PROCEEDINGS OF THE 16th SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
Bosiljka Glumac and Michael Savarese

Gerace Research Centre
San Salvador, Bahamas

2016

Cover photo: San Salvador coastline photo by Erin Rothfus.

Press: A & A Printing

ISBN 978-0-935909-15-9

ORIGIN OF LATE HOLOCENE STRANDPLAINS IN THE SOUTHERN EXUMA ISLANDS, BAHAMAS: PROGRADATION, EPHEMERAL HIGHSTANDS, AND STORMINESS

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ABSTRACT. Hanna Bay Member limestones, belonging to the Rice Bay Formation, are extensively distributed around the periphery of the southern Exuma Islands, including Little Exuma and Great Exuma, and provide a record of late Holocene carbonate deposition and sea-level effects on development and spatial distribution of coastal environments. Three lithofacies occur here, as elsewhere in the Bahamas, and represent foreshore, backshore, and dune environments. Progradational beach-ridge strandplains, composed of eolian rather than wave-formed ridges, are common and are particularly well developed throughout the region. These ridges were lithified rapidly by freshwater vadose cementation, which increases their preservational potential. Dune forms are remarkably well preserved and exposed, and exhibit original lee and stoss surfaces, physical sedimentary structures, and vegetative and faunal trace fossils. Though these ridges were formed as low amplitude parabolic dunes, they have catenary or zetaform shapes, mimicking the geomorphology of the active coast. This suggests that the ridges originated through wave action, but were later enlarged by eolian deposition.

Foreshore and backshore deposits sit either stratigraphically below or outboard and laterally adjacent to eolian sands, indicating that dune facies often prograded over beach deposits, in at least some instances, or that beach deposits were involved in strandplain ridge formation. Outcrops commonly exhibit multiple phases of foreshore deposition and erosion. Within strandplains at Moriah Harbour Cay and at Casuarina Beach on Great Exuma, wide limestone pavements exist between adjacent dune ridges and are interpreted as preserved backshores. The landward edge of the former backshore at Casuarina Beach is 195 m behind the back of the current backshore and sits 139 cm above the modern backshore. At Moriah Harbour Cay, the old backshore sits 95 m landward, and the backshore pavement is at the same elevation as the modern high tide line. The former may represent a temporally significant sea-level highstand, while the latter is consistent with modern mean sea level. Cross-cutting relationships of dune ridge sets indicate periods of erosion and set-back punctuating times of progradation. The unconformable contacts separating ridge sets may exhibit beach erosional features including paleo-cliff faces and boulder breccias. Trace fossils are prolific in dune and backshore/upper foreshore facies as exposed at Moriah Harbour Cay and Cut House Beach. *Psilonichus upsilon*, the distinctive burrow made by the ghost crab *Ocypode quadrata*, is common in beds of the beach facies, including specimens formed by juveniles. Insect burrows, particularly stellate burrows, previously attributed to the activity of halictid bees, are distinctive, large, and commonly dense in beds of the dune facies. Foreshore limestones occur at elevations up to 2 meters above modern mean sea level. Elevated intertidal deposits of this height have been cited elsewhere in the Bahamas as evidence for one or more late Holocene sea-level highstands. However, similar to the foreshore facies of Hanna Bay limestones on San Salvador and Eleuthera, sedimentologic, petrographic, and fossil evidence is more consistent with an ephemeral, non-eustatic sea-level high caused by localized coastal phenomena. The radiocarbon ages obtained for foreshore limestones and for eolian limestones on the strandplains date reasonably consistently within the Medieval Warm Period, between 1200 and 700 years BP.

We propose that the foreshore deposits represent local, ephemeral "highstands" generated during tropical storms, but under constructional, rather than erosive wave conditions. These deposits were later eroded to form backshore scarps with catenary or zetaform shapes. Those scarps served as obstructions for

wind-transported sands, resulting in the formation of foredunes. Repetition of this process created the multiple ridges of the strandplain. The Medieval Warm Period predisposed the region to strandplain development by imposing a warm and arid climate during a time of increased regional storminess.

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INTRODUCTION

The last 3000 years of the late Holocene has been a time of coastal progradation and estuary formation worldwide, a consequence of modest rates of sea-level rise coupled with offsetting rates of sedimentation (Davis and Fitzgerald, 2004). Coastal progradation can significantly enlarge subaerial land mass, creating new habitat for natural and human development. In cases where progradational areas are separated from the mainland, back-barrier environments form, promoting the retention of freshwater and leading to development of estuarine habitats. In other situations, like throughout the Bahamas, progradational dunes can generate dune-swale lakes behind the seaward-growing coastline.

The gross geomorphology of the Bahamas confirms that extensive progradation occurred during the late Holocene, a time of relatively slow sea-level rise (Boardman et al., 1989). This history is encoded within the litho- and chronostratigraphy of the Hanna Bay Member of the Rice Bay Formation (stratigraphy of Carew and Mylroie, 1995). Nonetheless, the details of this environmental history and the specific effects of sea-level rise and progradational sedimentation have remained largely unresolved and elusive.

Late Holocene history of Bahamian coastal development also has implications for predicting future effects of sea-level rise. The rate of sea-level rise has accelerated since the beginning of industrialization in the middle 19th Century and is predicted to accelerate further as a consequence of global climate change (IPCC, 2007). This will certainly affect the disposition of coastal geomorphology and ecology throughout the Bahamas Archipelago. Our hope is that this research will provide insights as to how these island coasts will respond in the future.

Elsewhere around the globe, investigators have made compelling cases for one or more late Holocene sea-level highstands, regional sea-level positions sitting higher than at present. Examples include: Gulf Coast, USA (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 (Baker and Haworth, 1997; Twiggs and Collins, 2010), Tunisia (Jedoui et al., 1998), Hawaii (Calhoun and Fletcher, 1996; Fletcher and Jones, 1996), equatorial Pacific (Grossman et al., 1998), and South China (Davis et al., 2000). Although the evidence for at least several of these regional sea-level highstands is controversial, the possibility of occurrence of short-lived, eustatic highstands in the late Holocene has significant relevance for the potential of abrupt and catastrophic changes in sea level as the planet continues to warm. The existence of a foreshore facies within the Hanna Bay Member in the Bahamas residing 0-2 meters above modern mean sea level suggests there may be validity to the eustatic highstand hypothesis, though previous work published on this facies from San Salvador demonstrates otherwise (Savarese and Hoeflein, 2012).

Savarese and Hoeflein (2012) considered the environmental history of the Hanna Bay Member on the island of San Salvador and dismissed evidence of a eustatic highstand based on the pre-lithification overprinting of dune and backshore sedimentary features within foreshore sediments, but without considering the history of strandplain development. Hanna Bay progradational coastal strandplains are prolific elsewhere in the Bahamas, including San Salvador, but they are particularly well developed in the Exuma Islands (Figure 1A). This research considers the late Holocene history of the southern Exuma Islands and integrates this with earlier observations from San Salvador and Eleuthera. Two questions are addressed: (1) How are the Hanna Bay foreshore, backshore, and dune lithofacies inter-related, and do they have significance relative to sea-level positioning? (2) Progradational strandplains appear to be prolific throughout the Bahamas. How and when were they formed, and do they provide insights for sea-level rise as a driving mechanism?

HANNA BAY MEMBER STRATIGRAPHY

Limestones from the late Holocene Hanna Bay Member represent a progradational package deposited during time of decelerated sea-level rise (Boardman et al., 1989; Carew and Mylroie 1995, 1997, 2001; Mylroie, 2008). The type section is located along the shores of Hanna Bay on San Salvador Island, though the rocks are found prolifically throughout the Bahamas. Descriptions of the lithostratigraphic unit exist for other islands (e.g., Hearty and Kindler, 1993b; Kindler, 1995; Kindler and Hearty, 1996). Published accounts of Holocene geology of the Exuma Islands are limited to Mitchell (1984), Kindler (1995), Kindler and Hearty (1997), and Jackson et al. (2012). Hanna Bay Member beds are younger in age than those of the North Point Member, though a stratigraphic contact between these two members of the Rice Bay Formation has not been reported from all islands. The contact has been observed on Lee Stocking Island (Kindler, 1992, 1995), Long Island (Curran et al., 2004), Cat Island (Mylroie et al., 2006; Glumac et al., 2011 and this volume), and on Little Exuma (Savarese, unpublished data). Hanna Bay limestones also commonly rest unconformably on top of the Pleistocene Grotto Beach Formation.

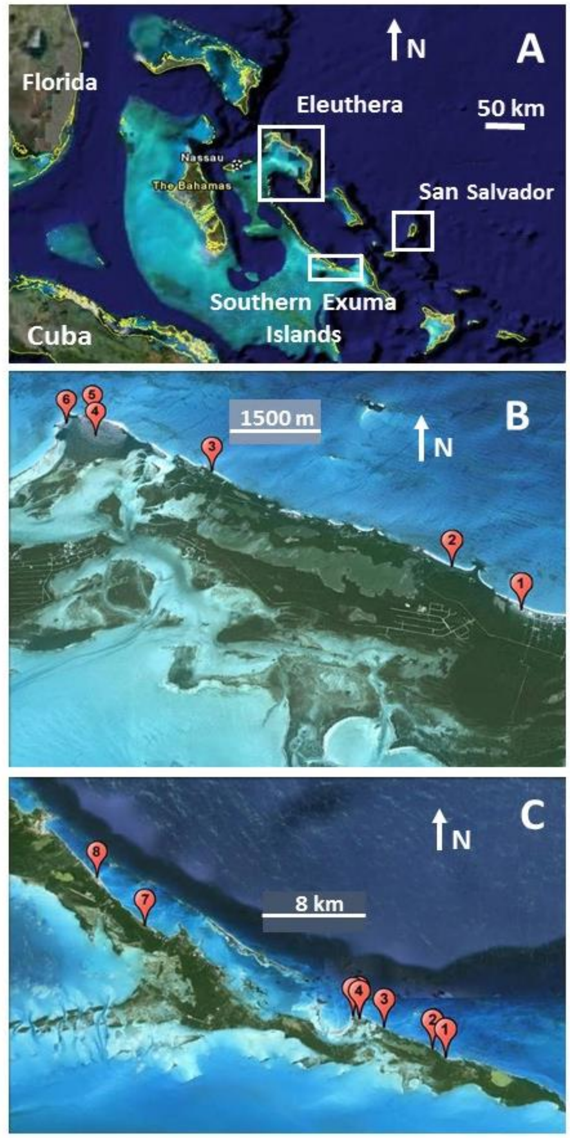

Figure 1. Maps showing field localities. A: Location of the Southern Exuma Islands, Eleuthera, and San Salvador within the Bahama Archipelago. B & C: The principal localities examined in this study on Little Exuma (1-3), Moriah Harbour Cay (4-6), and Great Exuma (7-8). Names and GPS coordinates for each locality are detailed in Table 1. Images taken and modified from Google Earth.

The most common facies represented in the Hanna Bay Member is an eolianite, deposited within dune or within wind- and wave-influenced backshore environments. Rocks representing foreshore environments do occur, but are

Number	Locality Name	Island	Latitude	Longitude
1	Moore Hill Strandplain	Little Exuma	23°26'25.86"N	75°36'18.12"W
2	Trio Isle Beach	Little Exuma	23°26'48.56"N	75°36'50.66"W
3	Cuthouse Beach	Little Exuma	23°27'42.26"N	75°38'53.40"W
4	Moriah Harbour Strandplain	Little Exuma	23°28'3.84"N	75°39'56.88"W
5	Moriah Harbour Beach	Little Exuma	23°28'14.30"N	75°39'59.77"W
6	West Moriah Harbour Strandplain	Little Exuma	23°28'11.34"N	75°40'13.55"W
7	Casuarina Strandplain	Great Exuma	23°32'15.97"N	75°49'39.70"W
8	Iva Bowe Strandplain	Great Exuma	23°34'37.89"N	75°52'6.66"W
---	Clear Pond Beach	San Salvador	23°58'20.10"N	74°32'54.30"W

Table 1. Field localities cited in this study. Sites 1-8 are located on the southern Exuma Islands and their geographic positions are noted on Figure 1. Clear Pond Beach is on San Salvador Island and is not figured in the text.

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 the section (Strasser and Davaud, 1986).

METHODS

Field work for this study was conducted in the southern Exuma Islands, specifically Great Exuma, Little Exuma, and Stocking Islands. Approximately 90 localities were visited in June and July, 2011; subsequent work was conducted in January 2013 (Figure 1B,C; Table 1). Of the 3 islands, exposures from Little Exuma are most numerous and informative. When appropriate, field data from previous work on Eleuthera and San Salvador are integrated. The geochronologic data presented are from all islands studied.

Outcrops were described using standard practices of stratigraphy and sedimentology. Lithofacies were differentiated based upon sedimentologic characteristics, the presence of diagnostic physical sedimentary structures, and trace fossils. In general, trace fossils in Bahamian rocks manifest best in vertical section, such as found along erosive reaches of rocky coast. The two prime Hanna Bay Member sites used in this study for examination of trace fossils were the cliffs of Moriah Harbour Cay and Cut House Beach on Little Exuma (Figure 1C).

The facies described from each locality were lithologically sampled for later petrographic study. In order to best infer lateral facies relationships, exposures of Hanna Bay Limestone oriented perpendicular to the modern shoreline were identified, described, and photographed. Thin sections were described using a Nikon Labophot-2 petrographic microscope. Cement textures were described petrographically to infer diagenetic history.

Whole-rock radiocarbon dates were

Sample #	Locality Name	Latitude	Longitude	Conventional Radiocarbon Age	Calibrated Intercept Age	1 Sigma Calibrated Range (68%)	2 Sigma Calibrated Range (95%)
0711-55	Moriah Harbour Dune Ridge 1, Little Exuma	23°27'52.07"N	75°39'54.87"W	1320 +/- 30 BP	Cal BP 700	Cal BP 790-640	Cal BP 910-540
0711-54	Moriah Harbour Dune Ridge 2, Little Exuma	23°27'56.60"N	75°39'55.70"W	1210 +/- 30 BP	Cal BP 630	Cal BP 670-550	Cal BP 720-510
0711-53	Moriah Harbour Dune Ridge 3.4, Little Exuma	23°28'2.90"N	75°40'2.00"W	1230 +/- 30 BP	Cal BP 640	Cal BP 680-600	Cal BP 750-520
0711-52	Moriah Harbour Dune Ridge 4.3, Little Exuma	23°28'7.40"N	75°40'3.10"W	1380 +/- 30 BP	Cal BP 760	Cal BP 890-670	Cal BP 960-620
0711-56	Moriah Harbour Dune Ridge 5, Little Exuma	23°28'4.70"N	75°39'48.70"W	2350 +/- 30 BP	Cal BP 1800	Cal BP 1870-1700	Cal BP 1950-1620
0711-44	Casuarina Strandplain, Great Exuma	23°32'16.10"N	75°49'39.70"W	1410 +/- 30 BP	Cal BP 780	Cal BP 890-720	Cal BP 930-660
0711-60	Moore Hill Strandplain, Little Exuma	23°26'12.20"N	75°35'52.10"W	2380 +/- 30 BP	Cal BP 1830	Cal BP 1900-1750	Cal BP 1980-1680
0711-64	Iva Bowe Eroded Dune Ridge, Great Exuma	23°34'34.90"N	75°52'0.10"W	1220 +/- 30 BP	Cal BP 640	Cal BP 670-590	Cal BP 730-520
0711-63	Iva Bowe Foreshore, Great Exuma	23°34'43.40"N	75°52'9.20"W	1340 +/- 30 BP	Cal BP 720	Cal BP 780-660	Cal BP 890-630
0611-34	Cuthouse Beach Foreshore, Little Exuma	23°27'42.30"N	75°38'53.40"W	1600 +/- 30 BP	Cal BP 970	Cal BP 1060-920	Cal BP 1160-870
0611-37	Cuthouse Beach Foreshore, Little Exuma	23°27'41.00"N	75°38'51.80"W	1720 +/- 30 BP	Cal BP 1130	Cal BP 1210-1040	Cal BP 1260-960
0611-24	Oasis Cove Foreshore, Little Exuma	23°27'59.20"N	75°39'29.90"W	1440 +/- 30 BP	Cal BP 830	Cal BP 910-750	Cal BP 960-680
0611-17	La Shante Beach West Foreshore, Little Exuma	23°26'17.09"N	75°35'8.19"W	3620 +/- 30 BP	Cal BP 3350	Cal BP 3420-3290	Cal BP 3500-3190

Table 2. Whole rock radiocarbon dates for Hanna Bay Member limestones analyzed and calibrated by Beta Analytic (URL: http://www.radiocarbon.com/).

obtained for 14 samples from the southern Exuma Islands; these were combined with 3 dates from San Salvador and 1 date from Eleuthera (Table 2). Of these 18 dates, 10 are from foreshore limestones and 8 from dune facies. Clean rock was exposed at the outcrop and then sampled; if any weathered surfaces remained, they were trimmed away. Samples were shipped to Beta Analytic for standard counting radiocarbon analysis and calibration. Details of their pretreatment and analysis are available online (URL in Table 2). 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.

FACIES DESCRIPTIONS AND PALEOENVIRONMENTAL INTERPRETATIONS

Foreshore Facies

This facies sits most commonly from 0 – 2 meters above current mean sea level, though slightly higher elevations are possible (Figure 2). The limestones are composed of medium- to coarse-grained carbonate sands, with fine sands less common, and deposited as laminations or as thin to thick beds. Allochems are dominated by lumps, then bioclasts, with lesser amounts of peloids and ooids (Figure 3A,B). Grains are typically micritized, commonly extensively; ooid-coated rims can occur. Gravel-sized shell fragments are present in discrete laminations. These are most commonly mollusks, though whole valves occur rarely.

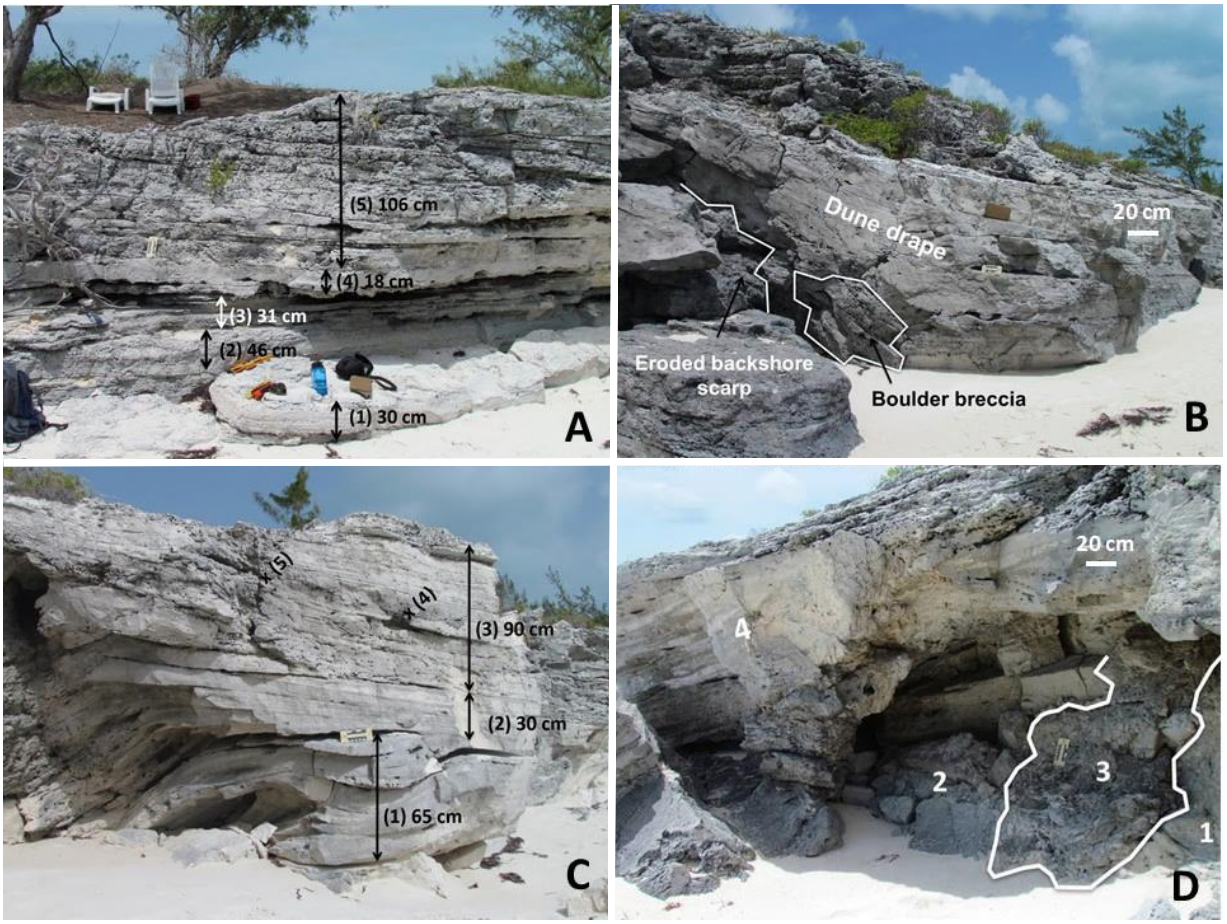

Figure 2. Outcrops of Hanna Bay Member from Cut House Beach, Little Exuma. A: Dewey's Staircase locality showing measured section. Described units (1)-(5) and corresponding thicknesses are shown. Units (1) – (3) represent foreshore settings; unit (4) backshore; and unit (5) dune. B: Outcrop oriented perpendicular to Cut House Beach showing lateral facies relationships. A lithified boulder breccia sits in front of a former backshore scarp; this is then overtopped by a drape of prograding dune sediment. C: Outcrop shows complex inter-relationships among a protodune facies (1), a superposed foreshore facies (2), and an overlying backshore to dune facies (3). Insect burrows (4) and (5) are found within the dune facies. D: Outcrop showing lateral facies relationships. Scarped foreshore facies (1) behind a boulder breccia (2). This is draped by a lithified dune spill-over (3) and massive dune facies (4).

Beds and laminations exhibit tabular cross-stratification and dip shallowly seaward, typically less than 10 degrees. Beds often thicken seaward and have erosional contacts at shallow angles with underlying beds. Swash-produced fenestrae are common. Though not noted on Exuma, rill lineations and swash lines can be found preserved on bedding planes of this facies, as on San Salvador (Savarese and Hoeflein, 2012).

Isopachous, contact, and meniscus blocky calcitic cements are common between grains, suggesting freshwater phreatic or vadose diagenesis (Figure 3B). Marine cements have not been observed in rocks from this lithofacies in southern Exuma. Marine phreatic cements were reported from a few Hanna Bay localities on San Salvador, but only in limestones low in the stratigraphic section, close to modern mean sea level (Savarese and Hoeflein, 2012). Likewise, marine phreatic cements have been reported from dune facies limestones of the North Point Member where those sediments are exposed to seawater saturation at

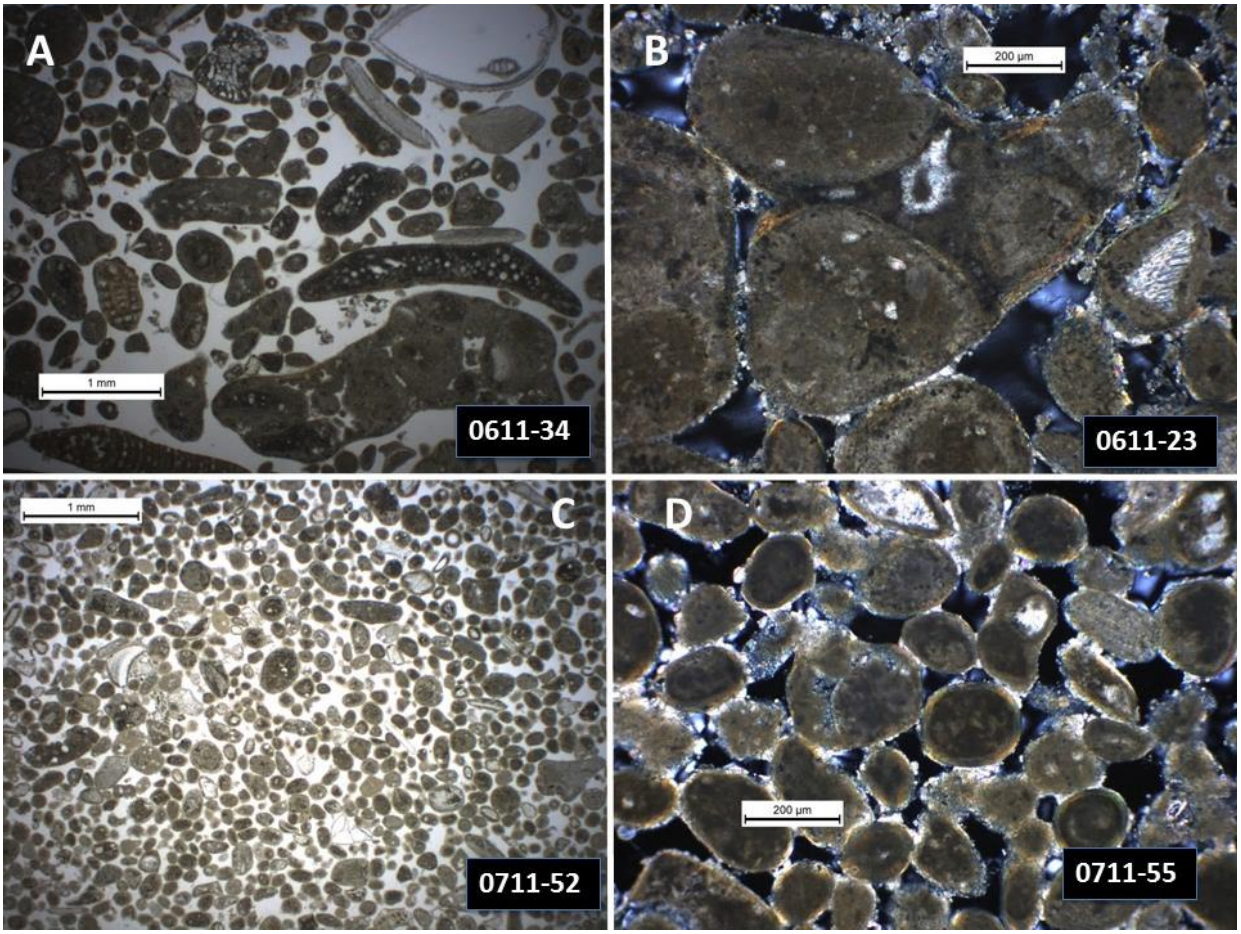

Figure 3. Photomicrographs of foreshore (A & B) and dune limestones (C & D). A: Sample from Dewey's Staircase, Cut House Beach, facies (2) in Figure 2A; plane polarized light; allochems include lumps and bioclasts (bivalves, foraminiferans, Halimeda, *and others). B: From eastern Moriah Harbour Cay; cross polarized light; coarse sand; large lumps (aggregate grains) with fine-crystalline contact and meniscus, blocky calcitic cements. C: From Moriah Harbour Cay strandplain, ridge 4.3 (Figure 7B); plane polarized light; very fine to fine sands with bioclasts, small lumps, and peloids. D: From Moriah Harbour Cay strandplain, ridge 1 (Figure 7B); plane polarized light; fine-crystalline isopachous blocky calcite cements.*

present-day sea level (White, 1995). Isopachous acicular aragonitic cements are rarely found filling the intraskeletal porosity of bioclasts, which is consistent with a marine origin for the allochems.

Stratigraphic relationships indicate these facies can undergo multi-generational histories of intertidal deposition, lithification, erosion, and subsequent deposition inter- or supratidally. Outcrops at Clear Pond Beach, San Salvador (Table 1; not figured), show such relationships well in lateral profile (Figure 4A,C). When seen from above in plan view, the same outcrops exhibit unconformable sutures, which represent the lateral juxtaposition of two periods of foreshore deposition (Figure 4B). At Cut House Beach on Little Exuma, the scarping of former beach sediments is preserved by now-lithified soft sediment spill-overs and boulder breccias (Figure 2B,D).

Trace and body fossils present in foreshore beds can be inconsistent with a typical foreshore origin. These beds are occasionally penetrated from above by the trace fossil *Psilonichnus upsilon*, attributed to the burrowing activity of the ghost crab *Ocypode quadrata* that likely occupied an overlying backshore or primary dune environment. In a similar manner, rhizoliths or other plant-

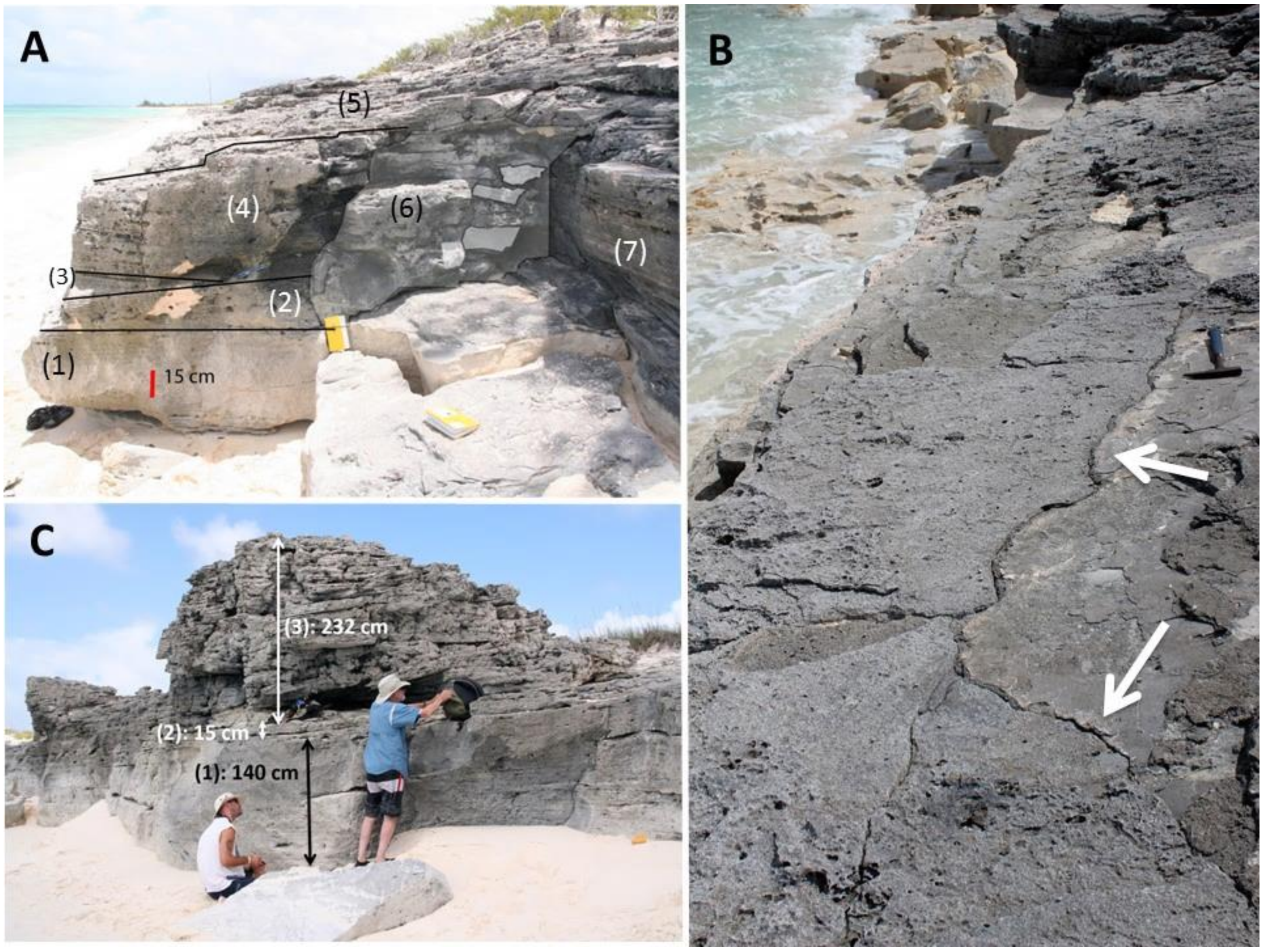

Figure 4. Outcrops of Hanna Bay Member from Clear Pond Beach, San Salvador. A: Measured section at North Clear Pond Beach showing lateral and vertical facies relationships; (7) a former foreshore, eroded to form a scarp; (6) boulder breccia out in front of the scarp; (1) – (4) four beds representing foreshore deposits younger than (7); (5) dune facies prograding over all other facies. B: Plan view of outcrop figured in A. Arrows denote a suture between two subsequent foreshore packages; foreshore sediments to left of arrows are coarser and lighter gray in color. Rock hammer for scale. C: Measured section at South Clear Pond Beach showing lateral and vertical facies relationships; (1) – (2) foreshore beds; (3) dune facies prograding over foreshore.

generated structures also may penetrate downward into foreshore beds from overlying dunal environments.

Whole-rock calibrated radiocarbon ages from this facies are highly variable ranging from 4100 to 700 years BP (based upon intercept ages), with the majority of the dates falling between 1200 and 700 years BP (Figure 5A; Table 2). Five of these dates come from Little Exuma; 1 from Great Exuma; 1 from Eleuthera; and 3 from San Salvador.

Backshore and Dune Facies

Differentiation of backshore from dune facies is often difficult. The best discriminating criterion is the existence of dune-form sedimentary structures in the latter (e.g., trough cross stratification, ripple laminations). Limestones formed within the backshore are mostly horizontally bedded but with undulatory contacts with under- and overlying beds. The sedimentology and petrography are similar in both, while the paleontology offers a means of facies differentiation, as discussed later.

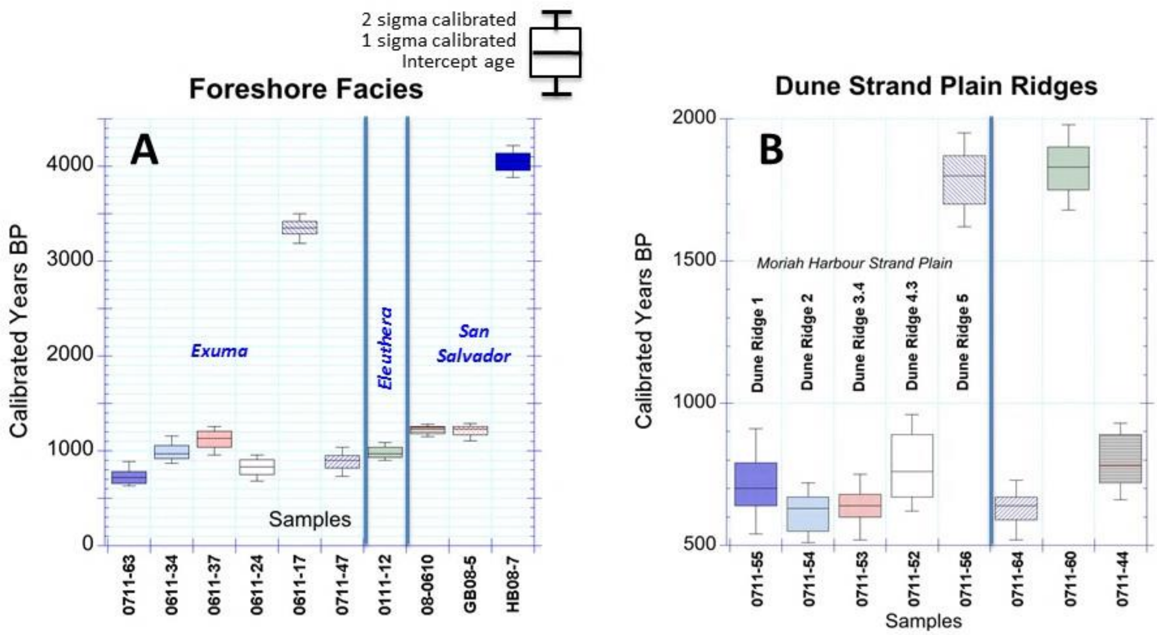

Figure 5. Distribution of radiocarbon ages obtained for foreshore facies (A) and dune strandplain ridges (B). Details concerning these dates are included in Table 2. Stem and whiskers denote intercept, 1 sigma calibrated, and 2 sigma calibrated ages in years before present. A: Foreshore samples come from Exuma, Eleuthera, and San Salvador. B: 5 dates come from Moriah Harbour Cay dune ridges (Figure 7B); remaining 3 dates are from other strandplains on Little and Great Exuma (see Table 2).

Backshore and dune facies commonly prograde over Hanna Bay foreshore facies when present, or over older lithostratigraphic units. These facies most commonly overlie or are found laterally adjacent and seaward of the foreshore facies (Figure 2). Sediments consist of very fine to fine sands with allochems dominated by bioclasts, with lesser amounts of small lumps and peloids (Figure 3C). Cements are comparable to those seen in the foreshore facies. Contact and meniscus blocky calcite cements dominate. Less common are isopachous blocky calcite cements (Figure 3D). These textures indicate a freshwater vadose or freshwater phreatic diagenetic environment. Similar meteoric diagenesis was documented below the surface of Ocean Bight, a large Holocene strandplain north of our study area on Great Exuma (Wallis et al., 1991; McClain et al., 1992).

The dune forms are typically low in amplitude with heights between trough and crest less than 2 meters (Figure 6A). Stoss and lee surfaces are often well developed and observable both in cross section and plan view (Figure 6B). Both backshore and dune limestones commonly contain burrows produced by ghost crabs (backshore), insects (dunes), and vegetative structures (both backshore and dunes) as either discrete traces or as bioturbated fabric.

Typical Hanna Bay Member dune forms are well displayed in cross section along the outer coast of Moriah Harbour Cay and along Cut House Beach, where wave-cut erosion generates scarps and cliffs. It is in these sections that the facies succession of foreshore through backshore and dune is best observed. Dunes, however, are expansively displayed in plan view as part of strandplains that sit behind the active Moriah Harbour Cay coast. Based on the geomorphology of the plains and the onlapping of dune facies onto foreshore deposits viewed along the coastal cliffs, these plains are interpreted as progradational. Similar progradational strandplains cover significant area throughout the Bahamas. In the southern Exuma Islands, they are exemplified on

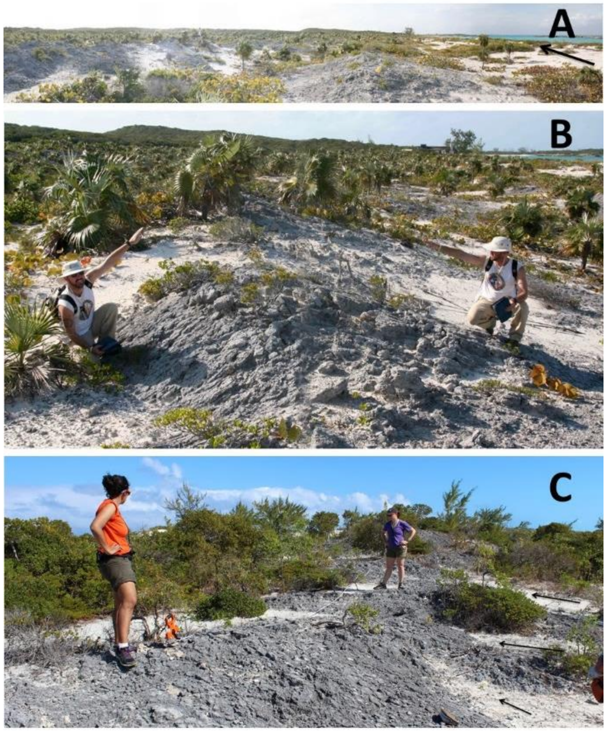

Figure 6. Dune forms on beach ridge strandplains; beach is to right in all photos. A: Moore Hill strandplain showing active foredune ridge (rightmost; at arrow) and 3 older lithified ridges (to left). B: Eolian ridge on Moore Hill strandplain showing steeply dipping lee (left) and shallowly dipping stoss (right) surfaces. C: Low amplitude dune ridge on Iva Bowe strandplain; arrows denote the upwind oriented arcuate shapes of these parabolic dunes.

Moriah Harbour Cay and Moore Hill on Little Exuma, and Casuarina Beach and Iva Bowe's Beach on Great Exuma (Figure 7).

Ridges composing the strandplains are long and conform to the shape of the outer coast. Some ridges are zetaform (Chapman, 1978), and drape down current of one headland; others are catenary, and positioned between two headlands. The headlands are formed by either Pleistocene or early Holocene North Point Member limestones. These shapes and coast-parallel morphologies indicate the ridges originated through wave action, with ridge orientations mimicking the refractionary propagation of waves approaching the coast. Though the constructional-deposition mechanism for ridge formation is wave-based, sediments exposed at the surface are clearly eolian. Ridges may have catenary or zetaform arrangements at gross scales, but at the outcrop level they clearly exhibit eolian dune-form sedimentary structures and parabolic shapes (Figure 6B,C). Consequently these structures are best classified as "strandplain beach ridges" (sensu Otvos, 2012). Because the term "beach ridge" has been used inappropriately for a variety of wave- or wind-deposited coastal features (for history of term use see: Otvos, 2000; Hesp, 2006) and because ridges may have a combination of wave and eolian origins, some investigators have wrongly assumed ridge heights reflect sea-level position (for review see Tamura, 2012). The current heights of these Bahamian strandplain beach ridges are not indicative of sea level. We hypothesize that storm-generated, wave-erosional scarps within beach sediments (backshore and foreshore sands) served as foundational obstructions for subsequent eolian deposition and formation of a foredune. This is one of a number of proposed mechanisms for beach ridge strandplain formation (Tamura, 2012), and one invoked for many strandplains throughout the world (e.g., for Lake Michigan: Johnston et al., 2007; for Japan: Tamura et al., 2007; and for Australia: Hesp, 1999).

Some strandplains are composed of multiple dune ridge sets with discordant orientations. Sets are separated by erosional unconformities. Evidence of erosion can be seen in places on the ground along the unconformable surfaces (Figure 8A). If waves are high enough, storm wave action can create a dune scarp, against which subsequent beach or dune deposition would occur. Consequently, the occurrence of scarps is consistent with the mechanism of strandplain progradation described above (Figure 8B).

At two strandplain localities, West Moriah Harbour Cay and Casuarina Beach, extensive limestone pavements interpreted as preserved backshores are discernible between widely spaced strandplain beach ridges (Figure 8C). These limestones are composed of polygonally cracked,

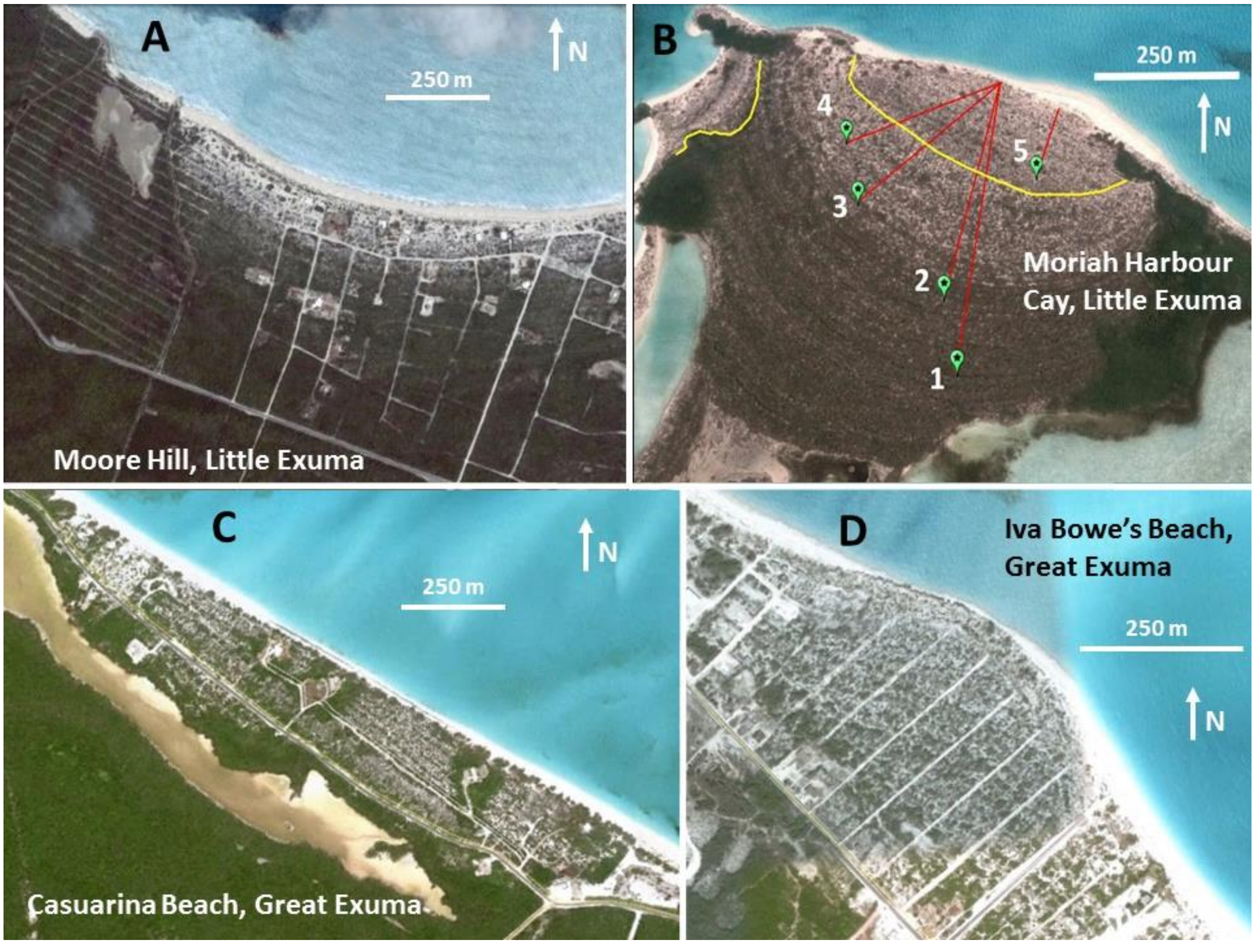

Figure 7. Aerial images of 4 strandplains on Little Exuma (A - Moore Hill; B - Moriah Harbour Cay) and on Great Exuma (C - Casuarina Beach; D - Iva Bowe's Beach). B: Graphical overlays show features discussed in text. Curved lines demark erosional unconformities separating ridge sets. Pins note dune ridges sampled for petrographic analysis and radiocarbon dating; ridge number, dates, expressed as calibrated intercept years before present, and distances to the active coast, shown as straight lines, are as follows: 1 – ridge 1 / 700 ybp / 0.62 km; 2 – ridge 2 / 630 ybp / 0.50 km; 3 – ridge 3.4 / 640 ybp / 0.42 km; 4 – ridge 4.3 / 760 ybp / 0.38 km; and 5 – ridge 5 / 1800 ybp / 0.17 km. Images modified from Google Earth.

fine-grained sands with occasional *Psilonichnus upsilon* burrows and horizontal vegetative traces presumed to be plant runner (prostrate stem) impressions. If wave-induced erosion created a scarp distally upon a wide beach, the distance between two successive strandplain beach ridges would be great and an extensive backshore surface would be preserved. At Casuarina Beach, the landward edge of the former backshore beach lies 195 m behind the current backshore; at Moriah Harbour Cay West, the former backshore sits 95 m landward. The backshore at Casuarina Beach is 140 cm above the modern backshore, while at Moriah Harbour Cay, the old backshore pavement sits at the same elevation as the modern high tide line (Figure 8C). These surfaces have relevance to the position of sea level. The former may represent a temporally significant sea-level highstand, though modern backshores normally occur 1-2 m above the foreshore, while the latter is consistent with modern mean sea level. Neither surface, consequently, serves as an indisputable highstand indicator.

Radiocarbon ages were obtained from a series of 5 dune ridges on the Moriah Harbour Cay

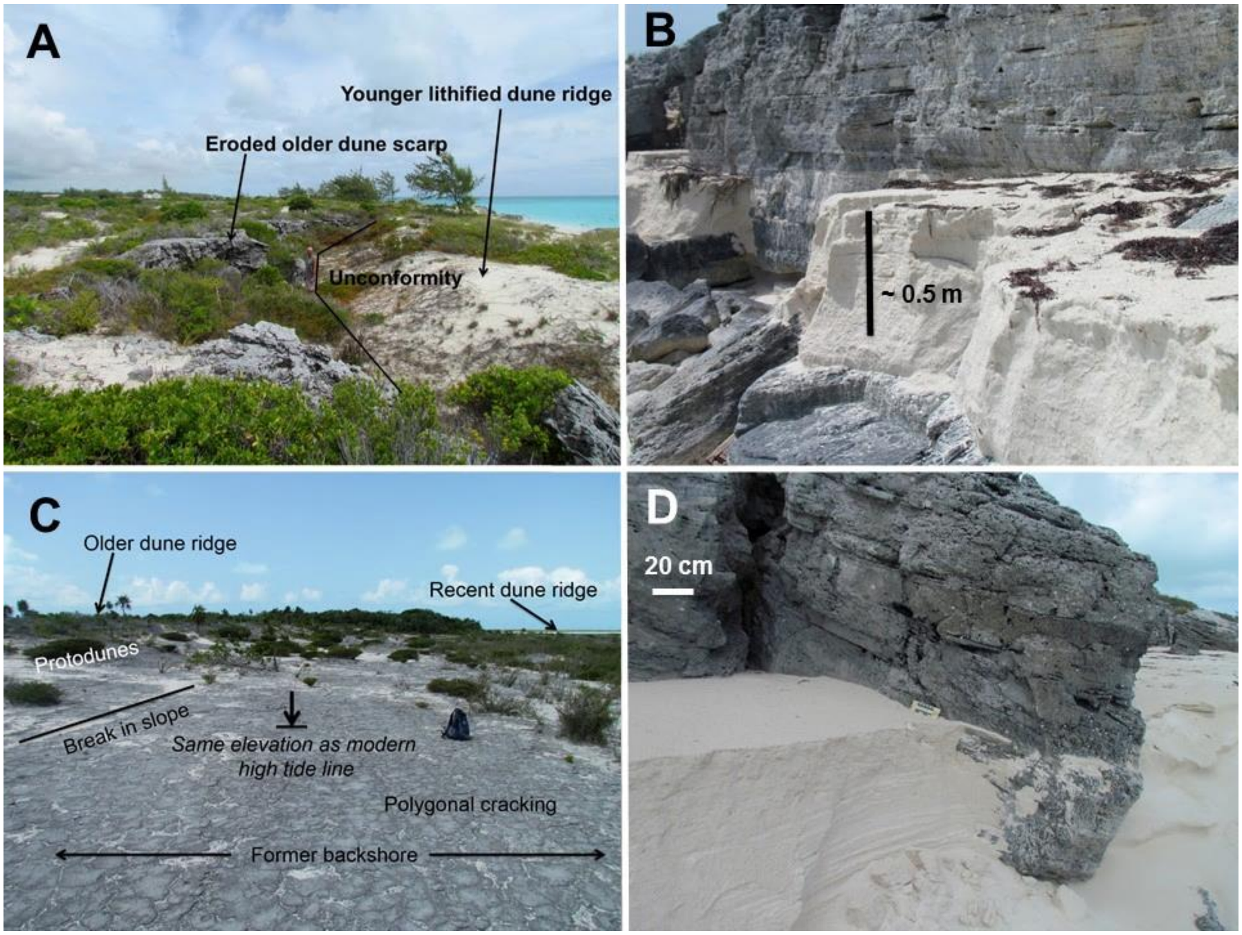

Figure 8. Facies relationships and unconformable contacts. A: Erosional unconformity between dune ridges at Iva Bowe's Beach (along black line); younger dune ridge adjacent to older ridge with a scarp separating the two. B: Modern high foreshore to backshore sands (lighter color) deposited against Hanna Bay Member foreshore to backshore facies (darker color) at Cut House Beach. Ocean is to the left. C: Relict backshore pavement located between 2 dune ridges of the West Moriah Harbour Cay strandplain. The former backshore exhibits polygonal cracking and is backed by lithified protodunes and then an older dune ridge. Relict backshore sits at same elevation as the current high tide line. Ocean is to the right. Backpack for scale. D: Modern high foreshore sands deposited against Hanna Bay Member dune facies at Cut House Beach; ocean is to the right.

strandplain (Table 2), with the intention of providing data for estimating progradational rates of strandplain development, and 1 from each of the 3 other strandplains in the southern Exuma Islands (Iva Bowe, Moore Hill, and Casuarina Beach; Figure 7). Figure 7B shows the geographic position of the Moriah Harbour Cay samples and their distance from the active coast; Figure 5B presents the distribution of whole-rock radiocarbon calibrated ages. Four of the samples from Moriah Harbour Cay (dune ridges 1-4; ridges are numbered from presumed oldest to youngest) yield indistinguishable ages with intercept calibrated ages ranging from 630 – 760 ybp; these dates are disordered, and lack a clear trend of younger dates toward the coast. The fifth date, for ridge 5, sits most seaward and has an intercept age of 1800 ybp, which is significantly older than the other four and in a position inconsistent with an older age. The dates obtained from Iva Bowe and Casuarina Beach strandplains, 640 and 780 ybp respectively, are comparable to ridges 1-4 at Moriah Harbour Cay.

The Moore Hill ridge date (1830 ybp) is relatively old and comparable to ridge 5 at Moriah Harbour Cay (Figure 7B).

Dating of these ridges is complicated by the whole rock nature of the analysis. The date obtained for each rock is the integrated sum of individual allochems, which could be significantly older than the eolian environment in which they accumulated, and the age of the post-depositional cements. Such ages are, therefore, unreliable. If the two 1800 and 1830 ybp dates are considered erroneous, the remaining 4 dates at Moriah Harbour cluster between 600 – 800 ybp, and may suggest that this strandplain prograded 0.6 km (the distance ridge 1 sits from the active coast) in approximately 200 years, equivalent to a rate of 3 m / year. The dates from the Iva Bowe and Casuarina Beach suggest these strandplains developed at roughly the same time as those on Moriah Harbour Cay.

ICHNOLOGY OF THE HANNA BAY MEMBER

The ichnology of Quaternary carbonate rocks of the islands of the Bahamas has been studied in some detail and is summarized in Curran (2007), Knaust et al. (2012), and papers cited therein. The ichnocoenoses, or ecological assemblages of trace fossils, present in the Hanna Bay Member fall within the *Psilonichnus* Ichnofacies, which includes upper intertidal to coastal dune facies. As mentioned earlier, backshore beds of the Hanna Bay Member commonly contain the distinctive trace fossil, *Psilonichnus upsilon* (Figure 9; Curran, 2007), formed by the burrowing activity of the ghost crab *Ocypode quadrata*. In some cases, the shafts of large *P. upsilon* can extend from backshore beds into underlying upper foreshore deposits. Although normally not present here in sufficient abundance to generate an appreciable level of bioturbation, examples of *P. upsilon* are easily found in the windward cliffs containing backshore exposures in the southern Exumas, particularly at Cut House

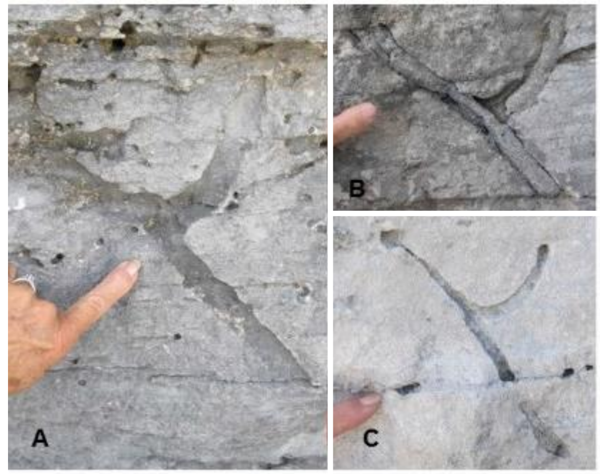

Figure 9. Psilonichnus upsilon *in Holocene backshore beds, Moriah Harbour Cay Cliffs, A,B: specimens produced by mature ghost crabs; C – juvenile specimen.* P. upsilon *specimens as shown here can be a useful sea-level position indicator.*

Beach and along the Exuma Sound-facing coast of Moriah Harbour Cay. The existence of well-formed *P. upsilon* specimens is a reliable indicator of the presence of a backshore paleoenvironment, with limits ranging from the upper foreshore to unvegetated, primary dunes (Curran, 2007).

The presence and characteristics of trace fossils of Holocene eolianites in the Bahamas was the topic of a specific study by Curran and White (2001). The eolianites of the southern Exumas exhibit all of the characteristics and trace fossils of the dunal ichnocoenosis as described by Curran and White (2001) and Curran (2007), including insect-generated trace fossils informally referred to as stellate burrows and cluster burrows. The spectacular sea-cliff exposures, with heights of 2.5 to 6 m of Hanna Bay Member eolianite that crop out along the windward, Exuma Sound-facing coast of Moriah Harbour Cay, reveal a highly distinctive ichnofabric characterized by the presence of abundant, large, and well-developed stellate burrows (Figures 10, 11).

Stellate burrows are characterized by having a central shaft of 3 to 5 cm diameter with numerous oblique, smaller, branching-upward

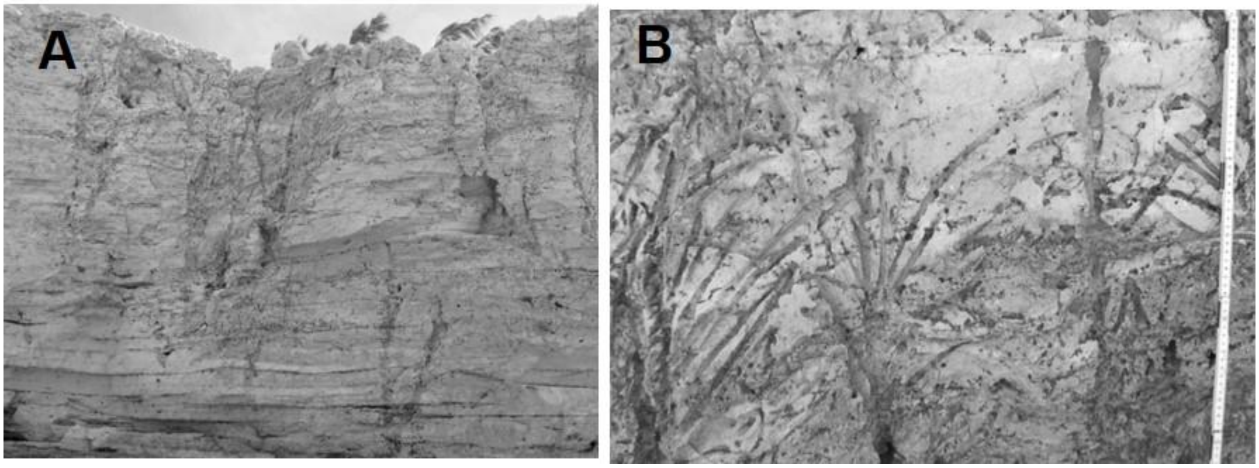

Figure 10. Stellate burrows exposed along cliff faces bordering the windward coast of Exuma Sound at Moriah Harbour Cay. A: Holocene carbonate eolianites containing numerous large and complex stellate burrows; height of exposure ~ 3 m. B: Close-up view of secondary shafts branching upward from the main shafts of stellate burrows; diameter of the secondary shafts typically 5 to 8 mm. The ichnofabric imparted by stellate burrows in these eolianites can reach levels of 3 to 3.5 on the Droser-Bottjer Ichnofabric Index scale.

shafts of about 1 cm diameter. These shafts have smooth, unlined walls, and commonly form a gentle arc toward their distal ends. Secondary branching does not appear to occur. In many cases, parallel central shafts join at the base, forming distinctive U-shaped structures that can reach total heights of greater than 1 m (Figure 11A). Other examples exhibit an irregular arrangement of shafts that merge to form exceptionally large and architecturally complex structures (Figure 11B). The informal "stellate" name comes from bedding plane exposures where a central shaft is cross cut and the branching smaller shafts are revealed to form a radiate pattern on the horizontal surface.

The Moriah Harbour Cay cliffs have the most prolific occurrence of stellate burrows discovered to date in the Bahamas. The result is a distinctive ichnofabric that can reach the 3- to 3.5-level on the 1 to 5 Droser-Bottjer (1989) Ichnofabric Index scale (Figures 10B, 11A). The excellent vertical cliff-face exposures in this area facilitated an effort to make point-intercept counts of stellate burrow shafts present along horizontal transect lines parallel with the beach at the base of the cliffs (Figure 11B). Eight transect counts were made, yielding an average occurrence of 4 shafts/meter (range = 3-5 shafts/meter). In addition, a bedding plane exposure of 1 m^2 (2 m length by 0.5 m width) had a count of 23 shaft intersections. This was a particularly rich occurrence of shafts, and the combined intercept and area counts plus the Ichnofabric Index numbers give some idea of the order of magnitude of occurrence of stellate burrows within these young eolianites.

Figure 11 shows large and complex examples of stellate burrows. The characteristic U-shape of the central shaft is emphasized in Figure 11A, with two large U-shaped stellate burrows side-by-side. The very complex nature of what appears to be a single stellate burrow is shown in Figure 11B; trace-maker organisms must have occupied this burrow for a considerable period of time.

Previously, stellate burrows were assigned to the ichnogenus *Cellicalichnus*, with their origin attributed to the burrowing activity of halictid (sweat) bees (Curran, 2007 and earlier references). The secondary shafts were interpreted as representing brooding areas and exit passageways for juveniles, and as such, the behavioral category for stellate burrows would be as large brooding structures or calichnia. Sweat bees are common today in the Moriah Harbour Cay study area, and

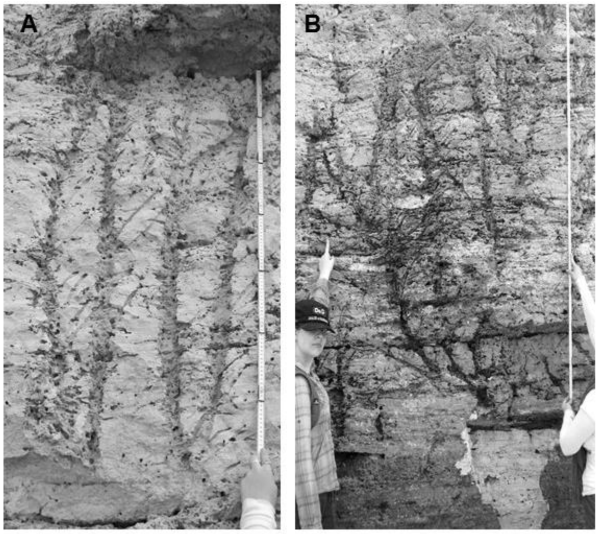

Figure 11. Large U-shaped stellate burrows. A: Two large U-burrows side-by-side with minimum height of 1.2 m and separated by about 20 cm. B: Large, complex stellate burrow with width of 1.8 m and height of >1.5 m; this specimen likely represents a prolonged period of construction and occupation by the tracemakers.

the stellate trace fossils are similar to previously described forms of *Cellicalichnus*. Nonetheless, important differences remain to be resolved, so the ichnogenus assignment remains tentative.

DISCUSSION

The investigation of the Hanna Bay Member on the southern Exuma Islands, when integrated with previous work conducted in the Bahamas on Eleuthera and San Salvador, demonstrates that sea-level position is critical to the deposition and preservation of the lithofacies present, but these data do not warrant nor require the invocation of eustatic sea-level highstands above present for geomorphic development of Bahamian coastlines during the Holocene. Rather ephemeral or local highstands, those caused by short-lived and local phenomena, are the initiators of coastal progradation and habitat expansion. Empirically derived sea-level curves for the late Holocene of the Bahamas are uncommon. Those studies undertaken either do not show a recent highstand (Hearty and Kindler, 1995; Toscano and Macintyre, 2003) or are too coarse temporally to well constrain sea level's position during this interval (Boardman et al., 1989).

Hanna Bay Member foreshore limestones have characteristics consistent with an intertidal, swash zone origin, but their post-depositional alterations are indicative of backshore modification. The cement diagenesis and ichnology are inconsistent with a tidal, marine influence; vegetation, crab burrows, and meteoric diagenesis are common within sediments that reside higher on the beach. The variation seen in radiocarbon ages for foreshore deposits is also inconsistent with eustatic highstand. A geographically and temporally extensive highstand would generate many similarly aged deposits across the Bahamian Archipelago with comparable vertical position. A more parsimonious explanation for anomalously high foreshore beds is that they were deposited in a short period of time, on the order of hours or days, during an unusually high tide, and were then left within a backshore setting after normal tidal heights resumed.

Perhaps the most compelling argument supporting this interpretation is the existence of similar phenomena that have occurred in recent history. Modern foreshore deposits, sitting within 0-3 meters above mean sea level, are found on beaches throughout the Bahamas, and juxtaposed against similar facies of Hanna Bay Member age. Figure 8B shows an example of this phenomenon at Cut House Beach on Little Exuma. Modern, unlithified foreshore sands sit seaward and up against the foreshore lithofacies of the Hanna Bay Member. In Figure 8D, also at Cut House Beach, modern foreshore sands are shown annealed to the dune lithofacies of the Hanna Bay Member. The outcrop pattern of Hanna Bay limestones at Clear Pond Beach on San Salvador (Figure 4) can be explained by such repetition of ephemeral foreshore environments. Each successive high tide has the potential to accrete a new foreshore package up against an older one. Early lithification of former foreshore deposits, followed by shoreline erosional scarping, creates the potential for future foreshore accretion and preservation.

The ages obtained for dune ridges composing the strandplains on the southern Exuma Islands – comparable to, though slightly younger than, the foreshore facies – suggest a relational origin to the foreshore facies. The catenary and zetaform orientations of the ridges further indicate a wave-influenced initiation. We propose that ephemeral highstand foreshore sands are deposited and then later eroded to form scarps upon which eolian dunes develop. In this scenario, strandplain ridges would then mimic the geomorphology of the active coast.

With this interpretation, no eustatic and persistent highstand is necessary. Some short-term regional mechanism is required. Savarese and Hoeflein (2012) posed a variety of possible causes including storm tidal surges, perigean spring tides, and shifts in oceanographic circulation patterns. Of these, a storm origin is most compelling. Donnelly and Giosan (2008) noted that during times of increased storminess, the height of waves and the frequency of impact by constructional swells can increase and subsequently deposit intertidal sediments well above mean sea level, which could be misinterpreted as evidence of a highstand. Such a phenomenon has been documented for the eastern seaboard of the U.S., where an increase in storm activity since the 1970s resulted in a significant increase in summer wave height (Komar and Allan, 2008). Finally, the passage of tropical storms creates broad regions of high storm surge under low pressure systems at significant distances from a storm's center of disturbance and wave erosion; such storm surges can result in significant deposition well above mean sea level.

The subsequent passage of a storm, with effects within the region of net erosion rather than deposition, would create a scarp needed for later dune formation. If correct, foreshore deposition and beach ridge strandplain development are predisposed to times of climatic storminess. Times of greater storm frequency are periods during which strandplain progradation is to be anticipated.

Interestingly, the ages of the foreshore facies dated from the southern Exuma Islands, Eleuthera, and San Salvador reside most commonly within the Medieval Warm Period, which occurred between 700-1200 ybp (800 – 1300 CE). Periods of elevated atmospheric and sea-surface temperatures within the tropics should coincide with greater storminess, and such a phenomenon has been documented specifically for the Medieval Warm Period (Mann et al., 2009b; Graham et al., 2011). Paleotempestological studies for the Bahamas, the Gulf of Mexico, and Southwest Florida have revealed similar patterns of greater tropical storm impact during this time period (Liu and Fearn, 2000; Donnelly and Woodruff, 2007; Mann et al., 2009a; Park, 2012; Ercolani et al., 2012; Toomey et al., 2013). The climate throughout North America was also more arid during this interval (Feng et al., 2008). Modelling of precipitation shows this aridity extended into the Bahamas and Caribbean (Graham et al., 2011). Aridity restricts the development of vegetation, which would promote eolian dune ridge proliferation and progradation.

The potential relationship between strand-plain genesis and storminess has been discussed by Scheffers et al. (2012). These authors contended that beach ridges on strandplains, assuming they had a constructional wave origin, can serve as "recorders of wave regimes or extreme wave events." Additionally, they propose that dated beach ridge sets, in which each ridge represents an individual storm event, can be used to estimate storm frequency. The examples they cited, however, concern ridges composed of coarse sediments (pebbles and gravels) and represent higher energy constructional wave regimes than were responsible for the Hanna Bay foreshore deposits.

Assuming our proposed mechanism for Bahamian strandplain formation withstands further testing, the Medieval Warm Period provided the right combination of climatological conditions, sea-level rise, and storminess to predispose the region for strandplain formation. Holocene beach-ridge strandplains are ubiquitous throughout the Bahamas. Their significant aerial coverage has been noted by a number of previous studies (for example, on San Salvador: Titus, 1987, Carney et al., 1993, Hearty and Kindler, 1993a; on New Providence: Garrett and Gould, 1984, Hearty and Kindler, 1997; on Lee Stocking: Kindler, 1995). If all or most Hanna Bay Member strandplains developed during the Medieval Warm Period, the Bahama Islands experienced a significant increase in coastal habitat expansion and a profound reconfiguration of its coastal geomorphology in a relatively brief period of time. Such geomorphic change has great implications for former and future societal land use. The Medieval Warm Period coincides with the initial colonization and expansion of Lucayan civilization within the Bahamas (Berman et al., 2013), and Lucayan people preferentially exploited coastal dune and swale habitat for its resources. A logical inference, though not yet tested, is that the shift away from the Medieval Climate Anomaly resulted in a more hospitable climate upon the newly developed strandplains, allowing for support of a larger Lucayan population. These same strandplains are vulnerable to future climate change and sea-level rise. As sea-level rise accelerates, a switch to a more erosional transgressive regime, jeopardizes the permanence of a significant land area upon which modern Bahamian society depends.

CONCLUSIONS

The peripheries of most Bahamian islands are composed of late Holocene Hanna Bay Formation strandplains, whose origins reflect the combined effects of wave and eolian processes. Strandplain ridges originated during times of ephemeral highstands, during passage of storm events that deposited foreshore sands and shell gravel high on the beach. These were later scarped through subsequent wave erosion with the scarps becoming nucleation sites for eolian deposition. Each strandplain was constructed by progradation of multiple generations of eolian ridges. Ridge ages fall within the Medieval Warm Period, between 1200-700 ybp, which coincides with an interval of increased storminess and modest sea-level rise rates for the region.

There is no evidence supporting eustatic highstand origins for the Hanna Bay foreshore facies. Though these sediments possess sediment-ologic and structural characteristics consistent with foreshore deposition, their cementational history, their ichnofauna, and the occurrence of vegetative traces all support the environment's quick transition to a backshore position.

The eolian dune facies of the Hanna Bay Member harbors an extravagant and prolific collection of crustacean and insect traces, including ghost crab burrows (*Psilonichnus upsilon*; also found in the backshore facies) and stellate burrows presumably formed by halictid bees.

ACKNOWLEDGMENTS

This research was supported by funding to MS provided by Florida Gulf Coast University's Coastal Watershed Institute, the U.S. Department of Education, and the South Florida Water Management District, and to HAC by the Smith College Committee on Faculty Compensation and Development. Field, laboratory, and intellectual support was provided by Boch Hoeflein, Lisa Park Boush, Bosiljka Glumac, and Ilya Buynevich. Special thanks to our friends in Exuma: Dave and Lorraine Dewey, Norm and Tina Hertz, and Alexander Bartholomew; and to our family members: Jane Curran, Mona, Matthew, and Allison Wright. We are indebted to the Director and staff of the Gerace Research Centre for facilitating the research permitting for this study.

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