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GEOMORPHOLOGY OF THE LATE HOLOCENE SANDY HOOK STRANDPLAIN, SAN SALVADOR ISLAND, THE BAHAMAS: A RECORD OF CHANGING HYDRODYNAMICS

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ABSTRACT

The geomorphology of Sandy Hook, a late Holocene strandplain on the isolated Bahamian carbonate platform of San Salvador, is evaluated using subsurface geophysics and a GIS-based characterization of ridge orientation and spacing. The integrative dataset establishes an evolutionary framework model for the 1.5 km² strandplain, which is situated along the island's southeast coast. Four sets of *en echelon* beach ridges are distinguished at Sandy Hook. Bound by erosional surfaces that truncate paleoshorelines obliquely, they vary in ridge spacing and vegetation cover. Ground-penetrating radar data, collected perpendicular to shore, image prograding clinoform geometries within the upper 4 m of the subsurface. Seaward-inclined reflection surfaces delineate shapes of former foreshore profiles, chronicling the progression of shoreline advance. The architecture of Sandy Hook is characterized by sedimentary sequences bound by discontinuities, which are recognized by truncation of landward, older units and onlap of seaward, younger ones. This attests to a pattern of net growth punctuated by episodic erosion. Studies of siliciclastic analogs have attributed similar architectures to variances in storm climate and/or sediment supply. At Sandy Hook, it is likely that the progressive reduction in shallow-water shelf area fronting the shoreline affected strandplain development by modifying nearshore hydrology and sediment availability. This is suggested by a decrease in ridge spacing over time, which may also reflect changes in hydrodynamic forcing associated with the transition from the Hurricane Hyperactivity Period (1000-3400^{14}C yr B.P.; Liu and Fearn 2000).

INTRODUCTION

The morphology of beach ridges provides information on a variety of paleoenvironmental variables, including sea level, storm climate, and nearshore hydrology (Scheffers et al., 2011). Strandplains, which are comprised of many beach ridges (often grouped into beach ridge sets based on shared characteristics), are studied for insight into changes in environmental forcing over time (Goy et al., 2003; Dougherty et al., 2004; Nott et al., 2009; Forsyth et al., 2010; Tamura, 2012). Strandplain development requires conditions of high sediment supply and hydrodynamic variances in promotion of punctuated shoreline advance (e.g., changes in storm climate); they are most commonly affiliated with wave-dominated river mouths (Matin and Suguio, 1992; Stanley and Warne, 1993; Anthony, 1995; Bondesan et al., 1995; Vella et al., 2005) and regressive portions of barrier islands and compound spits (Timmons et al., 2010; Hein et al., 2013; Mattheus, 2016). Strandplains also occur in more confined coastal settings, such as embayments of the Laurentian Great Lakes, where they provide information on Holocene glacio-isostatic adjustments and lake-level changes (Thompson, 1992; Larsen, 1994; Lichter, 1995; Thompson and Baedke, 1995, 1997; Baedke and Thompson, 2000; Johnston et al., 2007). While many studies document beach morphodynamics and strandplain development along siliciclastic coastal margins, carbonate platform analogs are under-represented in the literature.

Hearty et al. (1998) and Hearty and Neumann (2001) interpreted former sea-level positions from late Pleistocene Bahamian beach ridges, attesting to their usefulness as archives of paleoenvironmental information. Shinn et al. (1969) evaluated Holocene carbonate strandplains within stratigraphic context of the greater tidal flat environment of Andros Island, The Bahamas, providing architectural blueprints. Sediment textures of Pleistocene-Holocene carbonate strandplains and their implications for hydrocarbon and/or groundwater reservoir potentials were studied by Ward and Brady (1979) and Wallis et al. (1991). While these studies and others have improved our understanding of carbonate strandplain sedimentology and stratigraphic architecture, more work distinctly addressing process geomorphology is needed to facilitate paleoclimate reconstructions.

This study investigates landscape evolution at Sandy Hook, a Holocene carbonate strandplain on the Bahamian island of San Salvador, where past investigations have elucidated paleoclimate information from lacustrine and lagoonal sedimentary archives (Niemi et al., 2008; Dalman, 2009, Park et al. 2009; Dalman and Park, 2012; Park, 2012). A geomorphic model of the strandplain is presented and discussed in relation to late Holocene sea-level rise and storm climate. It builds upon prior work, including that of Boardman and Carney (1992) and Carney et al. (1993), who evaluated Sandy Hook's depositional history in context of San Salvador's framework geology and Quaternary sea levels. Addressing potential linkages between hydrodynamic variables (e.g. storm intensity and frequency), sea-level rise, and strandplain geomorphology complements ongoing late Holocene coastal reconstructive efforts on the island.

FIELD SITE DESCRIPTION

San Salvador sits atop an isolated carbonate platform along the eastern edge of the Bahamian Archipelago, where shallow coastal waters (of <10 m in depth) abruptly transition to 4 km-deep Atlantic Ocean waters over a distance of around 10 km. The

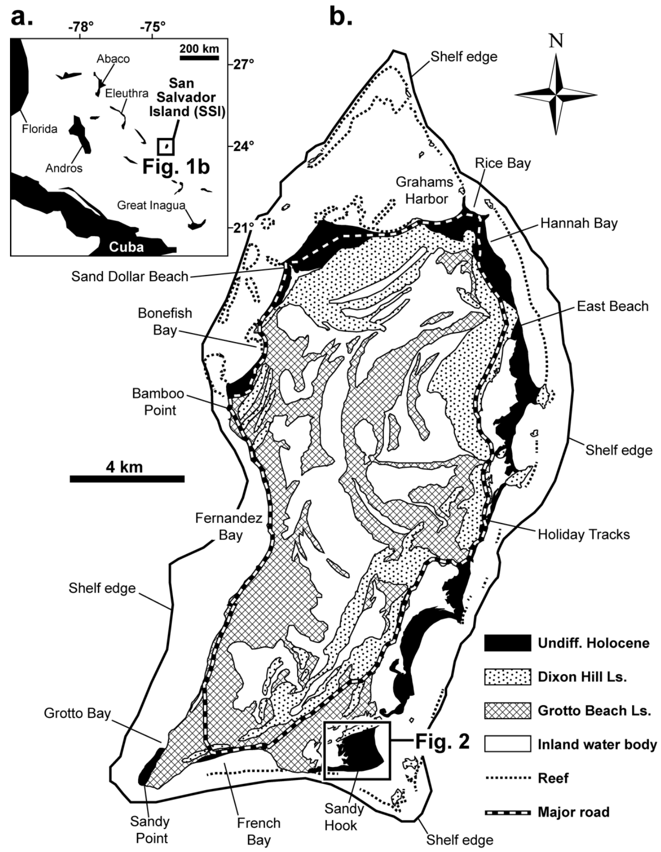

Figure 1. Maps showing the location of San Salvador Island (a) and its geology (b). The Sandy Hook study area (shown in greater detail in Figure 2) is highlighted. Prominent landform features (e.g. shelf-edge reefs) are marked and labeled. Part b is modified from maps by Robinson and Davis (1999) and Titus (1987).

island is vulnerable to strong storms and hurricanes that frequent this particular region (Klotzbach, 2011). The N-S oriented San Salvador measures around 23 km in length and is up to 11 km wide. About a third of the island is covered by water as numerous shallow ponds, lakes, and lagoons occupy swale portions of a Pleistocene dune-bedrock topography (Titus, 1987; Figure 1). Holocene sediments on San Salvador are thin and discontinuous; unconsolidated sands here exist only along select stretches of coastline (Figure 1b). The Sandy Hook strandplain, which started forming around 3-5 ka (Hearty and Kindler, 1993), is the largest sandy lithosome of Holocene age. It is located in the

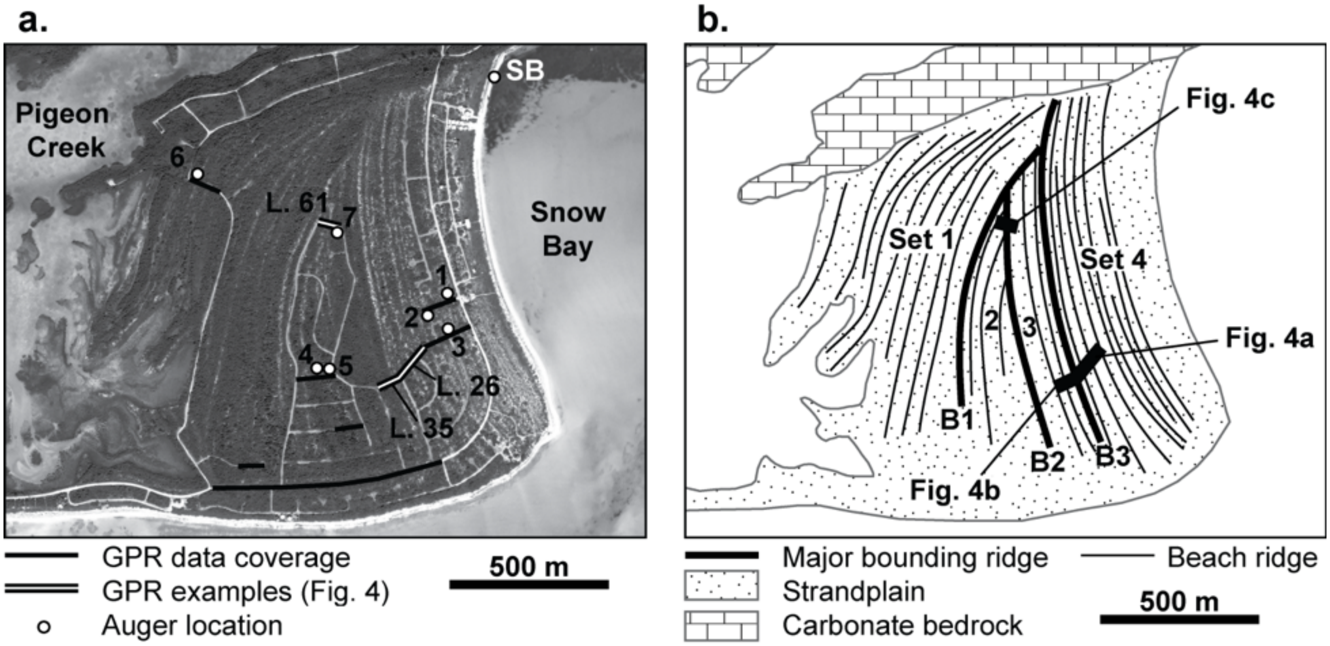

Figure 2. Annotated aerial photograph of Sandy Hook (a) and corresponding geologic map (b), plotting data distribution, axes of beach ridges, and locations of GPR examples shown in this paper (in Figure 4).

southeast corner of the island, bound on its landward side by the western arm of the Pigeon Creek tidal estuary (Figure 2). The total aerial extent of the strandplain is approximately 1.5 km^2 and it houses over 30 beach ridges (Carney et al., 1993). Sandy Hook is separated from the open Atlantic by a shelf lagoon, the 1.5 km-wide Snow Bay. It has an aerial extent of around 5 km² and is partly rimmed by limestone cays and shelf-edge reefs (Robinson and Davis, 1999; Figures 1b and 2). A network of unpaved roads provides access to the more landward parts of the densely shrub-vegetated strandplain, which is defined by a subtle ridge-and-swale topography averaging 3 m in elevation (Bahamian Land and Surveys Department, 1972). Sandy Hook is bound to the north by a Pleistocene carbonate-bedrock ridge, which exceeds 6 m in elevation (Titus, 1987; Carew and Mylroie, 1995; Figure 2).

METHODS

The project relied on a GIS-based study of landforms (using remotely-sensed data) and subsurface geophysics. Ground-penetrating radar (GPR) data were collected on San Salvador in March of 2015. Subsequent analysis was undertaken at Youngstown State University and Lake Superior State University facilities in Ohio and Michigan, respectively.

GIS-based mapping

Ridge orientations and spacing were determined from historic aerial photographs (dating to 1942 and 1968), obtained from the Bahamian Lands and Surveys Department, and Google Earth-derived satellite images (collected between 2012 and 2016). Mapping was performed using the ArcGIS 10.3 software package and its auxiliary toolsets. Image files were georeferenced to existing base layers using fixed and easily distinguished landmarks (e.g. road intersections). Landforms were studied from the imagery across a seasonal spectrum to help minimize biased interpretations resulting from shadow effects or obscuration by cloud cover. Differences in vegetation between ridges and swales (in terms of type and density) facilitated their delineation and classification. Interpreted/digitized ridges were grouped into sets

Table 1. Spatial metrics by ridge set.

Ridge set	# of ridges	Ridge spacing (m)	Strandplain area (km²)	Foreset angle (°)
1	10	50	0.56	N/A
2	5	40	0.21	15-27
3	4	40	0.17	13-20
4	11	30	0.61	13-20

based on common measures of spacing, orientation, and spatial association. Field notes on vegetation cover (taken during geophysical mapping) supplemented insights from remotely-sensed information.

Subsurface geophysics

A total of 1.6 km of high-resolution GPR data were collected along 10 shore-perpendicular transects using a pulse Ekko Pro system by Sensors and Software, Inc., equipped with 200 MHz antennae and a calibrated odometer trigger (Figure 2). Basic data processing was performed using the EkkoView Deluxe software package. Digital radar files required no topographic correction as non-vertical beam orientations were avoided by imaging through flat and horizontal road segments. Radar velocities were established by hyperbola fitting (during post-processing) and used to convert two-way travel time to depth. The average radar velocity used, 0.1 m/ns, is in agreement with values published for other carbonate environments (Annan, 1992; Grasmueck and Weger, 2002; Xia et al., 2004). An AGC gain function was applied to the radar files to disproportionately amplify weakened subsurface reflections at depth. Radar sequences were mapped based on fundamental stratigraphic principles (e.g. superposition and cross-cutting relationships), relying on the recognition of different stratal termination patterns.

RESULTS

This study relies on two types of information: 1) A surficial assessment of strandplain morphology, as captured by metrics of ridge spacing, orientation, and grouping; and 2) Stratigraphic interpretations based on high-resolution reflection geophysics.

Ridge orientation and spacing

Beach ridges at Sandy Hook are generally N-S trending and decrease in age eastward (i.e. in the offshore direction). They are slightly arcuate and grouped into four distinct sets, which are separated by erosional surfaces that truncate paleoshorelines obliquely (Figure 2b; Table 1). Ridge sets, which vary in aerial extent and are numbered from oldest to youngest (i.e. landward to seaward), are characterized by different ridge characteristics (Figure 2b; Table 1). Ridge Set 1, the oldest and most landward, covers an area of 0.56 km^2. It is comprised of 10 ridges at an average spacing of approximately 50 m. Ridge Set 4, the youngest, is the most extensive (at 0.61 km^2) and includes the modern beach at Sandy Hook. It contains 11 ridges, spaced an average of 30 m apart (Table 1; Figure 2). Sets 2 and 3 are less extensive (at 0.21 km^2 and 0.17 km^2, respectively) and contain fewer ridges (5 and 4). Both have a ridge spacing of around 40 m. Ridge Sets 1-3 are covered in dense *Coccothrinax* shrub (Smith, 1992; Robinson and Davis, 1999; Figure 3a). Vegetation cover across Ridge Set 4 is noticeably less dense, as shrubs are largely absent and patches of dune grass dominate the flora (Figures 3b and c).

Stratigraphic architecture

Two distinct radar facies are mapped within the upper 4 m of Sandy Hook's subsurface. These represent major sedimentary environments geologic processes of deposition of the beach system—foreshore and aeolian dune. The foreshore facies is characterized by parallel and shoreward-inclined radar-reflection surfaces, representing foreset beds of an advancing shoreline intertidal environment (Figure 4). Slopes of these inclined strata range

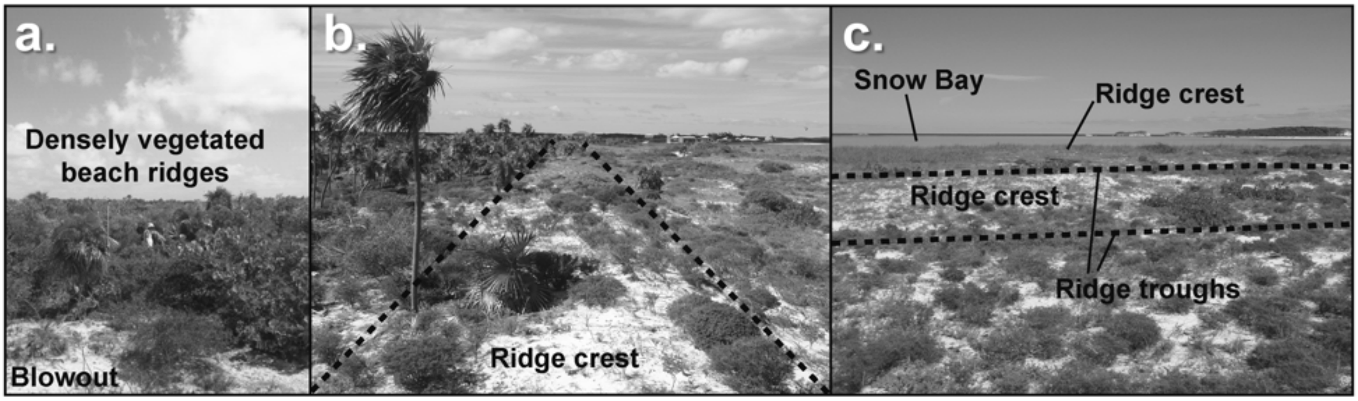

Figure 3. Field photographs taken in March of 2015, showing examples of the densely vegetated, shore-distal portion of the strandplain (a), and the sparsely-vegetated shore-proximal portion in coastal strike (b) and dip (c) orientations. The dense vegetation depicted (a) exemplifies Coccothrinax shrub (Robinson and Davis, 1999).

from 13° to 27° and there are no strong distinctions between ridge sets. While foreset slopes of Ridge Set 2 range from 15° to 27°, those for Sets 3 and 4 are between 13° and 20° (Table 1). GPR failed to image the internal architecture of Ridge Set 1 due to strong signal attenuation just below the surface. It is likely that the proximity to Pigeon Creek and diagenetic effects of sediment-groundwater interactions may be the cause.

The bottomsets of prograding clinoform profiles were not imaged in our dataset. Carney et al. (1993) report depth-to-bedrock ranges between 6.5 m and 10.5 m. Topset beds, which generally reflect accretion in backshore (e.g. berm) environments, were mostly found to be absent. Foreshore sediments are unconformably overlain by aeolian sands and/or road fill, recognized in radar imagery as parallel-horizontal reflections within the uppermost 1-1.5 m of the subsurface (Figure 4).

Disconformities mapped using GPR do not correlate distinctly with ridge-set boundaries delineated from aerial photographs. Line 26, for example, was collected across the shore-distal portion of Ridge Set 4 (Figure 2b) and is shown to contain around 10 distinct sedimentary packages, each bound by erosional surfaces (Figure 4a). However, only 3-4 ridges are recognized in aerial photographs (Figure 2b). GPR Lines 35 and 61, collected across Ridge Sets 2 and 3 (Figures 4b and 4c), are characterized by a similar degree of subsurface complexity. Again, many more signs of erosion are imaged using GPR than are inferred by aerial photography. This makes linking architectural elements of the subsurface to surficial ridge morphologies difficult. It seems that even major set-bounding ridgelines are not distinguished in the subsurface. Although aerial photographs show Line 61 crossing the boundary between Ridge Sets 2 and 3 (Figure 2), no stratigraphic manifestation of what is interpreted as a major event is distinguished among the handful of erosional surfaces recognized in the reflection imagery (Figure 4c).

DISCUSSION

A model of landform succession is presented for the Sandy Hook strandplain. No absolute geochronology exists for this framework; it is based on key stratigraphic and geomorphologic principles alone. The evolution of Sandy Hook is likely to have taken place over the last 3-5 ka, based on sea-level reconstructions, constraint of bedrock topography, and the proposed timing of initial platform inundation (Boardman et al., 1988; Boardman and Carney, 1992). A reduction in the rate of sea-level rise from 1.7 m/kyr (from 3-6 ka) to 0.3 m/kyr (from 0-3 ka) likely facilitated the growth of the strandplain.

Sediment accommodation and strandplain development

Variances in beach-ridge height, spacing, and/or orientation are commonly attributed to changing

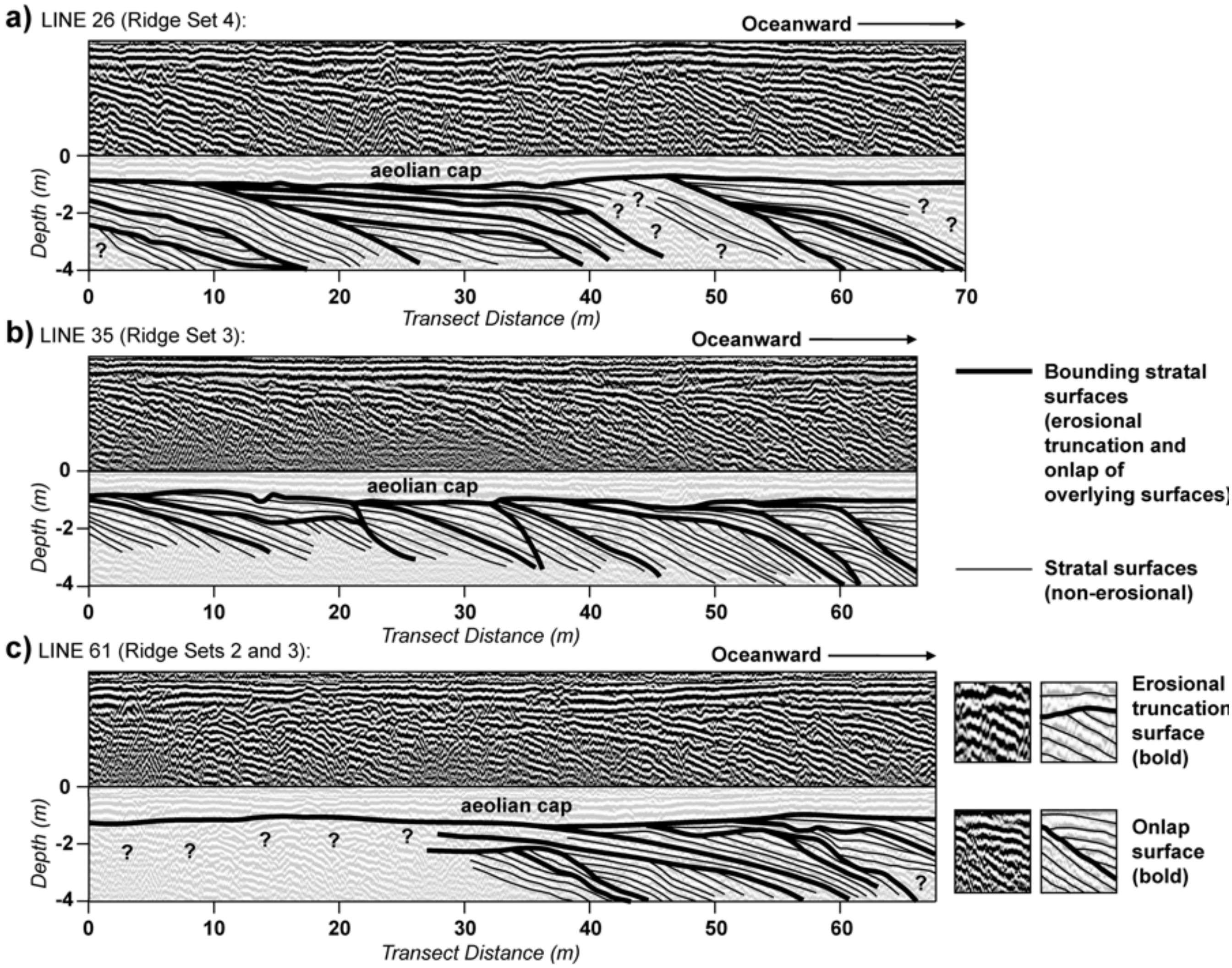

Figure 4. Raw and interpreted GPR reflection images of portions of Line 26 (a), Line 35 (b), and Line 61 (c). Locations are shown in Figure 2. Interpreted surfaces are traced in two distinct thicknesses, emphasizing cross-cutting relationships. Parallel-horizontal reflection configurations are not traced, but labeled 'aeolian cap'. Shoreward-inclined radar surfaces represent prograding foreshore deposits. Depths are based on an averaged radar velocity of 0.1 m/ns, derived by hyperbola fitting during post-processing.

hydrodynamic conditions (e.g. sea-level rise and storm climate) and/or sediment supply (Tanner, 1988; Taylor and Stone, 1996; Mattheus, 2016). While this study lacks detailed topographic information, ridge spacing and orientation, well-constrained from aerial photographs, should reflect the nature of hydrodynamic forcing. Ridge Set 1, representing the oldest preserved episode of progradation, has the widest ridge spacing (at around 50 m), while Set 4, the youngest, is affiliated with the narrowest (at around 30 m; Table 1; Figure 2b). These end-members represent an environmental gradient. The reduction in the rate of sea-level rise and/or the progressive loss of shallow-water shelf area fronting the active beach (due to sedimentation; Figure 5) are likely culprits for the observed morphologic variances. Sandy Hook's present shoreline is around 1 km seaward of Ridge Set 1. An additional 4-5 km^2 of shallow-water shelf area would have therefore characterized the initial growth phase, factoring into different wave run-up and littoral

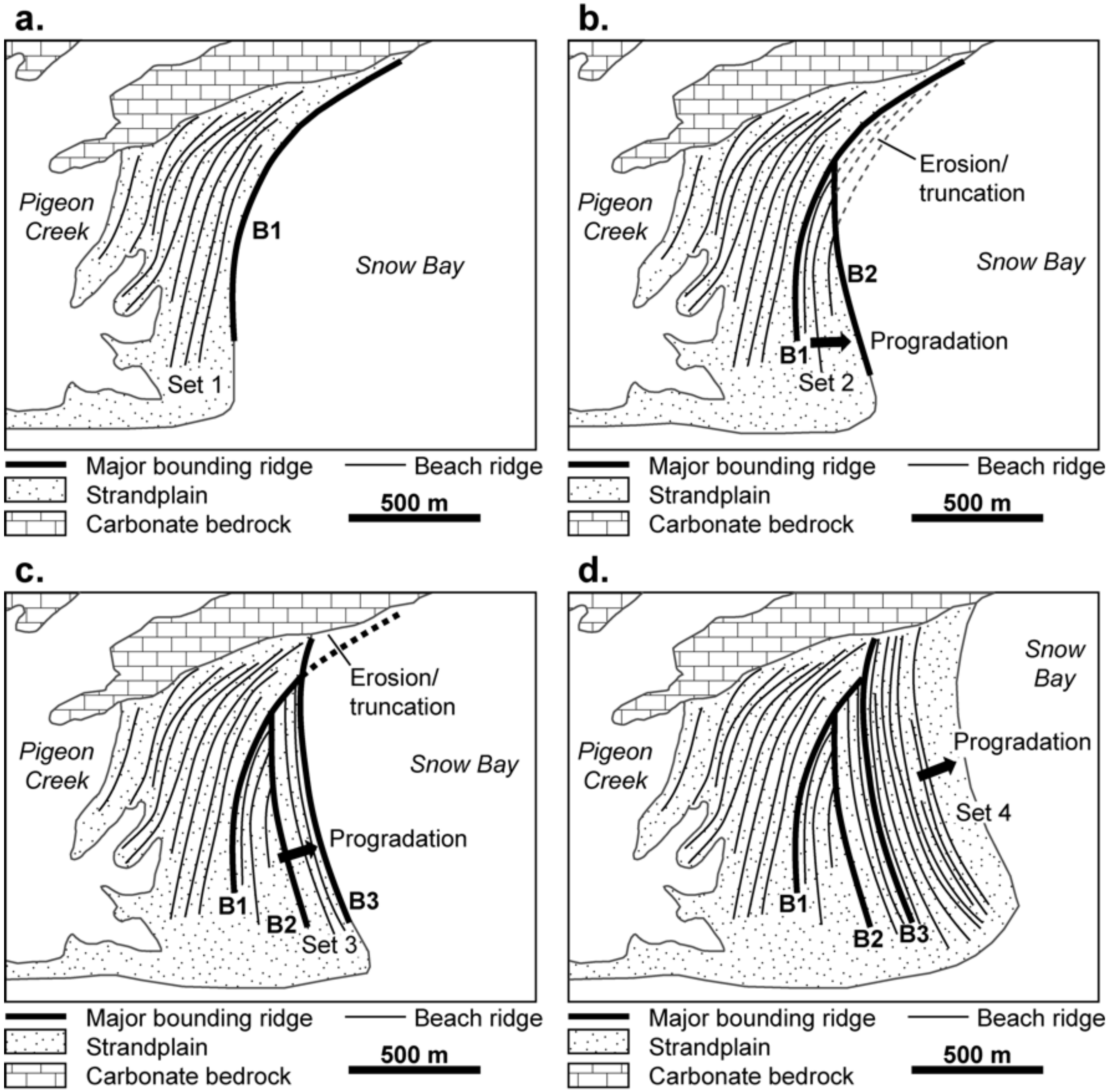

Figure 5. Model of landform succession for Sandy Hook in four stages: 1) The initial growth phase constructed Set 1, the portion of the strandplain closest to the western arm of Pigeon Creek (a); 2) Continued progradation created Set 2, which became truncated by B2 (b); 3) Following another episode of progradation (Set 3), erosional ridgeline B3 truncated the northern extent of the strandplain, including beach ridges of Set 1 (c); and 4) Steady strandplain growth (Set 4) ensued into modern times (d).

dynamics. Additional support to the idea of changing hydrodynamics is provided by the documented presence of ooids in foreshore deposits of Ridge Set 1 (Carney et al., 1993). Ooids, which are absent in today's beach sands, form under conditions of repeated grain resuspension and $CaCO_3$ coating under agitated water conditions (common to shoaling environments). Sandy Hook's early development might have favored such conditions, given the larger shelf area (i.e. of Snow Bay; Figure 5). However, a change in sediment source cannot be ruled out as their presence possibly relates to the reworking of ooid-rich Pleistocene dune deposits during early shelf inundation (Boardman and Carney, 1992).

Climate forcing

Insights by Boardman et al. (1988) and Boardman and Carney (1992) into the timing of platform inundation imply that the early growth of Sandy Hook occurred during the Hurricane Hyperactivity Period (HHP), which lasted from around 3.4 to 1.0 ka (Liu and Fearn, 2000). Lacustrine deposits along San Salvador's perimeter contain evidence of this period of heightened Caribbean storminess manifested as coastal washover layers (Park, 2012; Mattheus and Fowler, 2015; Mattheus and Yovichin, 2018). It is possible that the relatively large ridge spacing of Set 1 relates not only to the presence of a more extensive shallow-water shelf area during early strandplain development (Boardman and Carney, 1996), but also heightened storm activity and/or severity. While lack of an absolute geochronology prevents a more detailed reconstruction, the aerial extents of individual ridge sets may offer some insight into the relative timing of formation. Set 4 represents the most recent episode of progradation and is likely to be the most complete, given lack of truncation by the modern shoreline (Figure 5). It represents 39% of Sandy Hook's aerial extent and is thought to have formed during the quiescent period of the last 1,000 yrs. The uniform (and narrow) ridge spacing and sparse vegetation cover, which differentiate this portion of the strandplain from older ridge sets, support the idea of a fundamental hydrodynamic shift. That this occurred with the transition from HHP is suggested by the proportionality of the 1,000 yr timeframe, representing around a third of the evolutionary history of Sandy Hook based on insights by Boardman et al. (1988) and Boardman and Carney (1992), and the relative size of Set 4 (at ~39% of Sandy Hook's area). It must be stated that the sizes of ridge sets at their full extent (before truncation) are unknown and that older strandplain materials recycled by wave erosion have been incorporated into younger ridges, offsetting temporal linkages between morphology and implied environmental change.

Establishing more distinct causal linkages between late Holocene climate change and patterns of strandplain growth requires chronostratigraphic constraint. This is difficult to achieve in carbonate environments, where dating using Optically-Stimulated Luminescence, the preferred means of dating beach ridges and dunes in siliciclastic environments (Nott et al., 2009; Tamura, 2012), cannot be employed. Regardless of these shortcomings, the evolutionary model of Sandy Hook provides conceptual insights into carbonate strandplain morphodynamics that offer comparison to siliciclastic system analogs.

Comparison to siliciclastic analogs

Several characteristics distinguish Sandy Hook from siliciclastic margin analogs. First, the nature of sediment supply varies as a function of intrinsic production rate and delivery. While climatic and hydrodynamic factors influence sediment delivery, in a carbonate system there is no reliance on a terrigenous source. In contrast, siliciclastic strandplains, such as those associated with river deltas, rely heavily on fluvial inputs, which can vary significantly over time. Systems along regressive portions of compound barrier islands can also benefit from high littoral sediment supply. Second, Sandy Hook's partial confinement by San Salvador's Pleistocene carbonate-bedrock topography set the bounds of sediment accommodation and determined the direction of strandplain growth. Siliciclastic systems (e.g. barrier islands), on the other hand, are for the most part unconfined. There are few restrictions on lateral movement, which often comes at the expense of older landforms as ridge preservation by means of shoreline progradation is inhibited (Mattheus, 2016). Sandy Hook more closely resembles embayed strandplains of the Laurentian Great Lakes, which are similarly perched atop shallow bedrock platforms and experience a progressive loss of accommodation space (albeit as a function of isostatic uplift in addition to sedimentation). Unlike carbonate strandplains, these systems also undergo cyclical changes in lake level (at seasonal to decadal timescales), which superimpose on the effects of isostatic uplift (Johnson et al., 2012). From a base-level perspective, Sandy Hook is more comparable to other oceanic (i.e. passive margin) systems, experiencing the effects of progessive late Holocene sea-level rise.

CONCLUSIONS

The depositional architecture of the Sandy Hook strandplain is mapped using GPR and aerial photographs. The resulting model of landform succession suggests that changing environmental conditions are responsible for variances in the spacing and orientation of beach ridges. Four distinct ridge sets, defined by an overall decrease in ridge spacing over time, are separated by erosional strandlines that truncate older landforms obliquely. The subsurface shows that there are many more discontinuities; however, no correlation is established between subsurface structures and surface topography. Older ridge sets are characterized by larger ridge spacing than more recent ones and were likely emplaced during a period of increased hurricane activity at ca 3.5 to 1 ka (Liu and Fearn, 2000). Additional work, particularly constraint of landform ages, is needed to more closely establish linkages between late Holocene climate and Sandy Hook's geomorphology.

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