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# ADHESION-RIPPLE STRUCTURES IN QUATERNARY CARBONATE EOLIANITES, SAN SALVADOR ISLAND, THE BAHAMAS

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## ABSTRACT

Newly discovered eolian adhesion ripples and related pseudo-crosslaminations occur in calcarenites of the Pleistocene Cockburn Town Member, Grotto Beach Formation and in the Holocene North Point Member, Rice Bay Formation, San Salvador Island, the Bahamas. Typified by heights and spacings of < 1 cm (0.4 in), the ripple marks are asymmetrical with wavy to lobate crests. Although associated pseudo-crosslaminations resemble true cross-stratification, they reflect only the direction from which the ripples had migrated and climbed and not true paleowind direction. Adhesion ripples and pseudo-crosslaminations described herein compare directly with those formed in siliciclastic (non-carbonate) sand. In modern sedimentary environments, dry sand, driven by wind, is captured by wet sand through surface tension and capillary action. Small bulbous ripples build up, migrate and climb into the wind, and deposit pseudo-crosslaminations that dip downwind. Preservation of adhesion structures in carbonate sedimentary rocks of San Salvador Island records episodes of windy rainstorms in the Northeast Trade Wind region during Quaternary time.

## INTRODUCTION

An eolian or wind-blown origin for Pleistocene and Holocene bedrock of San Salvador Island, the Bahamas has been known since the initial observations by Adams (1980). Sedimentary structures created unequivocally by eolian ripple, grainfall, and grainflow processes, as explained by Hunter (1977a, b), have been recognized in the French Bay and Cockburn Town Members of the Grotto Beach Formation (Caputo, 1989, 1993, 1995) and in the Holocene North Point Member of the Rice Bay Formation (White and Curran, 1985, 1988; Caputo, 1993, 1995).

Adhesion ripples are created by relatively dry wind-driven sand adhering to wet sand by surface tension and capillary action, and have been known since van Straaten (1953). Kocurek and Fielder (1982) summarized the history of study on adhesion structures mainly in siliciclastic sand and sandstone. They further classified adhesion structures as adhesion ripple, adhesion wart, and adhesion plane bed according to their physical appearance and strata they deposit (Figure 1). Modern adhesion ripples are known to build-up and migrate into wind currents and can be likened to larger, ripple-like bedforms called antidunes that migrate upcurrent in subaqueous channelized flows (Gilbert, 1914), and volcanic antidunes that migrate upcurrent in fluidized pyroclastic flows (Wohletz and Sheridan, 1979).

The purpose of this study is to describe and document the first-time discovery and identification of new sedimentary structures exposed locally in Pleistocene and Holocene carbonate sedimentary rocks on San Salvador Island, and provide evidence for their origin by eolian adhesion ripples. The first-ever discovery of adhesion ripple structures in

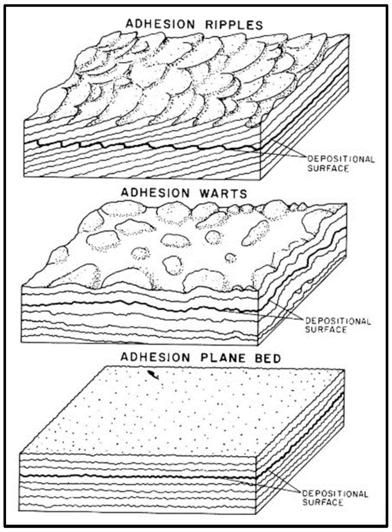



*Figure 1. The family of adhesion structures: adhesion ripples, adhesion warts, and adhesion plane bed classified in Kocurek and Fielder (1982, p. 1,230). Used with permission from the Society of Economic Paleontologists and Mineralogists (SEPM).*

carbonate eolianites of Quaternary age on any Bahamian island was by Hunter (late 1980s) at Bannerman Point near the southern limit of Eleuthera Island (Hunter, 2011, written communication).

STUDY SITES

In early summer, 2010, eolian adhesion structures were discovered in the Pleistocene Cockburn Town Member of the Grotto Beach Formation on southern San Salvador Island, and in the Holocene North Point Member of the Rice Bay Formation at North Point (Figure 2). Along the southern margin of the island, Pleistocene sites, S1 and S2, are on a topographic bench along sea cliffs between the easternmost pocket of French Bay called Blackwood Bay and an area of sea cliffs referred to as the Gulf (i.e. Snow Bay of other maps) further east (Figure 3). Site S1 is located at 23° 56' 50" N latitude and 74° 30' 30" W longitude, and is approximately 55 meters (180 ft) by foot-pace east of an erosional embayment called "the Cut." Site S2 is located at 23° 56' 50" N latitude and 74° 31' 11" W longitude.

Both sites are approached by traveling south to Sandy Point from the Gerace Research Centre on Queen's Highway along the western side of the island (Figure 3). At its southernmost limit, Queen's Highway turns sharply east at the junction with a segment of paved road, 200 m (~0.125 mi) long, that leads to a human-made structure labeled "jetty" on the map of southern San Salvador Island, Bahamas (Sheet 2, Bahamas Government, 1972) and labeled "government dock" (Index map, Mylroie, 1988). From this junction, Queen's Highway continues eastward and parallel to northern French Bay. At about the longitude of Blackwood Bay, a segment of the unmaintained road -an artifact of an abandoned housing project- branches southeastward from Queen's Highway and proceeds eastward to the Gulf area and beyond to Sandy Hook (Figure 4).

Adhesion structures are also found in the North Point Member of the Rice Bay Formation (Figure 2) on the east side of the North Point peninsula (Figure 3). The structures are exposed in the seaward-sloping headwall of a rocky cove at study site E3 (see Figure 8 in Caputo, this volume).

ADHESION STRUCTURES
IN QUATERNARY EOLIANITES

**Description**

*Pleistocene Cockburn Town Member, Grotto Beach Formation at site S1.* In the Pleistocene Cockburn Town Member at site S1, two sets of calcarenite microridges, a term used by Hunter (1969), are exposed on eroded, weathered bedding surfaces (Figures 5A, B). In plan or bedding-plane view, microridge crests are <1-2 cm high (0.4-0.8 in), and are wavy, lobate, and bifurcated (Figure 5A. In profile view, crests are rounded to pointed. Slopes facing northeast (42°-53° and 67°-75° azimuth are narrower and steeper than the wider less steep slopes that face southwest.

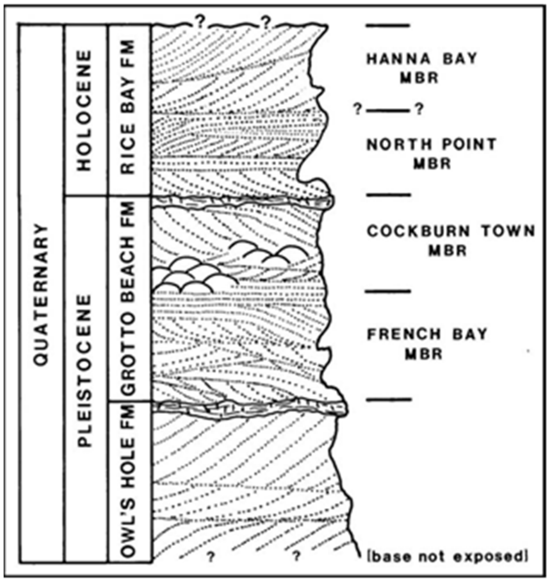



*Figure 2. Lithostratigraphic subdivisions of carbonate bedrock on San Salvador Island. The Cockburn Town Member of the Grotto Beach Formation and North Point Member of the Rice Bay Formation are stratigraphic units in which adhesion structures are found. Redrawn and modified from Carew and Mylroie (1995).*

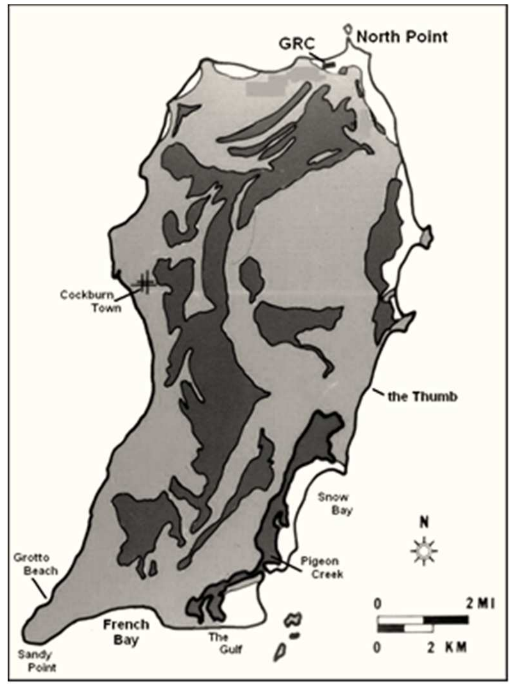



*Figure 3. A simplified geologic map of San Salvador Island shows the general distribution of Quaternary bedrock and principal locations (labeled) mentioned in this report. Much of the island is underlain by Pleistocene limestone (medium gray). Holocene limestone (white) crops out discontinuously along the northern and eastern margins of the island. Interior and coastal lakes are shown by irregular dark gray areas. Redrawn and modified from Carew and Mylroie (1995). GRC = Gerace Research Centre.*


*Figure 4. Aerial image of part of the southern coast of San Salvador Island, and sites S1 and S2 where adhesion structures were discovered in the Cockburn Town Member, Pleistocene Grotto Beach Formation. Image courtesy of Google Earth.*

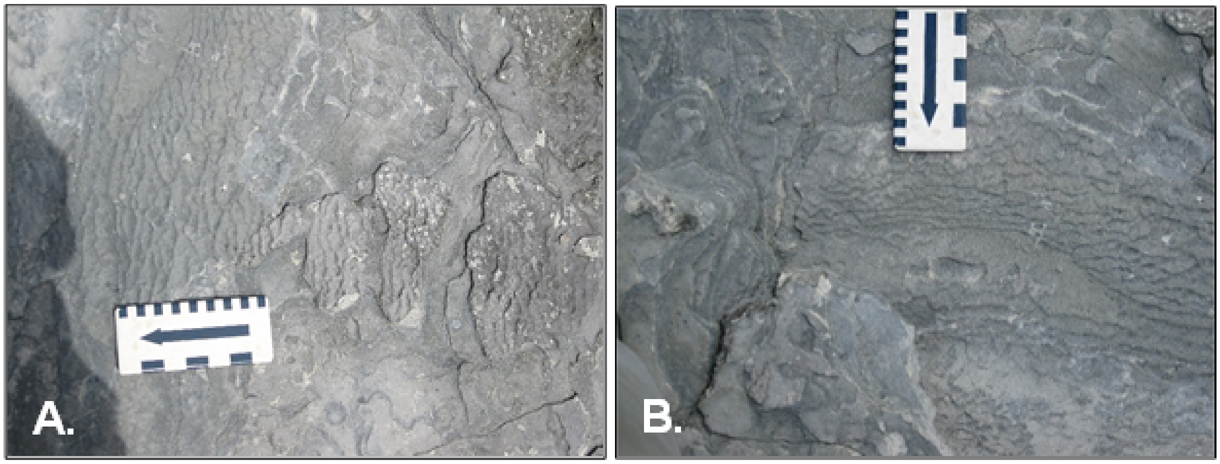



*Figure 5. Ripple-form microridges in the Cockburn Town Member at site S1. A. First set: subparallel, wavy crests with steeper slopes that face northeast (arrow on scale). Scale is marked in centimeters and in inches. B. Second set of adhesion ripples: parallel wavy to lobate crests near lower right corner of scale, which is marked in centimeters and in inches. Arrow on scale points northeastward, in direction toward which steep ripple-slopes face.*

*Pleistocene Cockburn Town Member, Grotto Beach Formation at site S2.* Microridges on a bedding-plane exposure of the Cockburn Town Member at site S2 are similar to those at site S1 (Figures 6A, B). Pointed, wavy crests, spaced 1 cm (0.4 in) apart, trend north-northeast to south-southwest (4° azimuth), and display wide gentle slopes facing westward and narrow steep slopes facing eastward (96° azimuth). Lenticular beds, up to 10 cm (4.0 in) thick), display internal structures that resemble normal foreset laminations but are actually pseudo-crosslaminations described by Hunter (1973). Their nature will be explained in a later section, Interpretation and Discussion. These foresets are straight to slightly convex upward, dip 30°-44° west, and are interbedded with strata deposited by non-adhesion, ordinary wind ripples (Figure 6C). Compare with Figure 6D (courtesy of Ralph Hunter), which shows a stratum, 3-8 cm (2-3 in) thick, composed of pseudo-crosslaminations deposited by eolain adhesion ripples in strata equivalent to the North Point Member on Eleuthera Island, Bahamas.

*North Point Member, Rice Bay Formation at site E3, North Point Peninsula.* At least four lenticular beds, up to 6 cm (2.4 in) thick, are found locally interbedded with normal wind-ripple laminations in bedrock swales at site E3 in the North Point Member, Rice Bay Formation on the east side of the North Point peninsula (Figures 7A, B, C). See Figure 8 in Caputo (this volume) for location of site E3. The beds are traceable laterally over a distance 4.6 to 7.1 meters (15 to 23 ft) to where they wedge-out into enclosing normal wind-ripple laminations (Figure 7A). Coastal erosion and weathering have stripped back layers of rock to expose bedding surfaces characterized by dimples less than 0.5 cm (0.2 in) deep and by wavy microridges (Figure 7B) with shape and dimensions similar to those exposed in the Pleistocene Cockburn Town Member in sea cliffs on southern San Salvador. The microridges are asymmetrical with steepest slopes that face east-northeast (76° average azimuth). Nearly vertical outcrop surfaces reveal pseudo-crosslaminations with apparent dips to the southwest. Dip angles are 16° to 19° near the base of one particular pseudo-crosslaminated bed and increase to 53° toward the upper bounding surface of the bed (Figure 7C).

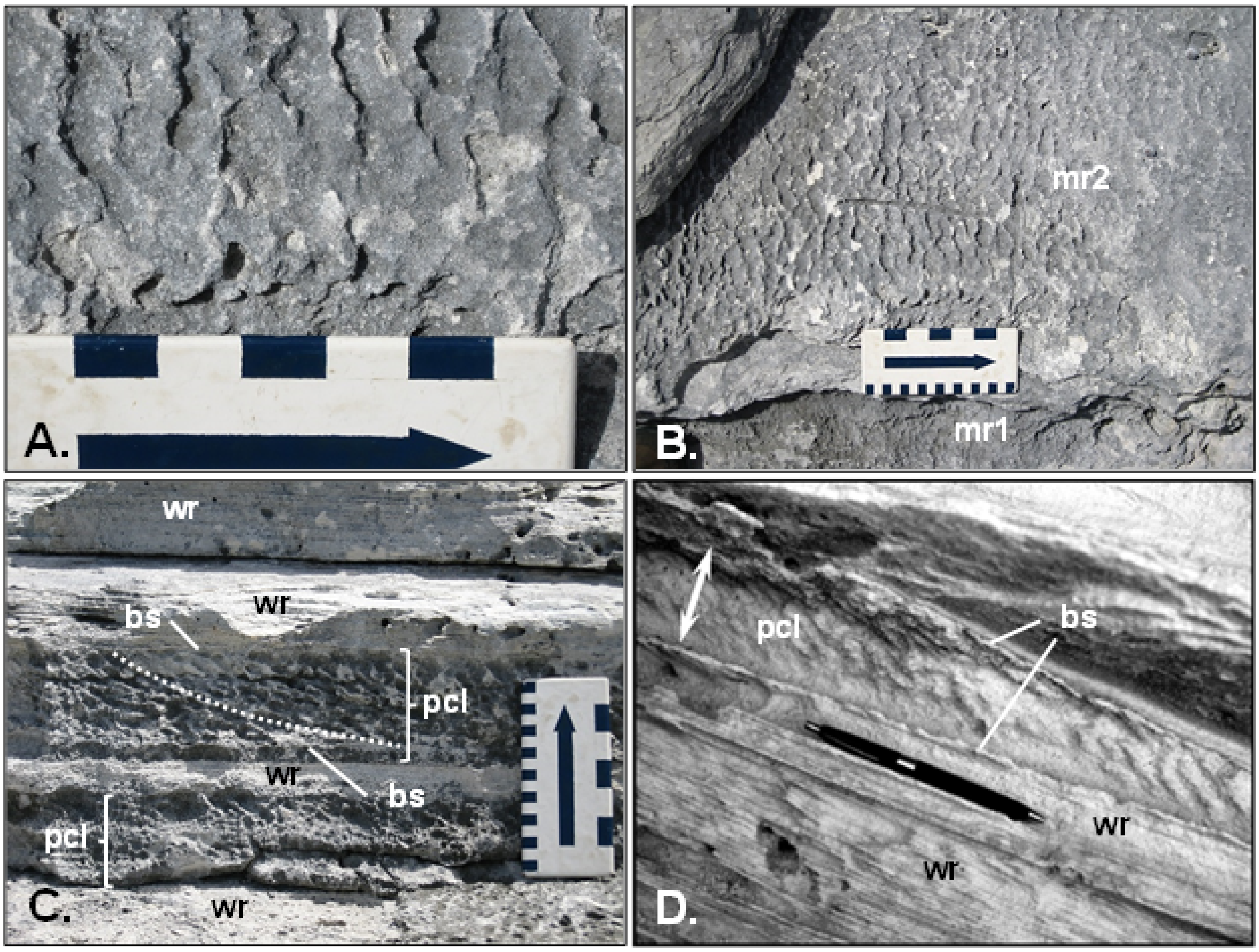
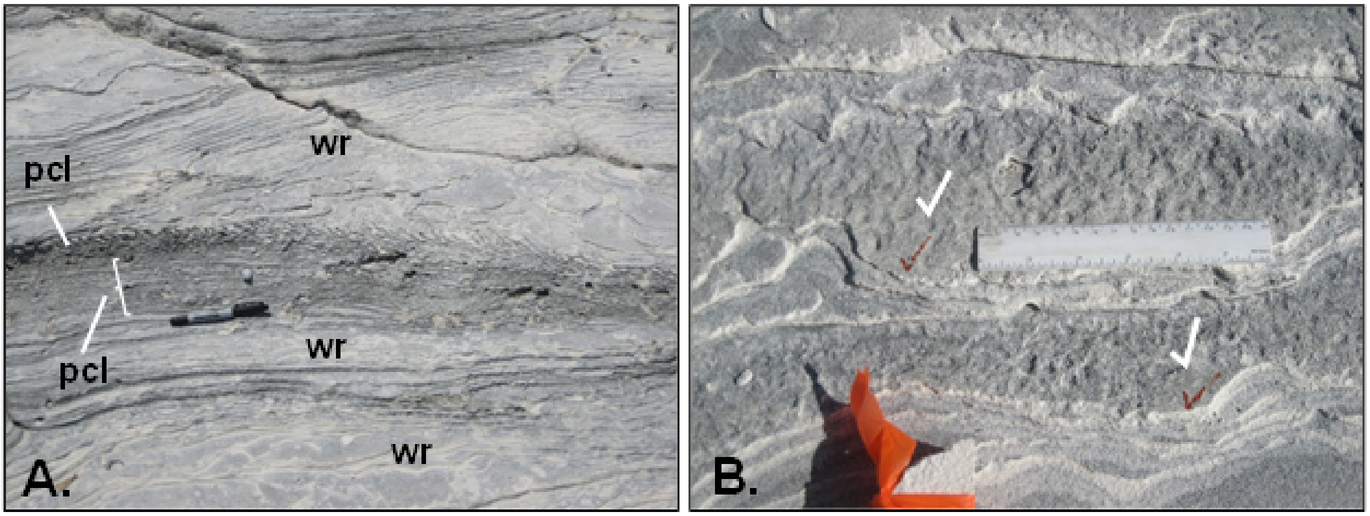



*Figure 6. Surface and internal bedding structures in Cockburn Town Member, Grotto Beach Formation at site S2 on south San Salvador Island (photographs A-C). A. Local bedding-plane view of wavy microridges. Steep slopes (highlighted by shadows) face northeastward, in direction of arrow on scale, which is marked in inches. B. Zoom-out view of wavy microridges (mr1) in 6A, and underlying set of microridges (mr2). Scale is marked in inches and centimeters. Arrow points northeast. C. Vertical outcrop face parallel to current direction for 2 beds of pseudo-crosslaminations (pcl) interbedded with sets of parallel wind-ripple laminations (wr). Upper and lower bounding surfaces (bs) define contacts with wind-ripple (wr) strata. Single white dotted curve highlights shape of pseudo-crosslaminations for upper bed. Scale is marked in centimeters and inches. D. Localized bed of pseudo-crosslaminations (pcl) (white double arrow) defined by upper and lower bounding surfaces (bs) and underlain by wind-ripple laminations (wr). Pseudo-crossaminations dip 35º-37º to the right. Holocene North Point Member (?), Light House Point (also known as East End Point or Eleuthera Point (John Mylroie, 2020, written communication), southernmost Eleuthera Island, Bahamas. Photograph taken by Ralph Hunter in the 1980s and used with permission. Pen is 14 cm (5.5 in) long.*



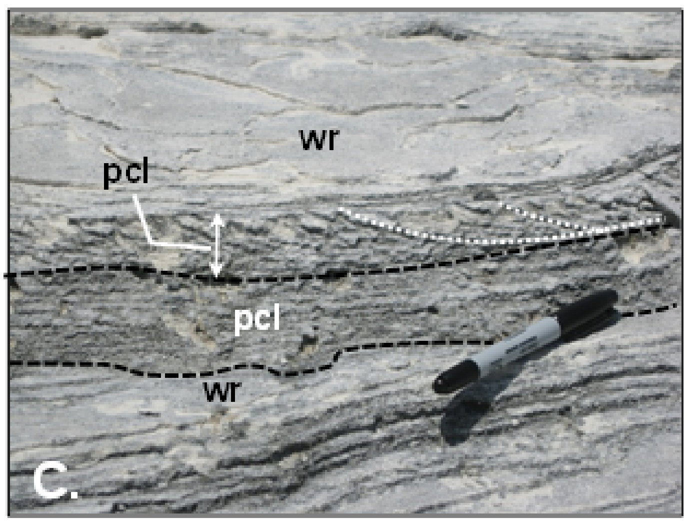




*Figure 7. Adhesion structures. A-C in the North Point Member, Rice Bay Formation, North Point peninsula, north San Salvador Island. A. Laterally discontinuous beds of pseudo-crosslaminations (pcl) that interrupt a uniform succession of normal wind-ripple laminations (wr). White bracket highlights bed of pseudo-crosslaminations viewed parallel to trend of microridges. Scale is Sharpie ™ pen. B. Microridges (white check marks) up to 0.5 cm (0.2 in) tall exposed on bedding surface Orange tape is stratigraphic reference marker. Ruler is 15 cm (6 in) long. C. Bed of concave-upward pseudo-crosslaminations (pcl, douible arrow) interbedded with normal wind-ripple strata (wr). Two laminations are highlighted with white dashed curves. Maximum dip is $53^o/249^o$ azimuth direction. Black dashed lines mark bed of pseudo-crosslaminations viewed parallel to trend of microridges. Scale is Sharpie ™ pen.*

## Interpretation and Discussion

*Eolian adhesion ripples.* Ripple-like microridges exposed on bedding surfaces of the Pleistocene Cockburn Town Member, Grotto Beach Formation and Holocene North Point Member, Rice Bay Formation are eolian adhesion ripples. They are nearly identical in morphology and physical dimensions to modern siliciclastic (i.e. non-carbonate) adhesion ripples described and illustrated in Hunter (1973), Reineck and Singh (1980), and Kocurek and Fielder (1982), and especially to those on Plum Island, Massachusetts (Figures 8A, B).

The adhesion ripple marks in the Cockburn Town and North Point Members could be considered similar to wrinkle marks or runzelmarken described and pictured in Reineck and Singh (1980). However, wrinkle marks are only surface structures, and do not transport sediment and deposit stratification as ripples do. Instead, they develop by wind distorting the surface of a mass of water-saturated fine sand and silt to create the small ridges and furrows of wrinkle marks. The overall shape, larger size, and associated pseudo-crosslaminations all support an adhesion-ripple origin for the calcarenite microridges described herein.

In another example, the ripple-like microridges studied herein are comparable in shape and size to rain-impact ripples described in Clifton (1977). However, a rain-impact interpretation cannot be supported for the following three reasons (Clifton, 2011, oral communication). Reason 1: Rain-impact ripples develop steep lee slopes that face downwind

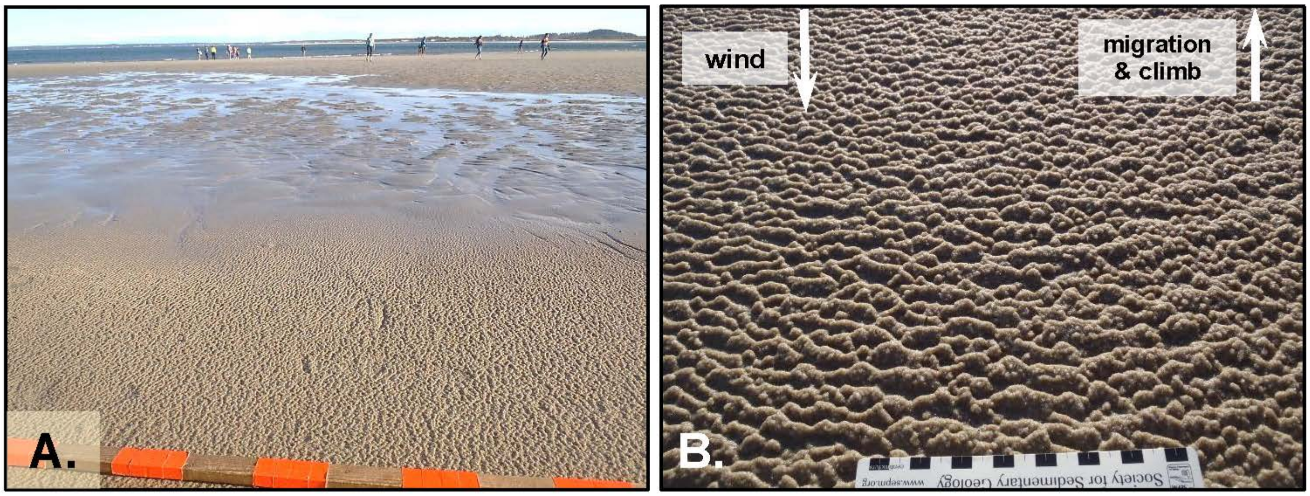



*Figure 8. Modern eolian adhesion ripples in siliciclastic sand. A. Adhesion ripples forming on wet, low-tide beach, Plum Island, Massachusetts. Staff is marked in decimeters. B. Bumpy, bulbous adhesion ripples on wet low-tide beach, Plum Island, Massachusetts. Steep "stoss" slopes face upwind (toward photo top). Less steep "lee" slopes (in shadow) face downwind (toward photo bottom). Ruler is marked in centimeters. Photographs by Bosiljka Glumac and used with permission.*

However, known eolian adhesion ripples migrate with their steep "stoss" slopes facing upwind. The steep "stoss" slopes for the adhesion ripples (microridges) interpreted in this study face northeast and upwind relative to the Northeast Trade Winds active during Quaternary time for San Salvador Island.

Reason 2: Bedform climbing is absent and stratification is not deposited. As will be explained in a later section, ripples and dunes climb by necessity in order to deposit stratification. In the sedimentary rocks studied here, the occurrence of eolian adhesion ripples and associated pseudo-crosslaminations, which are inclined at an angle with respect to overlying and underlying strata, is evidence that adhesion ripples, as bedforms, climbed in order to deposit pseudo-crosslaminations.

Reason 3: Rain-impact ripples are seen, so far, only as surface features in modern sediment and have low preservation potential in rocks. The physical presence of eolian adhesion ripples in the Quaternary sedimentary rocks on San Salvador is evidence for preservation and further nullifies a case for a rain-impact origin for the ripple-like microridges identified in this study.

*Cross-stratification.* Subaqueous (i.e. underwater) ripples and dunes and eolian dunes deposit dipping or inclined strata called cross-stratification (also called cross-strata or cross-bedding) as they move in a water or wind current. Sediment is eroded simply from the stoss or upcurrent slope and is transferred to the lee or downcurrent slope where it is deposited as cross-stratification mainly by grainflow (i.e avalanching) and grainfall (Figure 9). Cross-strata are so named because they "cross" or are inclined with respect to the general horizontal layering of sedimentary deposits (Figure 10).

By comparison with subaqueous ripples, wind ripples are not as tall; only about 1-2 cm (0.4-0.8 in) high and grain avalanching on lee slopes is absent. Eolian ripples migrate with the wind and build-up and deposit sand in the following simplified manner. Coarser grains are impelled by saltation (i.e. grain hopping or jumping) impacts and advance by rolling and sliding to the ripple crest where they settle. The result is an upward-coarsening wind-ripple stratum (Figure 11).

*Figure 9. Simple profile of an ordinary subaqueous dune or ripple or eolian dune to show a conventional stoss slope that faces upcurrent, and lee slope that faces downcurrent. Sand is mobilized by wind ripples, grainfall, and grainflow to deposit cross-stratification on the lee slope that downcurrent.*

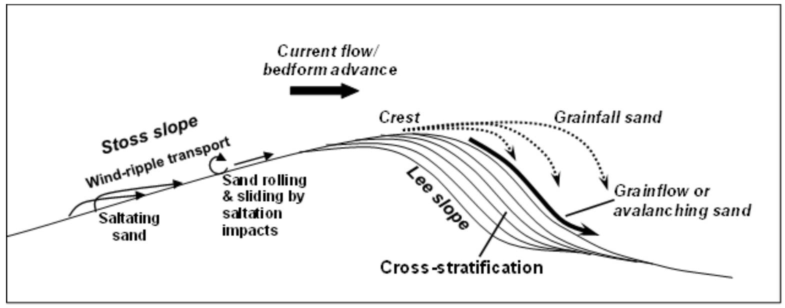
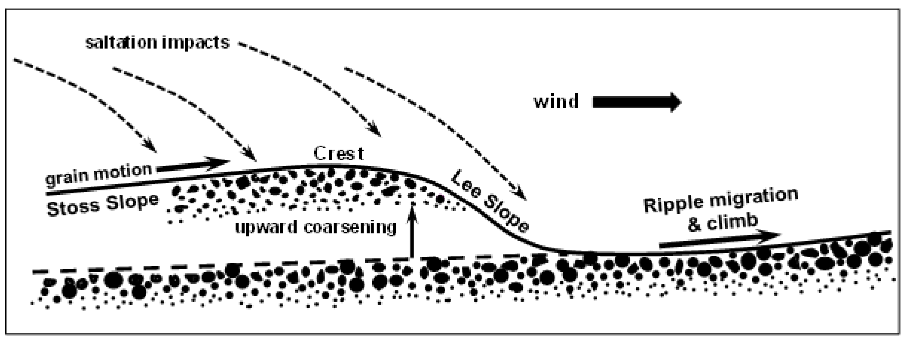



*Figure 10. Sets of cross-straification (inclined grayish strata) in between nearly horizontal pinkish bounding surfaces. Trees are several meters tall. Jurassic eolian Navajo Sandstone at Zion National Park, southwest Utah.*

*Figure 11. Simple profile of a non-adhesion eolian ripple to show essential morphological parts: stoss slope (upwind facing), crest (ripple summit), and lee slope (downwind facing). Propelled by kinetic energy imparted by saltation impacts, coarsest grains roll and slide along stoss slope and settle at the crest or tumble down lee slope to form an upward-coarsening stratum. Redrawn and modified from Collinson and others (2006, p. 90).*




*Eolian pseudo-crosslaminations.* The thin dipping or inclined sedimentary layering in localized beds of the Cockburn Town and North Point Members (Figures 6C and 7C), including that in Figure 6D from Eleuthera Island, Bahamas, appear as cross-stratification. A viewer is given the impression that these cross-stratified beds were deposited either by tall ripples or by small dunes. See previous section, *Cross-stratification.* The resemblance to true cross-stratification is made apparent by the traces of bounding surfaces (wrinkled bounding surfaces in Figure 12), which, although dip in the direction of wind flow, they do not indicate the direction of movement in wind of the adhesion ripples themselves. In this sense, the dipping strata are pseudo-crosslaminations (Hunter, 1973) or pseudobeds (McKee, 1965).

For a normal wind ripple, the crests and lee slopes face downwind and are the sites of sediment accumulation. The gentle stoss slopes face upwind. However, this relationship between ripple shape and wind direction is reversed in eolian adhesion ripples. The "stoss" slopes of eolian adhesion ripples are steep slopes, face upwind, and are the

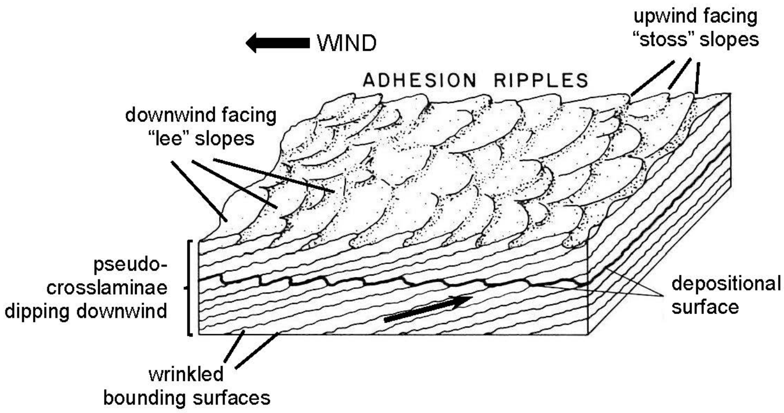



*Figure 12. The sedimentary nature of eolian adhesion ripples in a wet, sandy environment. Steep "stoss" slopes face upwind and are sites of capture of wind-transported sand by surface tension and capillary action. Adhesion ripples migrate and climb upwind (black arrow on front panel) and leave traces of their upwind climb as wrinkled bounding surfaces. Modified from Kocurek and Fielder (1982, p. 1230); used with permission from Society of Economic Paleontologists and Mineralogists (SEPM).*

sites of sand accumulation (Figure 12).

*How adhesion ripples form.* In a coastal eolian dune field, low-relief interdune swales may be wetted temporarily either by rain, storm overwash, spring-tide flooding, or by streams (i.e. wadis) that flow among the dunes. Rain will also moisten dunes but low-lying interdunes are likely places where water can pool and remain wet longer. Loose dry sand is reworked by wind from the beach or adjacent dunes, and saltates across the wet, sandy surfaces. Adhesion ripples are born when the loose, dry sand is captured by wet sand through surface tension and capillary action of water. Multiple ripples develop as sand, saltating in the wind stream, adheres to the steep upwind "stoss" slope through water capillarity. Consequently, the ripples build out by "stoss" slope accretion and migrate and climb into the wind to form the bumpy, bulbous ripple surface (Figure 8B). As long as areas of wet sand and sand capture persist, adhesion ripples will continue to form.

*Bedform climbing.* The nature of sediment transport in normal subaqueous or eolian ripples and dunes compels them to climb over the next downcurrent bedform in order to leave behind a stratified deposit. Otherwise, in the absence of bedform climb, that deposit will be removed by erosion. The angle of bedform climb is controlled by the amount of sediment available and the strength of the current to move it laterally (Harms et al., 1982; Hunter, 1977b).

Because adhesion ripples migrate and climb into the wind, the pseudo-crosslaminations formed dip downwind. Each downwind-dipping lamination is the depositional product of one climbing adhesion ripple and is delineated by upper and lower bounding surfaces (wrinkled bounding surfaces in Figure 12), which mark the passage of adhesion ripples above and below as they climb into the wind.

The angle of climb for eolian adhesion ripples is controlled by wind speed, angle of descent of saltation impacts (see Figure 11), the amount of dry sand available, and the water content of the sand mass over which the dry sand saltates. The wetter the sand, the capillary attraction between dry and wet sand increases and the angle of climb for adhesion ripples increases (Kocurek and Fielder, 1982). The gently increasing angle of climb of concave-upward pseudo-crosslaminations in beds of the Cockburn Town and North Point Members (see previous sections and Figures 6C and 7C) suggests that the water content of the wet mass of sand over which dry sand saltated increased slightly upward over time.

## CONCLUDING REMARKS

Adhesion ripples and the pseudo-crosslaminations they deposit are newly discovered sedimentary structures in the Cockburn Town Member of the Pleistocene Grotto Beach Formation and in the North Point Member of the Holocene Rice Bay Formation on San Salvador Island, the Bahamas. They reinforce the interpretation of a coastal eolian dune system for these lithostratigraphic units.

Adhesion ripple marks cropout on bedding surfaces as low-amplitude, wavy and lobate microridges oriented roughly northwest-southeast, perpendicular to the Northeast Trade Wind direction during Quaternary time for the Bahamas. Steep "stoss" slopes face easterly and upwind, in the direction of ripple migration. When adhesion ripples were mobile, they climbed one over the other into the wind. In so doing, they deposited pseudo-crosslaminations that dip downwind and westerly. Although these laminations deceptively resemble foresets of cross-stratification, they record only the easterly direction of upwind climb of the adhesion ripples, and not the lee slope build-out and migration of the ripples that is typical for normal current ripples and dunes.

By comparison with modern adhesion ripples observed in siliciclastic, non-carbonate sediment, the Quaternary adhesion ripples on San Salvador evolved from loose, dry carbonate sand, re reworked by wind from backshore beaches and eolian dunes. The wind-driven dry sand eventually saltates across areas of wet sand. Here, surface tension and capillary action of the water in the wet sand capture the dry sand grains. The results are steep "stoss" slopes of bumpy, bulbous adhesion ripples that accrete or build out into the wind. As the ripples climb into the wind, they deposit pseudo-crosslaminations that dip downwind.

In modern coastal eolian environments, wetting of an area of sand can be achieved either by rain, storm-washover, or spring tidal flooding enhanced by wind, especially of low-lying interdunes. It is unlikely that the coastal dune fields preserved in the Cockburn Town and North Point Members were washed by tidal or storm floods. There is outcrop evidence for reef, nearshore tidal, and shoreline deposits that underlie the eolian rocks in the Cockburn Town Member (Carew and Mylroie, 1995). However, no outcrop evidence has been uncovered, so far, to suggest episodes of tidal or storm currents invading the Pleistocene eolian environment. For the Holocene North Point Member, it is also unlikely that the coastal dune field was affected by any marine incursion, given that global sea level was 2 meters (6.6 ft) lower than present sea level (John Mylroie, 2020, written communication).

Conclusively, episodic rain was responsible for wetting parts of the coastal dune fields preserved in the Cockburn Town and North Point Members. Intervals of laterally discontinuous adhesion ripples and their pseudo-crosslaminated deposits are interbedded locally with cross-bedded dune strata in the Pleistocene Grotto Beach Formation (Caputo, 1989, 1995) and with dominantly wind-ripple strata in the North Point Member (Caputo, this volume). This sedimentary relationship suggests that conditions of dry, loose, wind-blown carbonate sand in dunes and in wind ripples were interrupted briefly by rain-wetting and adhesion-ripple sedimentation. The gentle upward-concave shape of pseudo-crosslaminations indicates a slight increase in the water content of the wet sand and a slight increase in the angle of climb of the adhesion ripples. When rainfall stopped and storm clouds moved on, the wet sand dried, adhesion-ripple sedimentation terminated, and dry dune and wind-ripple sedimentation resumed until the next rainfall. Consequently, a record of localized, short-lived dry-wet-dry cycles is preserved in these Quaternary sedimentary rocks on San Salvador Island.

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