshore processes, the sediments' higher-than-mean sea level depositional height was within the normal position of the backshore and foredune. After the short-lived sea-level high receded, the foreshore sands were then exploited by backshore and foredune burrowers and beach vegetation. Over longer time periods, the sands were cemented in a freshwater vadose or phreatic diagenetic environment. Subsequent extreme high tides, after some lithification, would erode these older heightened foreshore limestones into shallow cliffs. This would explain the lithified breccia observed along the base of some Hanna Bay Member outcrops (Figure 8A). The patina of coarser sands cemented onto the tabular cross-stratified limestones represents sands left behind by a subsequent extreme high tide (Figure 8B); here, however, the majority of the foreshore sands were eroded before having a chance to lithify.

The specific mechanism generating ephemeral sea-level highs is not clear, but a variety of oceanographic phenomena could be responsible. Extreme high tides can be generated during storms or during spring-tide intervals.

Spring tides during times of lunar perigee (i.e., perigean spring tides) can generate extreme high tides for a number of consecutive days without the associated high-wave energies of a storm (Wood, 2001). Finally larger-scale oceanographic circulation perturbations can generate higher-than-normal high tides for durations of months rather than days. Shifts in the Florida Current or within the North Atlantic Oscillation can generate bulges in the geoid over portions of the western Atlantic Ocean. For example, a shift in the Florida Current during the summer of 2009 generated extreme high tides along the Middle Atlantic Coast of the United States (Sweet et al., 2009).

This phenomenon of a heightened foreshore is common. In fact, while conducting fieldwork for this study recent relict foreshore sediments sitting as much as 1.5 m above MSL were observed. The eroded berm sands sampled at Grotto Beach are one example. Figure 12A shows these sands juxtaposed against Pleistocene limestones. We recently discovered a similar situation while conducting fieldwork on Little Exuma Island; here heightened modern foreshore sands were plastered against foreshore tabular cross-stratified limestones of the Hanna Bay Member (Figure 12B).

Foreshore sediments have extremely low preservation potential. Subsequent tidal cycles rework previously deposited sands. Heightened foreshore sands, however, have a greater chance of persisting until lithification simply because they are deposited well-above the height of normal tide and wave action. And because of their relative youth as middle to upper Holocene deposits, they have yet to be eroded by eustatic sea-level rise. Consequently, this facies should be relatively common across the Bahamas. We would predict that if these tabular cross-stratified limestones could be accurately dated wherever they occur, the dates obtained would be diachronous – each outcrop could very well represent a different ephemeral high tide during the 5000 years of the middle to late Holocene. This potentially explains the very different radiocarbon dates obtained for the Grotto Beach and Hanna Bay outcrops.

Ultimately the Hanna Bay Member heightened foreshore sediments do not support the hypothesis of one or more sea-level highstands of the middle to late Holocene. Though the evidence for a foreshore interpretation is compelling, a case cannot be made for a foreshore of long-enough duration to support a eustatic rise in sea level's position due to some paleoclimatic change. Their geologic origin can be explained by simpler causal mechanisms – ephemeral high tides driven by normal oceanographic variation. This does not

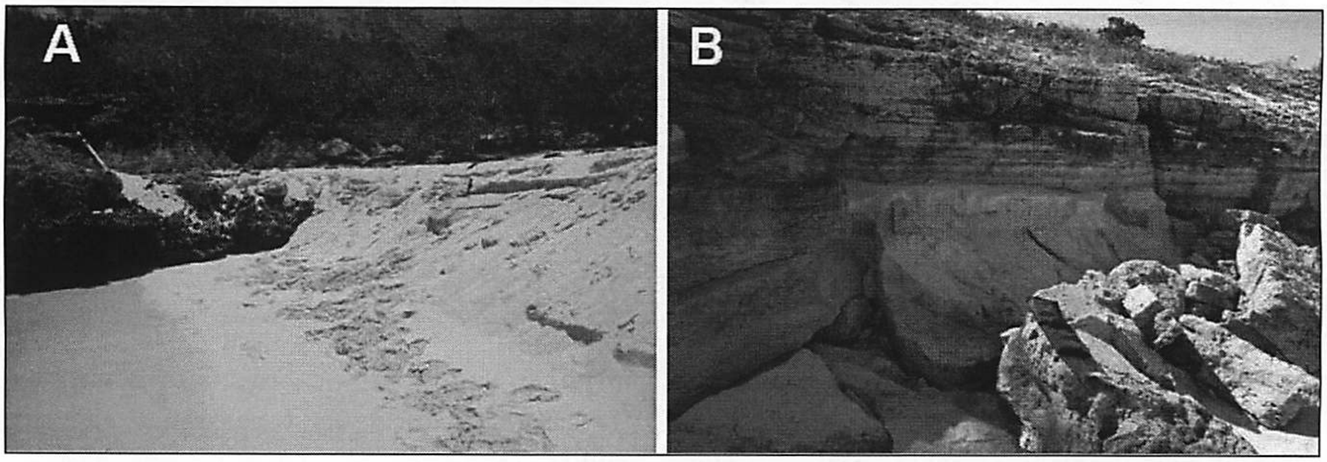

Figure 12. Modern foreshore sands deposited by extreme high tides at different locations. A: Grotto Beach; sands deposited ~ 1.5 m above the current tide height; deposited up against Pleistocene limestones. B: Cut Beach on the windward, eastern shore of Little Exuma Island; modern, extreme high- tide foreshore sands deposited ~1 m above current tide and against tabular cross-stratified limestones of the Hanna Bay Member

mean that middle to late Holocene sea-level highstands or high-frequency, short duration fluctuations did not exist, merely that these limestones do not support their existence. A more compelling case supporting one or more eustatic highstands could be made if Hanna Bay foreshore deposits exhibited consistent ages and stratigraphic heights across the Bahamian platforms. This is something we hope to further test with subsequent work in Eleuthera and the Exumas. Unfortunately accurate absolute dating is problematic with these sediments and fossils, however, with enough dates the problem may be surmountable statistically.

Finally, these results do demonstrate the importance of selecting an appropriate eustatic sea-level indicator when producing sea-level curves. Foreshore deposits are problematic. Sedimentologic features formed at or close to sea level that require longer intervals of time to generate (e.g., coral reefs, mangrove peats, phreatic caves) are less suspect.

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