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DOME AND COPPICE DUNES: A REINTERPRETATION OF HOLOCENE CARBONATE EOLIANITES, NORTH POINT, SAN SALVADOR ISLAND, THE BAHAMAS

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ABSTRACT

Earlier studies of the North Point Member, Rice Bay Formation on San Salvador Island, Bahamas clearly indicated sedimentation by wind during Holocene time. New views presented in this report of the internal structure of bedrock mounds and inter-mound swales, which characterize the physical appearance of the North Point Member, compelled a revisit to North Point and suggest dome dunes as the parent eolian dune for the North Point Member. Parallel, laterally continuous, and inversely graded *cyclic laminae* are the primary architectural elements that dominate internal structure in both bedrock mounds and swales. In bedrock mounds, these laminae preserve entire dune-forms in windward-set, topset, brinkset, foreset, and toeset strata. In bedrock swales, they record near horizontal sedimentation. Sets of *slipface crossbeds*, deposited by short-lived grainflows on dune slopes, are localized, secondary architectural elements. The cryptic nature of eolian *grainfall strata* renders them challenging to discern in outcrop. They are generally identifiable in association with slipface crossbeds and are subordinate architectural elements in eolian dome dunes.

Rainfall and coastal moisture rendered the dome-dune sand cohesive. Consequently, slipface grainflows depositing foreset sandflow strata were infrequent. Elliptical outlines exposed on a wave-cut bench on the east side of the North Point peninsula are erosional remnants of small-scale, elongate coppice dunes that accreted vertically by sand-trapping plants at the coastal margin of the main dune field. Axes of elongation of these coppice dunes are northeast-southwest, a trend consistent with inferred flow of Northeasterly Trade Wind at the time. Abundant wind-ripple laminations, scarcity of sandflows, mound-swale landscape of the present-day North Point peninsula, and the near 360^{o} span of dip azimuths of foreset cyclic laminae, bedset bounding and reactivation surfaces, and bedrock-mound-slopes argue for dome dunes that deposited the main dune ridge of the North Point eolianites. In the path of unobstructed Northeast Trade Wind, calcareous crusts and coastal plants enhanced vertical accretion and lateral expansion of eolian dome dunes to create the North Point peninsula during Holocene time on San Salvador.

INTRODUCTION

Overview

Quaternary geologic history of San Salvador Island, the Bahamas, is preserved in carbonate sedimentary rocks that were deposited in coeval reef, nearshore shelf, beach, and wind-blown environments. Sand-sized skeletal parts of once-living organisms: shell, coral, and algal fragments, and sand-sized nonskeletal grains: ooids, fecal pellets, and peloids constitute the framework grains (allochems) that have been biomineralized mainly by invertebrate organisms on the nearshore marine shelf. Rocks composed of such framework grains are classified as carbonate sandstones or *calcarenites* (Grabau 1904; Pettijohn 1957), “sparites” (Folk 1962), and grainstones (Dunham 1962). Sayles (1931) introduced the term, *eolianites* (aeolianites, British spelling), for sedimentary rocks deposited in wind-blown or *eolian* environments. The paradox for general carbonate eolianites is that the framework grains are typically created in either a marine or subaqueous environment. For modern and ancient Bahamian carbonate eolianites, constituent sand-sized grains were formed by mainly biogenic processes on the nearshore marine shelf. Later, grains were transported by wave-, tidal-, and storm-currents, deposited on beaches, and ultimately reworked and deposited by eolian processes to form what is considered a nonmarine or terrestrial deposit of dunes, interdunes, and dune-field margins.

Geologic and Geographic Setting

The Great Bahama bank or platform of the North Atlantic Ocean is a structural feature built mostly of carbonate sedimentary rocks as old as Jurassic and some older evaporite and siliciclastic sedimentary rocks underlain by deformed continental lithosphere of the North American tectonic plate (Kindler *et al.* 2010; Mullins and Lynts 1977). The Bahamas are a chain of islands emerging from carbonate platforms and extend southeastward from Grand Bahama Island to Great Inagua Island; weather and climate are influenced by the Northeast Trade Winds (Figure 1). San Salvador Island emerges from a small, isolated carbonate platform east of the Great Bahama Bank, and has served for decades as a center for geologic, archeologic, anthropologic, oceanographic, and biologic research supported by housing, conference, and laboratory facilities at the Gerace Research Centre (GRC) located on northern San Salvador (Figure 2A).

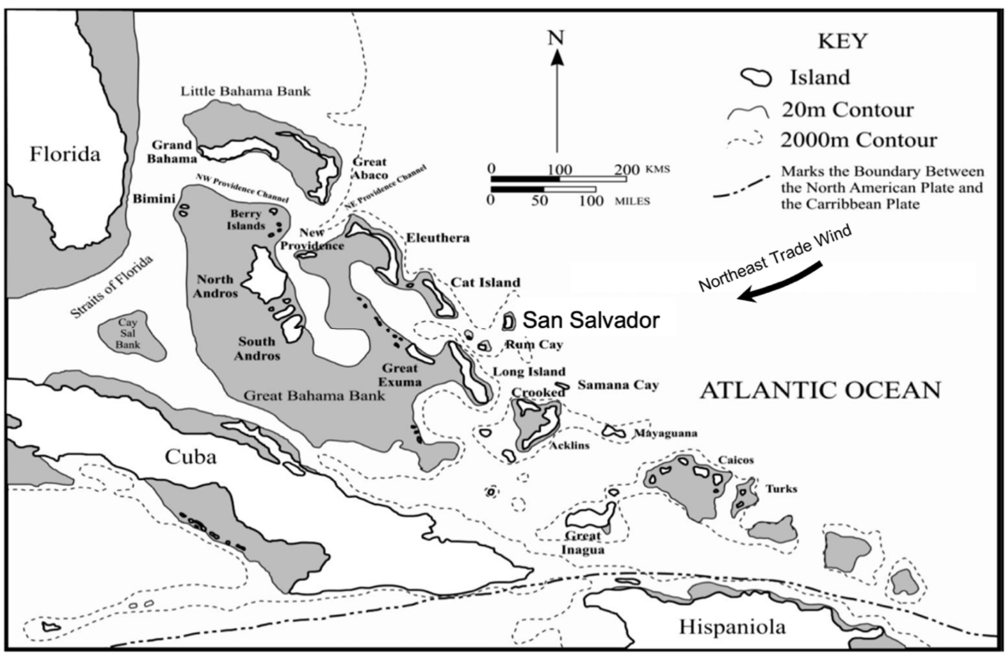
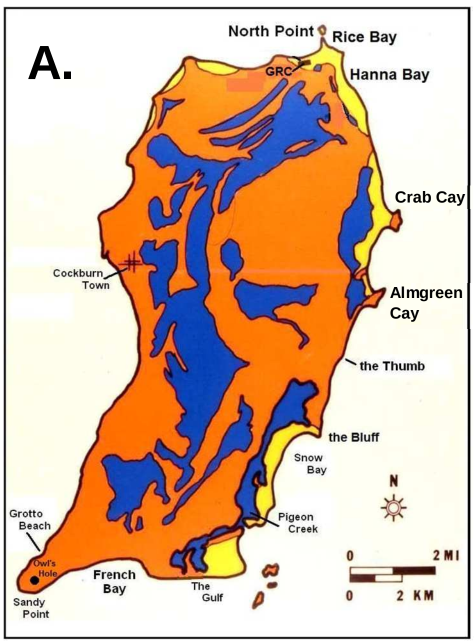


Figure 1. The Bahama Islands, including San Salvador, and the carbonate platforms (gray) from which they emerge in the North Atlantic Ocean. Gray areas at the margins of Florida, Cuba, and Hispaniola show extent of continental shelves. Adapted from Walker (2006) in Kindler et al. (2010) and used with permission from Gerace Research Centre.

Stratigraphic Setting

Orange- and yellow-colored areas on a simple geologic map of San Salvador Island (Figure 2A) show the generalized areal distribution of respective Pleistocene and Holocene sedimentary bedrock and correspond with the orange- and yellow-colored lithostratigraphic intervals of Figure 2B. The pioneering work of Carew and Mylroie (1995) refined the stratigraphic work of earlier geologists and built the original stratigraphic framework for San Salvador that proved useful for the greater Bahamas. Type localities were designated on San Salvador for the enduring lithostratigraphic units: the Pleistocene Owl's Hole and Grotto Beach Formations, and Holocene Rice Bay Formation, and respective member subdivisions. Kindler *et al.* (2010) supplemented this lithostratigraphic framework by recognizing units correlative with the Owl's Hole and Grotto Beach Formations on Great Inagua and Eleuthera Islands. They further recognized a lower Pleistocene Misery Point Formation on Mayaguana Island (southeast of San Salvador, Figure 1), an uppermost Pleistocene Whale Point Formation on Eleuthera Island (northwest of San Salvador, Figure 1), and Miocene and Pliocene deposits on Mayaguana Island.



B.

AGE			LITHOSTRATIGRAPHIC UNITS	
			Formation	Member
Cenozoic	Quaternary	Holocene	Rice Bay	Hanna Bay
				North Point
		Late Pleistocene	Whale Point	
			Grotto Beach	Cockburn Town
				French Bay
		Middle Pleistocene	Owl's Hole	
		Early Pleistocene	Misery Point	
	Neogene	Pliocene	unnamed sedimentary rocks	
		Miocene		

Figure 2. Bedrock lithostratigraphy and geography of San Salvador Island, the Bahamas. A. A generalized geologic map of San Salvador Island shows the areal distribution of middle and late Pleistocene (orange) and Holocene (yellow) lithostratigraphic units and their type locations. Pleistocene: Owl's Hole Fm (Owl's Hole), Grotto Beach Fm (Grotto Beach), French Bay Mbr (French Bay), Cockburn Town Mbr (Cockburn Town). Holocene: Rice Bay Fm (Rice Bay), North Point Mbr (North Point), and Hanna Bay Mbr (Hanna Bay). Colors correspond with those in Figure 2B. Other map features: interior bodies of water (blue), and Gerace Research Centre (GRC). Modified from Carew and Mylroie (1995). B. Quaternary and older lithostratigraphic units defined for the greater Bahamas. Only the Pleistocene Owl's Hole and Grotto Beach Formations and Holocene Rice Bay Formation are recognized on San Salvador Island. Redrawn from Carew and Mylroie (1995) and Kindler et al. (2010).

Purpose and Goals

This paper summarizes the results of a field study of Holocene eolianites exposed along the North Point peninsula, San Salvador Island, the Bahamas, conducted during summers, 2010 and 2013. The goals are to document sedimentary details that characterize the internal structure of the North Point Member, Rice Bay Formation, and to present an alternative interpretation on the type of eolian dune that deposited this eolianite.

Years before undertaking this study, I noticed bimodal foreset dip-directions in crossbed sets in the North Point Member, westward on the west side of the peninsula and eastward on the east side of the peninsula. I proposed testable hypotheses and field work to explain the bimodal dip pattern of foresets. One hypothesis is that westward-dipping foresets reflect normal northeasterly Trade Wind directions while eastward-dipping foresets reflect times of reversals in the Northeasterly Trade Wind, possibly related to El Niño conditions in the Pacific Ocean. A second hypothesis is that westward-dipping foresets reflect times of normal fair-weather flow of the Northeast Trade Winds, while eastward-dipping foresets reflect occasional storm winds blowing from the west, temporarily supplanting the Northeasterly Trade Wind. However, these hypotheses are refuted in this paper by evidence for eolian dome dunes and inter-dome swales.

Study Site and Methods

Within a 1.6 km (1.0 mile) walk eastward from the Gerace Research Centre lies North Point of San Salvador Island. It is a narrow ridge of rock, extends due north from the island proper, and is the northernmost point of land for the island (Figures 3A, B). In this report, the entire narrow ridge of rock is referred informally as the North Point peninsula. The peninsula once extended further north to where the island of Cut Cay is today. Sometime within the last 500 years, continued wave erosion broke through a low-lying narrow strip of land and detached the present-day North Point peninsula from Cut Cay (White and Curran, 1985). Fully accessible ground surface and moderately accessible rocky and sandy shore lend themselves to an investigation of the morphology and internal structure of Holocene carbonate eolianites preserved in the North Point Member, Rice Bay Formation.

Eleven accessible study sites on North Point peninsula were selected where photographs were taken, sketches were drawn, eolian strata were identified, and partial stratigraphic sections were measured and described. Angles and azimuth of dip of internal strata and of slopes of bedrock mounds were measured with a Brunton™ pocket transit. Sites are labeled according to their location on the east side of the peninsula as sites E1 through E10, and on the west side as site W1 (Figure 4). Stratigraphic sections were constructed by hand-leveling up from the shoreline to the highest level of exposure of a bedrock mound. Some photographic views are from the footpath that runs along the length of the peninsula northward from the Queen's Highway.

PREVIOUS WORK ON CARBONATE EOLIANITES

Historical

Since the central work on siliciclastic sediment by Henry Clifton Sorby in the 1800s, much experimentation and field work have advanced an understanding of how unconsolidated sediment is transported at the sediment-fluid interface by flowing water (subaqueous) and wind (eolian) to create bedforms such as ripples and dunes and internal architecture of cross-stratification. Eolian cross-strata have been

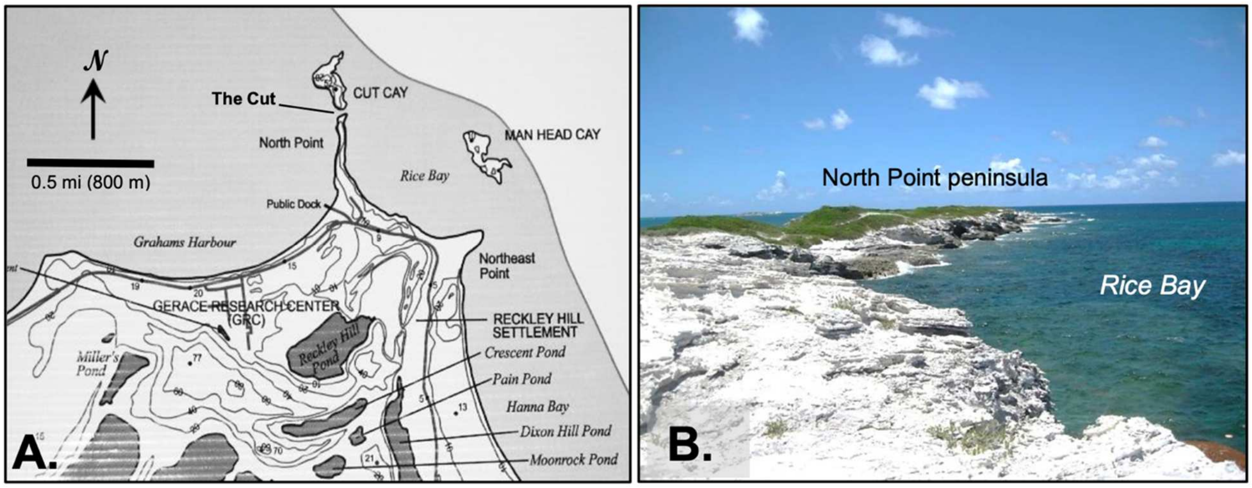


Figure 3. The North Point peninsula, northern San Salvador Island. A. Map perspective of the North Point peninsula relative to the Gerace Research Centre (spelled "Center" on map) and neighboring locations: Man Head Cay, Rice Bay, Grahams Harbour, Cut Cay, and the Cut. Courtesy of Gerace Research Centre, © 2003, and Department of Geological Sciences, Indiana University, Bloomington. B. Peninsula surface of bedrock mounds and plant-overgrown eolian sand hills. Eastern shoreline of formidable bedrock mounds modified by waves into headlands and rocky coves.

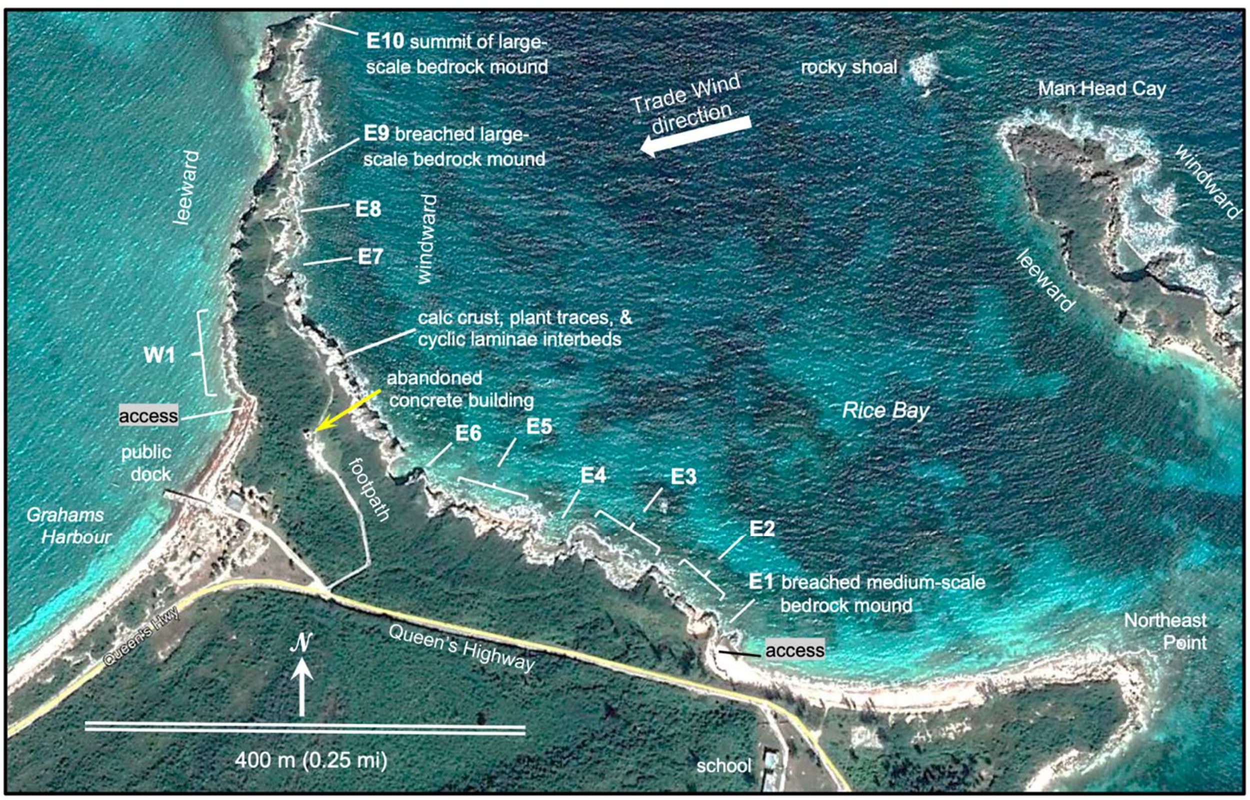


Figure 4. Aerial view of the North Point peninsula, San Salvador Island. Marked are locations of study sites where observations of surface and internal architecture of bedrock mounds and swales were recorded, measured, and photographed for this study. Study sites on east side are E1-E10. Study site on west side is W1. Image extends only to the northern tip of North Point peninsula. The "Cut" and Cut Cay are not shown. Image courtesy of Google Earth.

recognized in modern and ancient carbonate sand and sandstones (i.e. calcarenites) since the time of Charles Darwin during his voyages on the *HMS Beagle* in the early 1850s (Fairbridge 1995). Nelson (1837) is probably the first to make note of cross-stratified carbonate eolianites as a significant component of the bedrock of Bermuda, and Nelson (1853) drew some of the earliest sketches of carbonate "aeolian rock" from the Bahamas. Evans (1900) is acknowledged for his detailed study of the internal structure of carbonate eolianites in India. McKee and Ward (1983) assembled an encyclopedic reference on carbonate eolianites known in areas of the world where wind, climate, and marine conditions combine to build and preserve cross-stratified carbonate eolian dunes. Abegg *et al.* (2001) provided a much needed overview of carbonate eolianites and assembled a line-up of papers by authors who recognized ancient carbonate eolianites ranging in age from Paleozoic to Quaternary. Noteworthy in that book is the paper by Blay and Longman (2001), who identified cross-stratified carbonate eolianites on the volcanic island of Kauai, Hawaii.

On San Salvador Island

Previous work on the Quaternary calcarenites on San Salvador offered early interpretations on morphology and internal structure of formative eolian dunes. Adams (1980) and geoscientists after him have recognized the striking cross-stratified internal structure of Quaternary carbonate eolianites on San Salvador Island, and complementary terrestrial features: root and stem casts of plants, insect burrows, subaerial crusts, paleosols, and invertebrate fossils. Adams (1980) further alluded to mound- or dome-like Holocene dunes on the North Point peninsula when he described large-scale cross-strata on leeward, windward, and flanking dune slopes but considered the dune morphology as lobate, as did White and Curran (1985, 1988). Caputo (1995) applied azimuth measurements of crossbed foresets and linear trends in remnant paleo-topography and concluded that the French Bay and Cockburn Town Members of the Pleistocene Grotto Beach Formation were deposited by lobate, sinuous-crested dune ridges in northeasterly wind along the southern and eastern margin of San Salvador.

For an eolian dune, a set of cross-strata or foresets is usually comprised of sandflow beds deposited by grainflow or sand avalanches on dune slopes. Typically associated with eolian sandflows are inversely graded laminations deposited by migrating wind ripples, and fine-grained grainfall strata deposited by sand settling from suspension in wind (Hunter 1977a, 1981) (Figure 5). White and Curran (1985, 1988) recognized signature eolian ripple-, grainfall-, and sandflow-strata in the Holocene North Point Member, Rice Bay Formation on the North Point peninsula on San Salvador Island. In their 1988 paper, they were first to notice the association between grain texture, diagenesis, and weathering patterns of the different eolian strata in the Holocene North Point Member. This association was further demonstrated not only in eolian strata of the North Point Member but in recognizable eolian strata in Pleistocene calcarenites cropping out at the eastern, southern, and southwestern margins of San Salvador by Caputo (1989, 1993, 2015). In those studies, thin sections revealed that textural and diagenetic traits of wind-ripple-, grainfall-, and sandflow-strata can be correlated directly to weathering patterns seen in outcrops. Finer grained, tightly packed, and well cemented strata as in grainfall laminations and in basal parts of inversely graded wind-ripple laminations, weather into protruding micro-ledges. In contrast, coarser grained, loosely packed, and poorly cemented strata, as in sandflow beds and in upper parts of inversely graded wind-ripple laminations, weather as micro-recesses.

Wind-ripple strata in modern and ancient carbonate and siliciclastic deposits differ from water-ripple strata by their thin, upward coarsening laminations and faintly developed foreset laminations (Figure 6). Comparative features of eolian and subaqueous ripple strata summarized in Table 1 are derived from studies of siliciclastic sediments and rocks but apply also to carbonate eolian deposits. The presence of inversely graded wind-ripple laminations are positive indicators of an eolian origin for modern and ancient deposits that preserve them (Hunter 1981; Kocurek and Dott 1981.

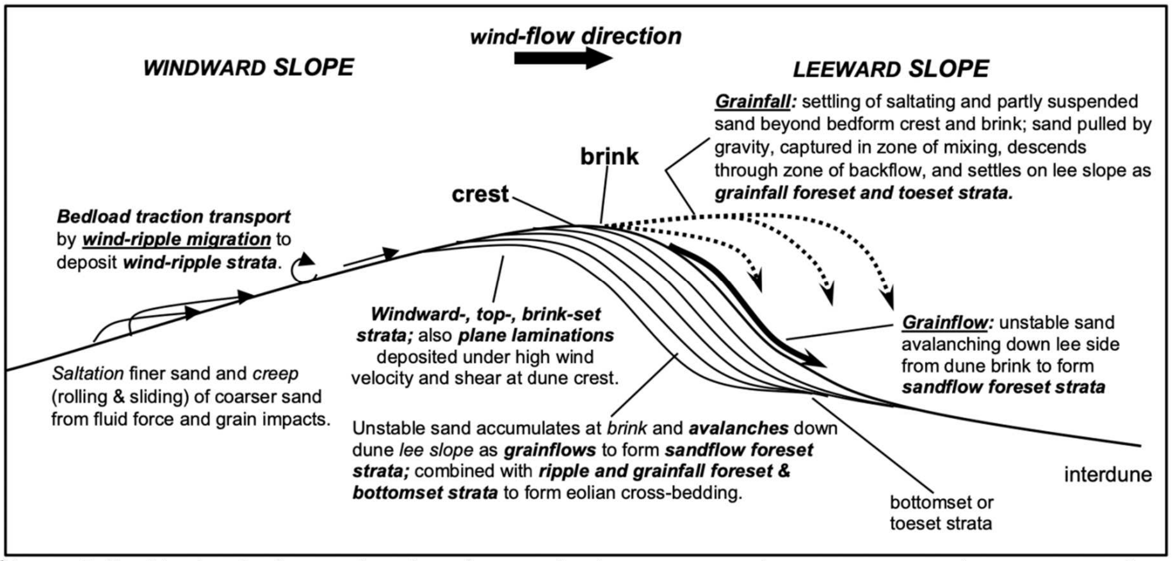


Figure 5. Profile sketch of a simple eolian dune, and eolian processes that create essential components of internal structure: 1) wind-ripple migration by traction transport (saltation and creep) to form wind-ripple strata, 2) grainfall of partly saltating and suspended sand settling on leeward slope of dune to form grainfall strata, and 3) grainflow of unstable sand avalanching down leeward slope to form sandflow foreset strata (from Caputo 2017; used with permission from Pacific Section SEPM, Society for Sedimentary Geology).

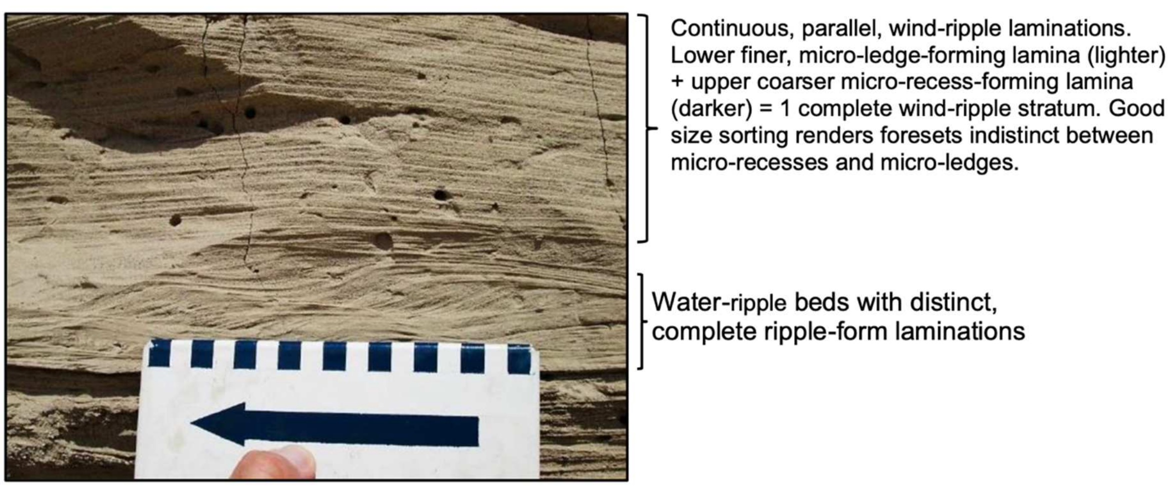


Figure 6. Contrasting wind- and water-ripple strata in siliciclastic sand. Exposure is in valley wall in alluvial Carrizo Wash, Anza-Borrego Desert, California. Water-current flow was to the left. Paleo-wind direction is indeterminable in the absence of distinct ripple foreset-laminae. Scale is in centimeters (modified from Caputo, 2017). See Table 1.

Table 1. Comparison of sedimentary characteristics between wind-ripples and water-ripples and their deposits (from Caputo, 2017; used with permission from Pacific Section SEPM, Society for Sedimentary Geology). See Figure 6.

Sedimentary Characteristics		Wind-Ripples	Water-Ripples
Bedform	Amplitude	**2-10 mm (0.08-0.40 in)** (Collinson et al., 2006; Hunter, 1977a)	**up to 6-8 cm (2.4-3.2 in)** (Ashley, 1990)
	Spacing	**5-20 cm (2-8 in)** (Lancaster, 1995)	**10-20 cm (4.0-8.0 in)** (Harms et al., 1982)
Grain Texture	Size	**Very fine- to medium-grained sand** (Lancaster, 1995)	**Silt to coarse-grained sand** (Middleton and Southard, 1984)
	Sorting	**Good** (based on above grain-size range)	**Poor** (based on above grain-size range)
	Grading	**Inverse/Upward-coarsening** (Collinson et al., 2006; Schenk, 1983)	**Normal/Upward-fining** (Simons et al., 1965)
Internal Stratification	Strata Thickness	**typically 1-10mm (0.04-0.4 in); average 2.0 mm** (Hunter, 1977b)	**Up to 6-8 cm (2.4-3.2 in)** (based on ripple amplitude)
	Cross-lamination	**Faintly developed cross-laminae** (Hunter, 1977a; Kocurek and Dott, 1981)	**Well-developed cross-laminae** (Kocurek and Dott, 1981)

KEY PHYSICAL FEATURES OF THE HOLOCENE NORTH POINT MEMBER ON NORTH POINT

Present-day Mound-Swale Topography

One key feature that lends support to the eolian-dune origin for the Holocene North Point Member is the present-day topography of the North Point peninsula. High-relief *bedrock mounds* and low-relief inter-mound *bedrock swales* are the characteristic physiographic features expressed by the North Point Member (Figures 7A-D). Ideal exposures are on the windward side of the North Point peninsula; from the nearest approach of the Queen's Highway near Rice Bay beach to the end of the peninsula (Figure 4). Bedrock mounds are exactly that; dome or hemispherical, positive-relief surface features. They are semi-circular to semi-oval in map view and vary in height from south to north, from the island mainland to Cut Cay, along the axis of the peninsula. From the eastern limit of the sandy beach at Rice Bay, bedrock mounds are only a few meters high. Continuing northward, bedrock mounds peak at more than 10 m (33 ft) in height about midway along the peninsula then decrease to less than 10 m (33 ft) in height approaching the tip of the peninsula and beyond to Cut Cay (Figure 8).

Internal stratification of Bedrock Mounds and Inter-mound Swales

Internal sedimentary architecture or structure of bedrock mounds and swales of the North Point peninsula further supports a re-interpretation of the eolian-dune origin for the Holocene North Point Member on San Salvador as follows: 1) internal stratification mimics and is parallel to the hemispherical shape of bedrock mounds, 2) internal strata and mound slopes dip in nearly all compass directions (see Table 2), and 3) the internal strata of bedrock mounds are laterally continuous with strata of inter-mound swales (Figures 7A-D).

Depositional and erosional processes operating in a sedimentary environment impart an internal arrangement of sedimentary components - architectural elements or internal structure- to a body of sediment or sedimentary rock. They yield clues as to how the deposit was constructed. Architectural elements are the building-blocks of a sedimentary deposit and range in scale from framework grains and intergranular pores (Caputo 1995) to the sediment fill of basins (Walker 1992).

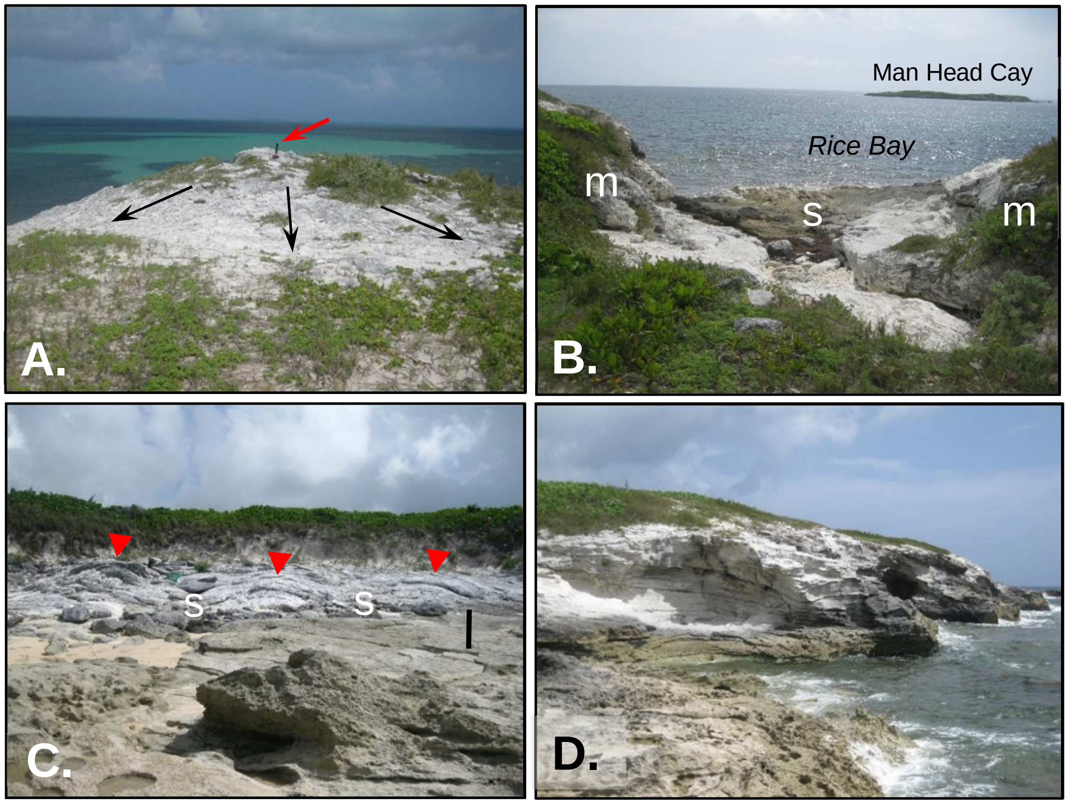
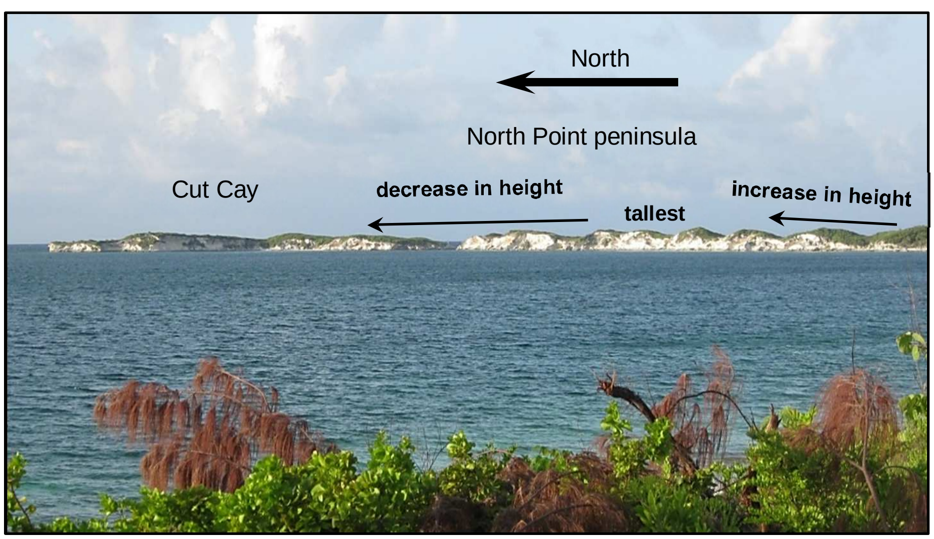


Figure 7. Outcrop features of the Holocene North Point Member, North Point peninsula, San Salvador Island. A. Large-scale bedrock mound exposed at study site E10 near the northern limit of the peninsula. Black arrows indicate slope directions of mound surface and dip of internal stratification. Red arrow points to short sledgehammer for scale. B. Bedrock swale (s) wetted by high tides and storm waves between headland-forming bedrock mounds (m). View from eastern North Point peninsula toward Rice Bay and Man Head Cay. C. Small-scale bedrock mounds (red triangles) with surfaces and internal bedding laterally continuous with that of inter-mound swales (s) overlain by modern eolian sand and maritime plants. Black scale bar is 1 m (3.3 ft) long. Rocky cove at study site E2. D. Large-scale breached bedrock mound with characteristic convex-upward, arching roof and internal strata. Dip directions of visible surface and internal strata span clockwise from north-northeast to southwest. Study site E9.

Figure 8. Bedrock mound and swale landscape of present-day North Point peninsula and Cut Cay. Mound height increases, reaches a maximum, then decreases northward along the peninsula to Cut Cay. Photograph is approximately the northern two-thirds of the peninsula; photograph taken from the Queen's Highway near front entrance of the Gerace Research Centre.



Eolian architectural elements at the stratification scale are wind-ripple-, grainfall-, and sandflow-strata. They result from wind-ripple, grainfall, and grainflow processes

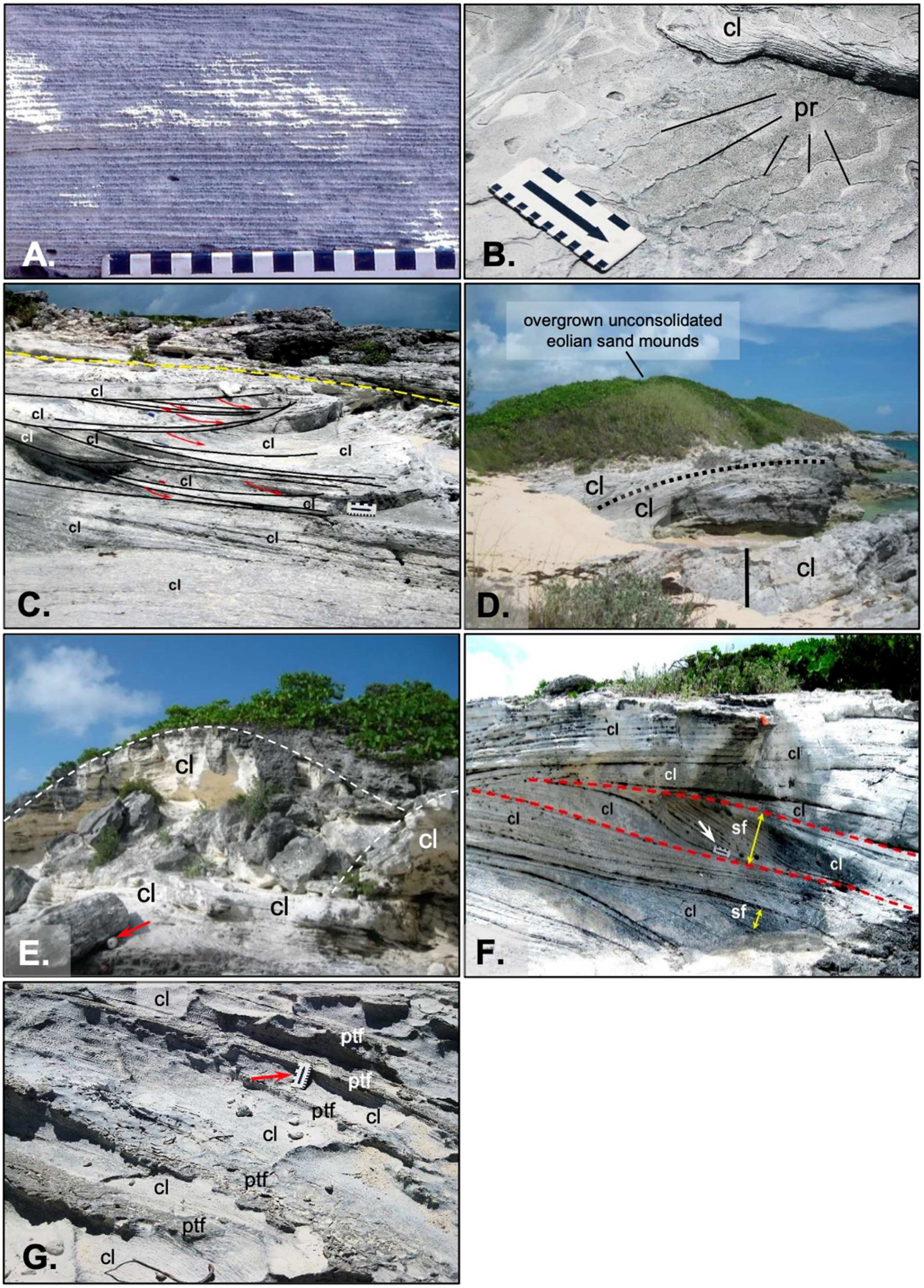
the carbonate eolianites on San Salvador Island. Grain-scale architectural elements for Quaternary carbonate eolianites on San Salvador are described in Caputo (1989, 1993). *Cyclic laminae* and *slipface crossbeds* are the stratification-scale architectural elements that are essential to a discussion of an eolian-dune origin for the North Point Member.

Cyclic laminae. Fine sandy laminations notably constitute the greatest proportion of internal stratification comprising both mound and swale bedrock. They are designated herein as the primary architectural elements in the North Point Member. The descriptive name, cyclic laminae, refers to a persistent recurrence of alternating white and gray laminations (2-5 mm; 0.1-0.2 in thick) of fine and medium calcareous sand grains, the textural, packing, and cementing attributes of which control a weathering pattern of regularly alternating micro-ledges and recesses (Caputo 1989, 1993) (Figure 9A). Cyclic laminae: 1) fill bedrock swales with nearly horizontal, alternating light and dark "pin-stripe laminations" (Fryberger and Schenk 1988) (Figure 9A); 2) weather locally along stratification contacts to form pseudoripples (Kocurek and Dott 1981) (Figure 9B); 3) occur in sets of concave-upward, low-angle foreset laminations, and convex-upward, arching beds that conform to the morphology of bedrock mounds (Figures 9C-F); 4) are punctuated by semi-uniform intervals of calcareous crusts with plant-stem trace fossils (Figure 9G), 5) comprise convex-upward windward-set, topset, and brinkset strata; 6) comprise foreset strata locally interrupted by reactivation surfaces; and 7) completely preserve entire dune-forms (Figure 10).

Slipface crossbeds. Secondary architectural elements in the North Point Member are herein named *slipface crossbeds.* They are what constitute conventional foreset bedding of cross-stratification. However in the North Point Member, their occurrence is markedly lesser in abundance relative to cyclic laminae. They are distinguished by the following characteristics: 1) upward-coarsening, medium-grained texture, 2) beds up to 3.0 cm (1.2 in) thick that taper down-dip into toesets of cyclic laminae, and 3) in transverse view, their lens-shaped cross-sections encased in grainfall strata (Figures 11A, B, C). Erratic northward and southwestward dip azimuths of sandflow crossbeds are inconsistent with those of mound-slopes, cyclic laminae and their bounding surfaces, all of which span nearly 360^o (Table 2).

Grainfall strata. The grainfall sedimentary process and resulting grainfall strata (Figure 5) are found typically interstratified with sandflow beds (i.e. slipface crossbeds of this report) (Figures 11B, C), are addressed in Caputo (1989, 1993, 1995), and are not essential to the reconstruction of the Holocene eolian dunes in this report.

Figure 9 on facing page. Details of interior structure of bedrock mounds and swales, North Point Member. A. Bed of cyclic laminae or "pin-stripe laminations" (Fryberger and Schenk, 1988) cropping out as white finer-grained micro-ledges alternating with gray, coarser-grained micro-recesses. Near vertical exposure of inter-mound swale-fill. Scale is marked in centimeters. B. Cyclic laminae (cl) and associated pseudoripples (pr) on weathered and eroded bedrock surface. Scale is 18 cm (7 in) long. Arrow points in direction of ripple migration and climb. C. Intricate concave-upward sets of cyclic laminae (cl) within bounding surfaces (solid black curves), and interbedded slipface crossbeds (red arrows). Cyclic laminae above yellow dashed line conform to hemispherical shape of bedrock mound. Study site E5. Scale is 18 cm (7 in) long. D. Partial profile of medium-scale bedrock mound composed of cyclic laminae excavated by wave erosion. Study site E1. Black vertical bar is 1 m (3.3 ft) long. E. Intersecting, large-scale bedrock mounds (outlined by white dashed curves) constructed of cyclic laminae (cl). West side, midway along North Point peninsula, north of study site W1. Red arrow points to cylindrical boat-bumper (flotsam) for scale. F. View of interior of upper bedrock mound composed of cyclic laminae (cl) and localized sets of slipface crossbeds (sf) (doubly pointed yellow arrows. Bed outlined by red dashed lines (bounding surfaces) displays down-dip transition from cyclic laminae (cl) to slipface crossbeds (sf) then back to cyclic laminae (cl). Study site E5. Rectangular scale is 18 cm (7 in) long (white arrow). G. Ledge- and bench-forming beds composed of plant-stem trace fossils and calcareous crusts (ptf) alternating with cyclic laminae (cl). Cliff top east of abandoned concrete building (see Figure 8). Scale is 18 cm (7 in) long (red arrow).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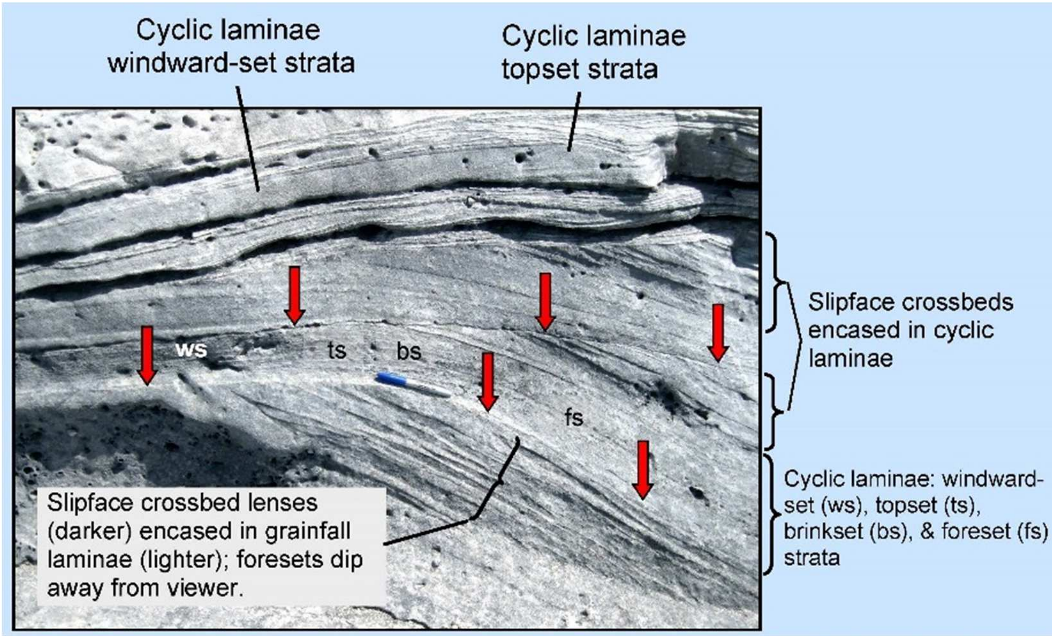


Figure 10. Complete dune-form strata constructed of cyclic laminae preserved as windward set (ws), topset (ts), brinkset (bs), and foreset (fs) strata. Note arching of uppermost windward and topset strata. Localized slipface crossbeds are marked by brackets along middle right edge of photograph. Reactivation surfaces are marked by red arrows. Blue Sharpie™ pen for scale. Modified from Caputo (2019).

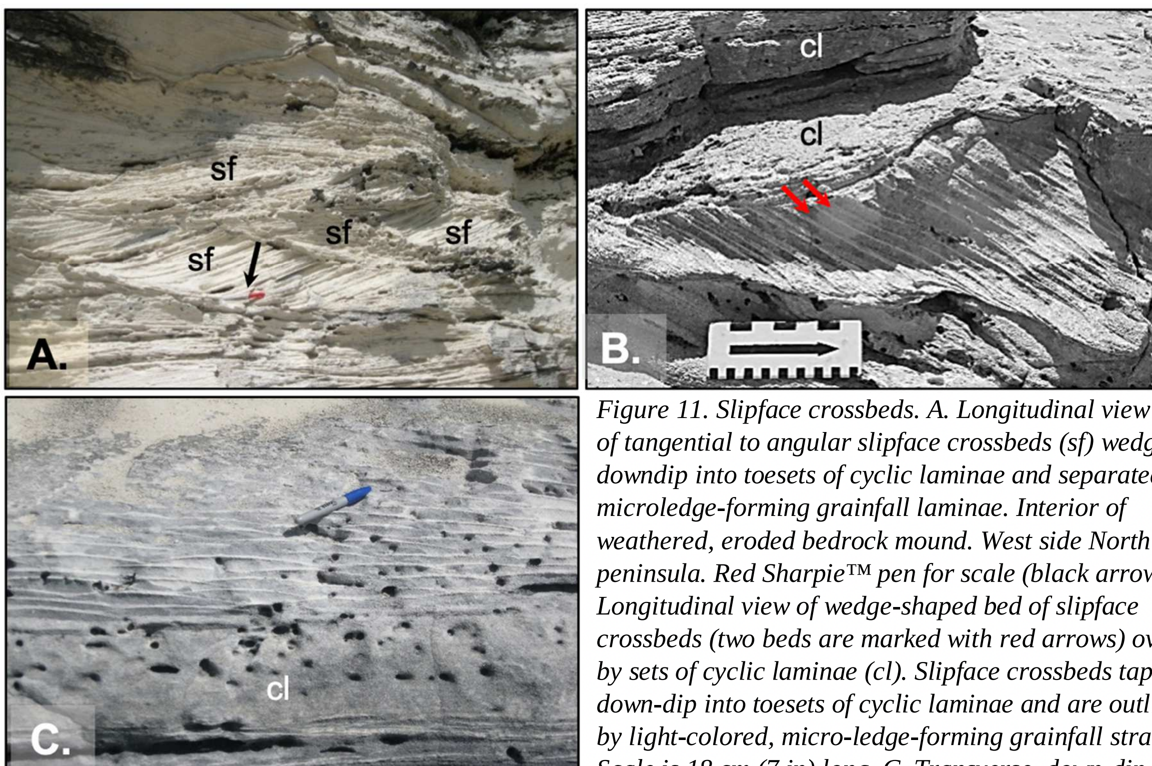


Figure 11. Slipface crossbeds. A. Longitudinal view of sets of tangential to angular slipface crossbeds (sf) wedging downdip into toesets of cyclic laminae and separated by microledge-forming grainfall laminae. Interior of weathered, eroded bedrock mound. West side North Point peninsula. Red Sharpie™ pen for scale (black arrow). B. Longitudinal view of wedge-shaped bed of slipface crossbeds (two beds are marked with red arrows) overlain by sets of cyclic laminae (cl). Slipface crossbeds taper down-dip into toesets of cyclic laminae and are outlined by light-colored, micro-ledge-forming grainfall strata. Scale is 18 cm (7 in) long. C. Transverse, down-dip view of lenses of slipface crossbeds, encased by white, lenticular outlines of grainfall strata underlain by cyclic laminae (cl). Blue Sharpie™ pen for scale.

Table 2. Span of dip directions (in degrees azimuth) for foreset cyclic laminae, bounding surfaces, and slopes of bedrock mounds. n = number of measurements at each study site. See Figure 4 for location of study sites.

Site	Azimuth Span of Dip: Internal Stratification & Mound Slopes	n
E1	82^o-310^o	14
E2	29^o-338^o	10
E3	8^o-355^o	30
E8	4^o-350^o	18
W1	3^o-336^o	25

Erosional remnants of strata crop out 4 to 6 cm (1.6 to 2.4 in) above a wave-washed bench as concentric, elliptical ridges that vary in length from 2-4 m (6.6-13.2 ft) along their long axes. Truncated strata along the elliptical outlines dip away from the core of each ellipse in all compass directions. The elliptical shape and bedding attitude resemble a view on a geologic map of an anticline, and suggest that, perhaps, some volume of bedrock mass in the vertical dimension had been stripped away over time by wave erosion, leaving the remains of strata curving around in elliptical configurations, the axes of which trend generally northeast-southwest (Figure 12A, B).

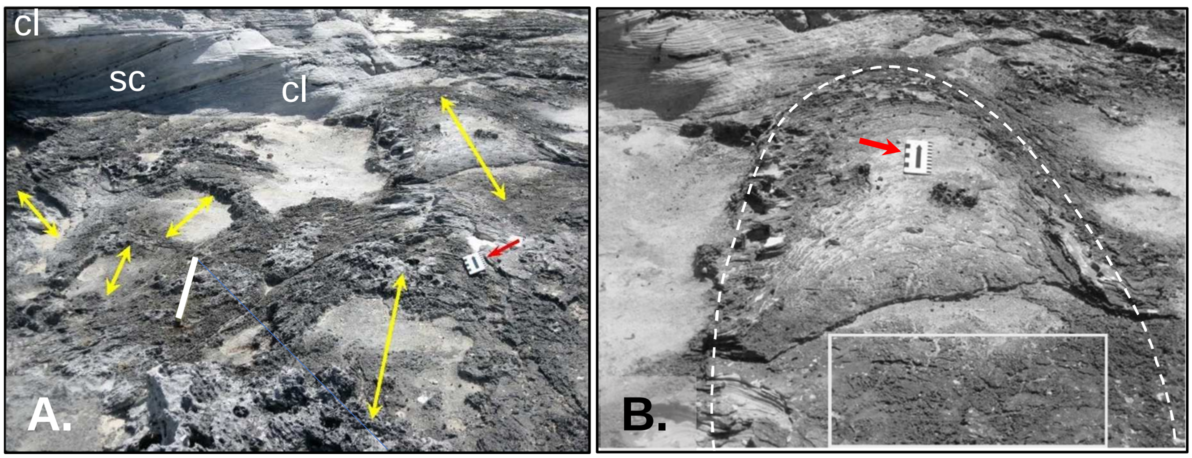


Figure 12. Concentric elliptical configurations made by ridges of erosional remnants of strata protruding up on a wave-washed bench cut into bedrock of the North Point Member at study site E5. A. Concentric erosional remnants of bedding in elliptical outlines; long-axes (yellow arrows) trend NE-SW. Headwall of cove is composed of cyclic laminae (cl) and slipface crossbeds (sc). White bar scale at center left is 0.6 m (2.0 ft) long; scale at center right (red arrow) is 18 cm (7 in) long. B. Close-up of part of the longest elliptical bedding trace (upper right in A) outlined by white dashed curve. Azimuth trend is 236^o. Fossil impressions of unidentifiable plant material are preserved in area enclosed in white rectangle. Scale (red arrow) is 18 cm (7 in) long.

EOLIAN DUNE INTERPRETATIONS FOR QUATERNARY EOLIANITES

Earlier Lobate Dune Interpretation for the North Point Member on San Salvador Island

Structure and origin of Bahamian and Bermudan carbonate eolianites of Quaternary age have been attributed to coast-parallel eolian dune ridges that evolved from coalesced, elongate lobate dunes (e.g. Mackenzie 1964a, b; McKee and Ward 1983), or what Ball (1967) referred to as "eolian spillover lobes." White and Curran (1985, 1988) published the first interpretations of eolian dunes for the North Point Member on San Salvador and proposed a lobate-dune origin for Holocene eolian dunes that deposited the North Point Member on San Salvador Island. Amplifying the lobate-dune interpretation, they described the Holocene North Point dunes as a series of downwind-extending lobes that advanced principally westward, and concluded that over time, individual lobate dunes coalesced laterally to form the north-south trending dune ridge of the North Point peninsula. The protruding lobes yielded a wavy ridge-crest perpendicular to the prevailing Northeast Trade Wind, and the "…hummocky dune ridge…with undulating topography…" of the North Point peninsula today.

Relative to eolian dunes that are normal to wind flow, such as transverse, barchan, and parabolic dunes, a lobate eolian dune is an elongated, finger-like eolian bedform, characterized by a convex downwind-facing leeside in longitudinal view, and lateral slopes in transverse view where grainflows can potentially mobilize and deposit sandflow cross-strata. As an example, Pleistocene lobate dunes interpreted by Mackenzie (1964a, b) on the Bermuda islands are up to 20 m (66 ft) high, with axial lengths of up to 100 m (330 ft). Crossbed sets are up to 23 m (~75 ft) thick and are composed of convex-upward sandflow foresets that conform to the leeside profile of the lobate dune. He described how lobate dunes merged laterally to form a continuous shore-parallel dune ridge perpendicular to onshore wind.

Lobate dunes have not yet been recognized in any morphological classifications of eolian dunes (e.g. Lancaster 1995; McKee 1979a; Pye and Tsoar 1990). They can be considered as terrestrial counterparts to submarine spillover lobes, which have been observed in oolitic sand belts in the Bahamas (Ball 1967). Although Quaternary eolianites on Bahamian islands and other worldwide locations where carbonate sand is generated are composed of marine allochemical grains, they differ in internal structure from those deposited by submarine spillover lobes in the following ways as described by Ball (1967): 1) complete dune-form preservation enhanced by early subaerial cementation and plant stabilization, 2) thicker cross-bed sets, 3) root casts interbedded with thin laminations, which are similar to the interbeds of cyclic laminae the $CaCO_3$ crusts, and the plant-stem fossils described herein. Blay and Longman (2001) conceptualized ideal, elongated lobate dunes in Quaternary carbonate eolianites on Kauai, Hawaii (Figure 13).

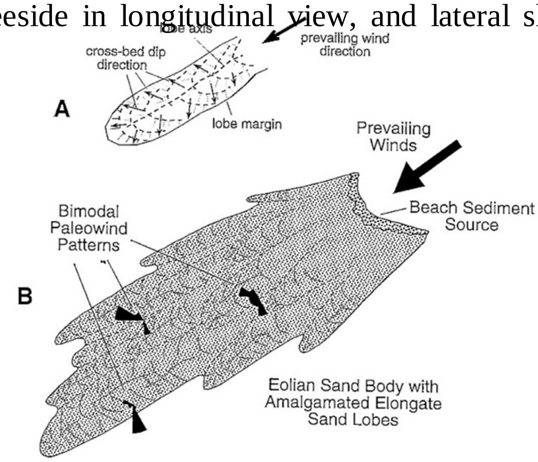


Figure 13. Lobate eolian dunes as interpreted by Blay and Longman (2001) for the carbonate eolianites exposed on southwestern Kauai, Hawaii. A. Basic intrinsic features of a single, elongated lobate dune inferred from eolianite outcrops. B. Depositional model for Quaternary carbonate eolianites resulting from the coalescing of individual eolian lobate dunes to form the amalgamated eolian calcarenite body. Used with permission from SEPM (Society for Sedimentary Geology).

Dome Dune Re-interpretation for the North Member on San Salvador Island

While earlier ideas proposed for Holocene sedimentation in the North Point Member by eolian lobate dunes or eolian counterparts to marine spillover lobes ideas are compelling, the outcrop features preserved in the North Point Member and described in this report support a case for eolian sedimentation in a complex of dome dunes during Holocene time. See also Caputo and Glumac (2013) and Caputo (2019). The outcrop features are: 1) dome- or hemispherical-shapes of bedrock mounds with internal stratification that conforms to the external dome shape, 2) cyclic laminae, which are the products of wind-ripple sedimentation, dominate the internal structure of bedrock mounds (i.e. dome dunes) and continue laterally into inter-mound swales (interdune areas between domes), 3) rare mobilization of carbonate sand by grainflows on dune slopes is evidenced by the low abundance of slipface crossbeds in the North Point Member and further suggests little lee slope accretion, 4) consistent dip azimuths in nearly all compass directions of dome-dune slopes and internal dome stratification, and 5) the present-day mound and swale landscape of the North Point peninsula is a relic of the mound and swale eolian landscape created by the vertical upbuilding of dome dunes on the North Point peninsula during Holocene time **(**see Figure 8).

Another name that may be applied to the carbonate eolian dome dunes preserved in the North Point Member is *medaño*, which is a Spanish name used for coastal sand hills built of siliciclastic sand. It is a unique, unvegetated coastal dune that is similar to a dome dune because it forms in bidirectional or poly-directional winds that transport sand upslope (probably by wind ripples) toward the crest from several directions and is relatively stable despite the lack of plants (Goldsmith 1985).

Wiggs (2019) classified dome dunes as a type of free or mobile dune, which can later be stabilized or anchored. He did not specifically describe a stabilizing or anchoring process. However, in the case of the North Point dome dunes, calcareous crusts and plants and plant-roots were the stabilizing and anchoring agents. Bristow and Lancaster (2004) documented the migration of a 1-meter-high, slipfaceless dome dune with poor sand retention in the siliciclastic Namib sand sea of Namibia, southwest Africa. Sand had been removed by deflation, then transferred by wind from a pre-existing dome dune to a new location downwind to the north-northeast. The Holocene North Point dome dunes did not advance downwind through lateral slipface accretion like eolian transverse, barchan, parabolic, and lobate dunes do. Unlike the small dome dune in the Namib desert of Bristow and Lancaster (2004), the Holocene North Point dome dunes were extremely efficient in retaining sand because dune build-up proceeded through vertical upbuilding or accretion of strata deposited by wind-ripples, aided by sea spray, early subaerial cementing, $CaCO_3$ encrusting, and plant stabilizing.

Wind-ripple sedimentation preserved as cyclic laminae in the North Point Member was responsible also for lateral expansion of dome flanks and overlapping adjacent dome dunes (Figure 14). Lateral expansion and dune overlap suggest that the North Point dome dunes would be classified as *compound dunes*, composed of two or more of the same dune type that overlap or are superimposed on one another according to McKee (1979a; Wiggs 2019), and *accumulating dunes,* characterized by little or no net advance or elongation, according to Tsoar (2008).

The increase then decrease in height of the Holocene dome dunes northward along North Point peninsula (see Figure 8)

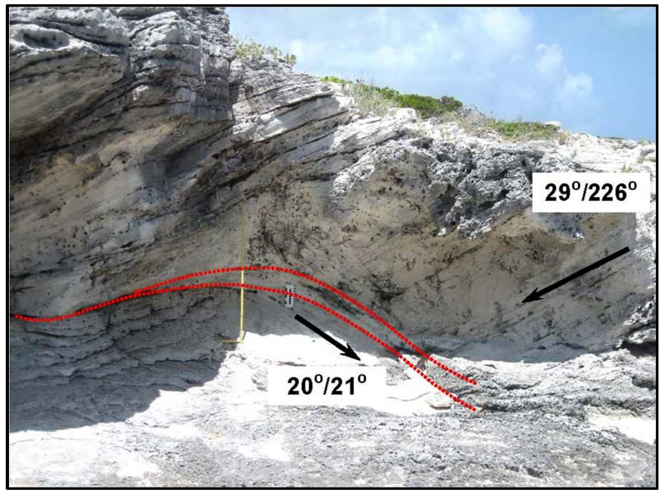


Figure 14. View of a shallow notch formed by cavernous weathering and wave erosion of the North Point Member at study site E5. During its growth, a larger mature eolian dome dune had expanded over a younger dome dune, the crest of which is outlined with red dotted curves. Stratification measurements: Mature dome dune: 29° dip in a 226° azimuth direction (southwest). Younger dome dune: 20° dip in a 21° azimuth direction (north-northeast).

suggests that eolian dunes may have grown initially on an isolated rocky cay a few tens of meters north of mainland San Salvador. Present-day North Point peninsula was not yet a landform. This location was the depocenter, where the thickest and tallest dome dunes developed. With continued sand accumulation and vertical accretion, enhanced by $CaCO_3$ crusts and plant growth, the dome-dune ridge expanded northward to the location of present-day Cut Cay and southward over a shallow bedrock shelf to ultimately attach itself to the mainland of San Salvador Island and become the modern North Point peninsula.

McKee (1966) and Qian *et al.* (2020) postulated that dome dunes may be transitional forms between incipient sand patches and more advanced barchan and transverse dunes, which migrate laterally by slipface accretion in wind. Incipient sand patches may have evolved into smaller coppice dunes and ultimately into larger dome dunes. However, the transition from dome dunes to laterally migrating transverse or barchan dunes did not happen at the site of the North Point peninsula for the following reasons: 1) no evidence of features characteristic of transverse and barchan dunes, 2) dome-dune growth was interrupted periodically by precipitation of calcareous crusts and growth of coastal plants, then halted early by subaerial cementation, and 3) sparse sandflow foresets indicating only brief slope failures and sand avalanches and not extensive lateral migration.

Internal Dome-dune Structure

Using Hunter (1977a, b) as foremost references, White and Curran (1985, 1988) and Caputo (1993, 1995) positively identified the three fundamental types of eolian stratification preserved in the Holocene North Point Member: wind-ripple-, sandflow-, and grainfall-strata. The inversely graded, fine sandy cyclic laminae described herein are the products of sand transported and deposited by wind-ripples on dome dunes preserved in the North Point Member. Pseudoripples (Kocurek and Dott, 1981) in Figure 10B are remnants of thin wind-ripple laminations, eroded and weathered back along lamination planes. Spacing of the headwardly-eroded edges is nearly equivalent to the distance between successive ripple crests when ripple migration was active, and further attests to the wind-ripple origin of the cyclic laminae.

In their interpretations on the eolian origin of the North Point Member, White and Curran (1988) were first to observe vertical successions of wind-ripple strata interbedded with calcareous crusts and associated trace fossils of plant stems. Analysis by Glumac *et al.* (2013) and observations herein confirmed their interpretation. During the growth of Holocene dunes at North Point, eolian sedimentation proceeded by wind ripples in increments of several centimeters (inches) in a given interval of time. Dune growth was paused seasonally or more frequently during a year by rain, which rendered the carbonate sand wet and cohesive, retarded sediment transport, and fostered plant growth and the precipitation of calcareous crusts on dune surfaces. At the onset of the next dry period, available loose sand was remobilized in wind ripples, dune sedimentation and growth resumed until the next wet period, and the dry-wet cycles repeated vertically through time.

The following factors suppressed grainflows and therefore are responsible for the low abundance of slipface crossbeds in the dome-dune bedding of the North Point Member: 1) dune-slope stabilization by grain cohesion from wetting in rain and salt spray from waves; 2) cyclical precipitation of $CaCO_3$ crusts; 3) growth of maritime plants; and 4) unobstructed strong wind that kept fine sand suspended beyond dune slopes; preventing grainfall sand from settling near dune brinks, where sand collects, becomes unstable, and remobilizes as grainflows (McKee 1966).

Coppice Dune Re-interpretation for the North Point Member on San Salvador Island

The elliptical configurations of low, concentric ridges of truncated strata, dipping away from a central core and cropping out at the bedrock surface on the east side of the North Point peninsula, are interpreted as erosional remnants of eolian coppice dunes, a name for small, oval or elliptical, vegetated dunes coined by Melton (1940). Modern eolian coppice dunes, also called nebkha dunes (Nickling and Wolfe 1994) or anchored vegetated dunes (Hesp and Smyth 2019; Pye and Tsoar 1990), build-up vertically without lateral migration and are common to both coastal and inland dune fields. A trace fossil of plant material associated with one of the elliptical patterns (Figure 12B) supports the idea of smaller plant-anchored, eolian coppice dunes co-existing with larger dome dunes. A corollary to this interpretation is that the larger dome dunes may have begun their growth as smaller coppice dunes or proto-dome dunes (a term modified from Warren 2013), a meter (3.3 ft) high or less, and later grew vertically at the center of the main dome-dune field into mature dome dunes. (i.e. the taller bedrock mounds on the North Point peninsula today). The northeast-southwest trends of long axes of the interpreted coppice dunes in the North Point Member are consistent with a southwesterly flow for the Northeast Trade Winds during Holocene time on San Salvador. Figure 15 captures a "snapshot" of the sedimentary scenario when coppice and dome dunes developed during Holocene time at the location of the North Point peninsula.

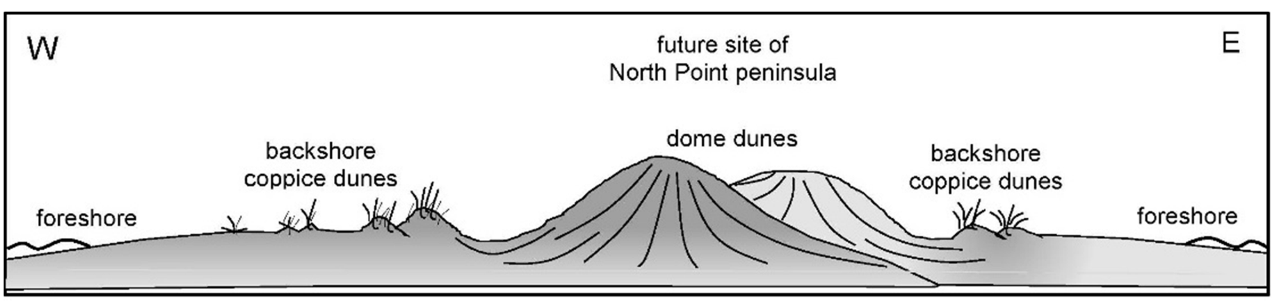


Figure 15. Hypothetical morpho-sedimentary setting of the North Point peninsula during Holocene sedimentation of the North Point Member. View is northward.

Coppice dunes growing today along the eastern shore of San Salvador may serve as possible modern analogues for the coppice dunes interpreted herein for the North Point Member (Figure 16A and B). On beaches there, heaps of dead seaweed have been washed onto the upper foreshore as a wrackline by wave swash at high tide or during storms. Eventually, plant seeds and wind-blown carbonate sand becomes trapped in the network of stems and fronds of the dead seaweed. Grasses and other plants, fostered by moisture from wave spray and rainfall, sprout from the trapped seeds. Eolian sand, saltating from the foreshore and lower backshore, is trapped by the swash debris and by shore plants sprouting at the swash line. Eventually sand accumulates into a plant-anchored mound as roots take hold and radiate to secure the mound of sand. A mature, mound-like coppice dune can grow vertically 1-2 m (3.3 to 6.6 ft) high as the base expands laterally and if plant growth can keep pace with the piling up of sand (Hesp and Smyth 2019) (Figure 17). Slipfaces are absent, wind ripples likely dominate traction transport of sand, and primary internal stratification is probably disturbed or destroyed by plant roots.

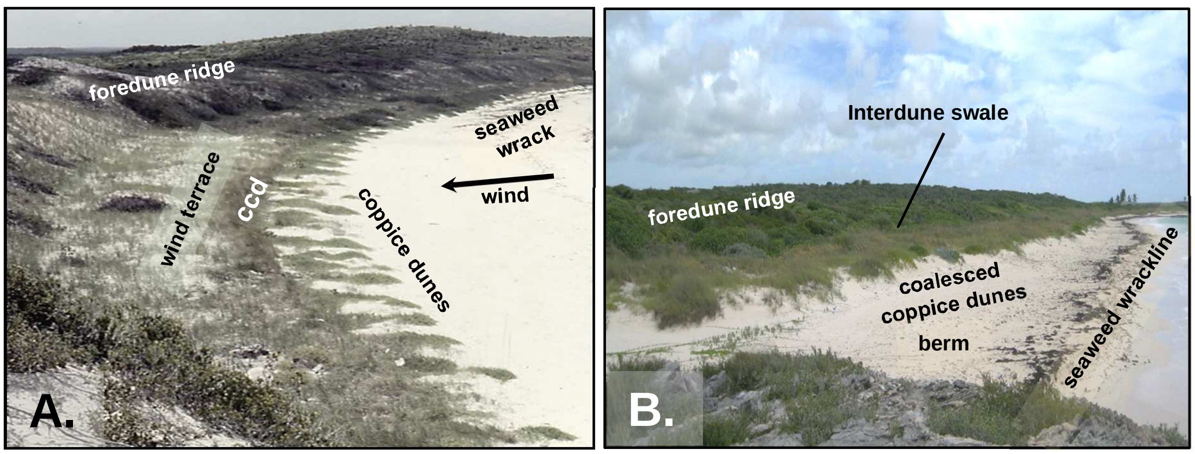
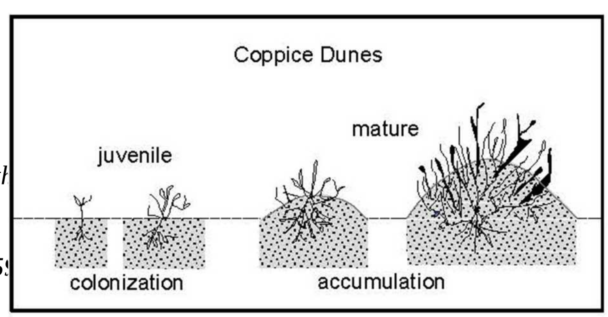


Figure 16. Recent eolian coppice dunes and coastal geomorphology of eastern San Salvador. A. At Snow Bay, eastern San Salvador (see Figure 2A for location), clumps of seaweed washed in by waves, trap plant-seeds and carbonate sand. Plant-growth keeps pace with vertical build-up of trapped sand to form elongate and elliptical coppice dunes, 1-2 m (3.3-6.6 ft) high, oriented parallel and subparallel to onshore wind. Morpho-sedimentary components shoreward of coppice dunes: older foredune ridge of coalesced coppice dunes (ccd), wind terrace, and oldest, tallest foredune ridge. B. Stages in the evolution of a coastal dune system from the shore landward: seaweed wrackline, berm, coalesced coppice dunes to form the youngest dune ridge separated by interdune swale from the older, higher, overgrown foredune ridge. Beach at the Thumb (see Figure 2A for location).

Figure 17. Possible model to explain the general development of coppice dunes, from juvenile to mature, at coastal and inland eolian environments. Wind-blown sand is trapped and stabilized by colonizing shore plants and their roots. Coppice dune growth progresses from juvenile to mature as plant growth keeps pace with sand buildup. Adapted and redrawn from Figure 7.3, p. 15 in Hesp and Smyth (2019).



CONCLUDING REMARKS

Much of the work on general eolian processes operating in coastal and inland dune fields and sand seas (i.e. ergs, an Anglicized Arabic word for eolian sand seas) has offered insight into the morphology, morphometry, sand texture, and origin of eolian dunes. Numerous studies have been published on modern barchan, transverse, parabolic, and large, complex linear and star dunes, and their depositional record in sedimentary rocks. This report may be the first to interpret a dome dune origin for carbonate sedimentary rocks on a tropical island. To date, I uncovered one publication (Thompson 1969) that interpreted an eolian dome-dune origin for a Triassic quartzose sandstone in England.

During Holocene time, an eolian dome- and coppice-dune complex evolved at the present-day site of the North Point peninsula and is preserved in the North Point Member of the Rice Bay Formation on San Salvador Island. Component allochemical sand was generated on the adjacent nearshore shelf during high stands of sea level by biomineralizing corals, molluscs, and algae and biochemical precipitating of ooids, fecal pellets, and peloids. Later, storm and normal marine currents mixed skeletal and nonskeletal grains and deposited the carbonate sediment on foreshore beaches where it was redistributed by wind and piled into dunes on backshore beaches. Juvenile, precursor coppice dunes were initiated by sand-trapping grasses and other plants, and, over time, matured, coalesced, and possibly provided a base for growth of eolian dome dunes. The eolian system continued to evolve as stationary, larger dome dunes accreted vertically, aided by $CaCO_3$ encrusting and plant stabilizing under the influence of the Northeast Trade Winds.

Sand-sized carbonate sediment was transported by wind ripples and deposited as cyclic laminae, which are preserved as windward-set, topset, brinkset, and foreset strata in dome dunes and horizontal to concave laminae in inter-dome swales. They are volumetrically dominant over other eolian strata and are the primary architectural elements in the North Point Member. Because the abundance of grainfall strata was negligible and not essential to the interpretation of eolian dome dunes, they were not assigned a rank in the scheme of architectural elements. Slipface crossbeds were essential to interpreting eolian dome dunes, but their low abundance relative to cyclic wind-ripple laminae rendered them secondary architectural elements. They were the depositional product of short-lived grainflows on temporary slipfaces of larger, mature dome dunes. Their paucity is directly related to the low amount of deposited grainfall sand and the incremental stabilizing of dome-dune surfaces by salt spray, calcareous crusts, and coastal plants. The eolian dome- and coppice-dune interpretation proposed herein for the North Point Member is based on evidence from outcrops and is made with little recourse to the few published sources, which contain sparse sedimentary details on eolian dome dunes (Table 3).

Figure 18 is an interpretive reconstruction of the eolian coppice- and dome-dune setting thought to exist during Holocene time at the future site of the North Point peninsula. Positions of lettered images show spatial locations where architectural elements described and shown earlier in the referenced figures would likely occur.

Table 3. Outcrop characteristics that suggest a dome- and coppice-dune origin for eolianites of the North Point Member, Rice Bay Formation on San Salvador Island.

Features Similar to Those Described in Modern Siliciclastic Eolian Dome Dunes	**References**
Oval to circular mound morphology, rounded summit; composed of sand-sized grains	Bigarella *et al.* (1969); Bristow and Lancaster (2004); Halsey and Catto (1994); Hesp and Smyth (2019); Lancaster (1995); McKee (1966, 1979, 1982), Pye and Tsoar (1990); Qian *et al.* (2020) and references cited therein
Few if any slipfaces, low proportion of sandflow cross-bedding and associated grainfall strata	
Distinguishing Features of Dome Dunes in the North Point Member Not Described in Modern Siliciclastic Eolian Dome Dunes	
Taller dune height, up to 10 m (33 ft)	
Greater dune height fostered by sand cohesion from coastal salt spray, and $CaCO_3$ encrustation and plant growth	
arching internal stratification that conforms to external dome shape	
Dominant wind-ripple processes depositing windward, crest, brink, and foreset strata	
Eolian dunes characterized only by vertical accretion and lateral expansion and no lateral foreset accretion	
No evidence for transitioning to downwind migrating transverse and barchan eolian dunes	
Nearly 360^{o} azimuth slope directions of bedrock mounds and dip directions of internal stratification	
Small eolian coppice dunes that are peripheral to the dome dune field and may be precursor dunes on which larger dome dunes evolved	

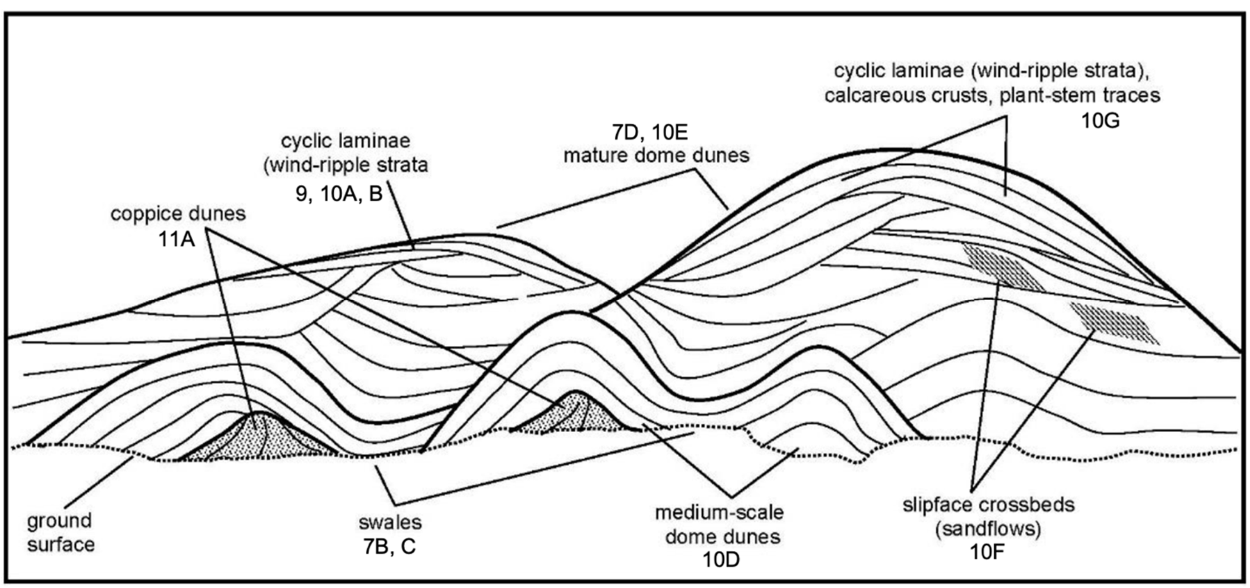


Figure 18. Interpretive diagram of the Holocene dome- and coppice-dune and swale complex in the North Point Member. Dune surfaces are outlined with bold curved lines; concordant and discordant bounding surfaces of wind-ripple bedsets are drawn as thin curved lines. Numbers and letters of figures in this report are placed in the diagram to show where outcrop features would occur hypothetically in this eolian system. Modified from Caputo (2019).

SUGGESTIONS FOR FUTURE WORK

Field methods that led to the interpretation of dome- and coppice-type dunes in the North Point Member at North Point, San Salvador Island, may serve useful for identifying eolian dune types, in the Holocene Hanna Bay Member of the Rice Bay Formation at the northern margin of San Salvador, and in the Pleistocene French Bay and Cockburn Town Members of the Grotto Beach Formation at the southern margin. Little information on dune type, internal structure, and paleogeographic conditions for the Hanna Bay Member has been published.

Caputo (1995) had suggested tentatively that the dune forms preserved in the Grotto Beach Formation resemble sinuous-crested, coastal foredune ridges with lunate recesses and linguoid lobes along the dune leeside. He further described the Pleistocene eolianite preserved in the Grotto Beach Formation may prove to be composed of lobate dunes that had merged to form a dune ridge transverse to wind similar to those described by Mackenzie (1964a, b), Ball (1967), and White and Curran (1988). Further careful, systematic distinguishing of wind-ripple, sandflow, and grainfall strata, and measuring azimuth directions of inclined foreset strata are needed.

Future field projects:

1. Document eolian calcarenite bodies in the Hanna Bay, French Bay, and Cockburn Town Members, including geometry, internal structure, and azimuths of dipping strata, reactivation surfaces, and windward and leeward dune slopes.
2. Systematically measure and record dip directions for slipface crossbeds (i.e. sandflow strata) in the North Point Member.
3. Gather and record GPS coordinates for precise locations of sites where observations were recorded for the North Point Member on the North Point peninsula.
4. Register a field project with the Gerace Research Centre and obtain permission from the Bahamian government to trench interiors of representative coppice dunes at sandy beaches on eastern San Salvador. Document plant-root burrows and internal physical structures of carbonate coppice dunes.
5. Re-examine an unusual structure, resembling stacked chevron- or teepee-like sedimentary structures up to a meter thick in the vertical dimension exposed on the east side of the North Point peninsula. Component wind-ripple laminae intersect at a sharp-pointed crest and dip in opposite directions from this crest. The structure may be evidence for eolian shadow dunes, another type of anchored, vegetated dune.

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