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Ichnology of Holocene Carbonate Eolianites on San Salvador Island, Bahamas: Diversity and Significance

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ABSTRACT

Wind-deposited, terrestrial carbonate grainstones, formed concurrently with sea-level transgression, comprise the greater part of the Holocene rock record throughout the Bahama Archipelago and are particularly common along windward coastal reaches. Eolianite exposures of the Rice Bay Formation on North Point and along the Hanna Bay cliffs on San Salvador are characterized by well-preserved physical sedimentary structures, most notably large-scale cross-stratification and distinctive, millimeter-scale, inversely graded lamination couplets, along with other mesoscale structures. These carbonate eolianites also typically contain a diverse assemblage or ichnocoenosis of plant and animal trace fossils. Structures formed by plant roots are near-ubiquitous in Quaternary Bahamian facies and commonly occur in these eolianites. In addition, the above-ground parts of plants and trailing roots may form distinctive trace fossils along the bedding planes of eolianites. Animal trace fossils, including *Skolithos linearis* formed by tube-dwelling insects and/or arachnids, small, irregular burrows formed by insects or insect larvae, large cluster burrows formed by digger wasps, large stellate burrows likely formed by burrowing bees, and small burrows likely representing ant nests, also characterize these eolianites. Indeed, the dunal ichnocoenosis commonly exhibits a higher level of diversity than that found in shallow subtidal and intertidal-supratidal environments, and the burrowing activity of several tracemakers of the dunal ichnocoenosis can produce ichnofabrics distinctive to carbonate eolianites. In a core sample, the occurrence of individual trace fossils generated by invertebrates or of an ichnofabric should not be used as evidence to rule out an eolian environment.

INTRODUCTION

Carbonate eolianites are wind-deposited, terrestrial sedimentary rocks composed of sand-sized grains and cement of calcium carbonate. Rocks of this origin make up the greater part of the Quaternary rocks that cap the islands of the Bahamian Archipelago. A particularly well-exposed and instructive succession of Holocene carbonate eolianites can be found in the sea cliffs and rocky shore platforms along the northeast coast of San Salvador Island. As sea level rose over the island's previously exposed shelf during Holocene transgression, the sediments that comprise these rocks were deposited, beginning about 6,000 years ago, when easterly trade winds blew sands landward from the beach zone.

In addition to the Bahamas, Pleistocene and Holocene carbonate eolianites form a major component of the shallowing-upward carbonate sequences in Bermuda, the Yucatan Peninsula of Mexico, and other, geologically similar tropical locations around the world. However, as recently as the early 1980s, pre-Quaternary carbonate rocks of eolian origin rarely, if ever, had been reported in the literature (McKee and Ward, 1983). This leads to the question of whether the apparent scarcity of carbonate eolianites in the more ancient rock record is real or results primarily from failure to recognize such rocks. More recently, there has been growing interest among sedimentary geologists in carbonate eolianites and in developing criteria for their recognition in the pre-Quaternary rock record. A recent symposium sponsored by SEPM (Society for Sedimentary Geology) at the 1998 AAPG Annual Convention in Salt Lake City addressed this very topic and its associated questions.

McKee and Ward (1983, p. 136-137) listed a number of criteria derived from the study of Quaternary carbonate eolianites that they deemed potentially useful for the recognition of more ancient eolian limestones. Most of these criteria relate to large-scale features such as bed geometry and associated facies or to microscopic fetures such as grain composition, size and sorting, and grain cements. Mesoscale physical sedimentary structures were mentioned only briefly, and it was stated that such rocks likely contained few, if any, trace fossils resulting from burrowing animal activity (McKee and Ward, 1983, p. 131). This dearth of knowledge about the mesoscale physical sedimentary structures and ichnology of carbonate eolianites motivated us to undertake a series of studies of the eolianites exposed at North Point and along the cliffs of Hanna Bay on San Salvador (Fig. 1). In addition to displaying mesoscale physical sedimentary structures diagnostic of wind deposition and likely recognizable in core samples (White and Curran, 1988), Bahamian carbonate eolianites

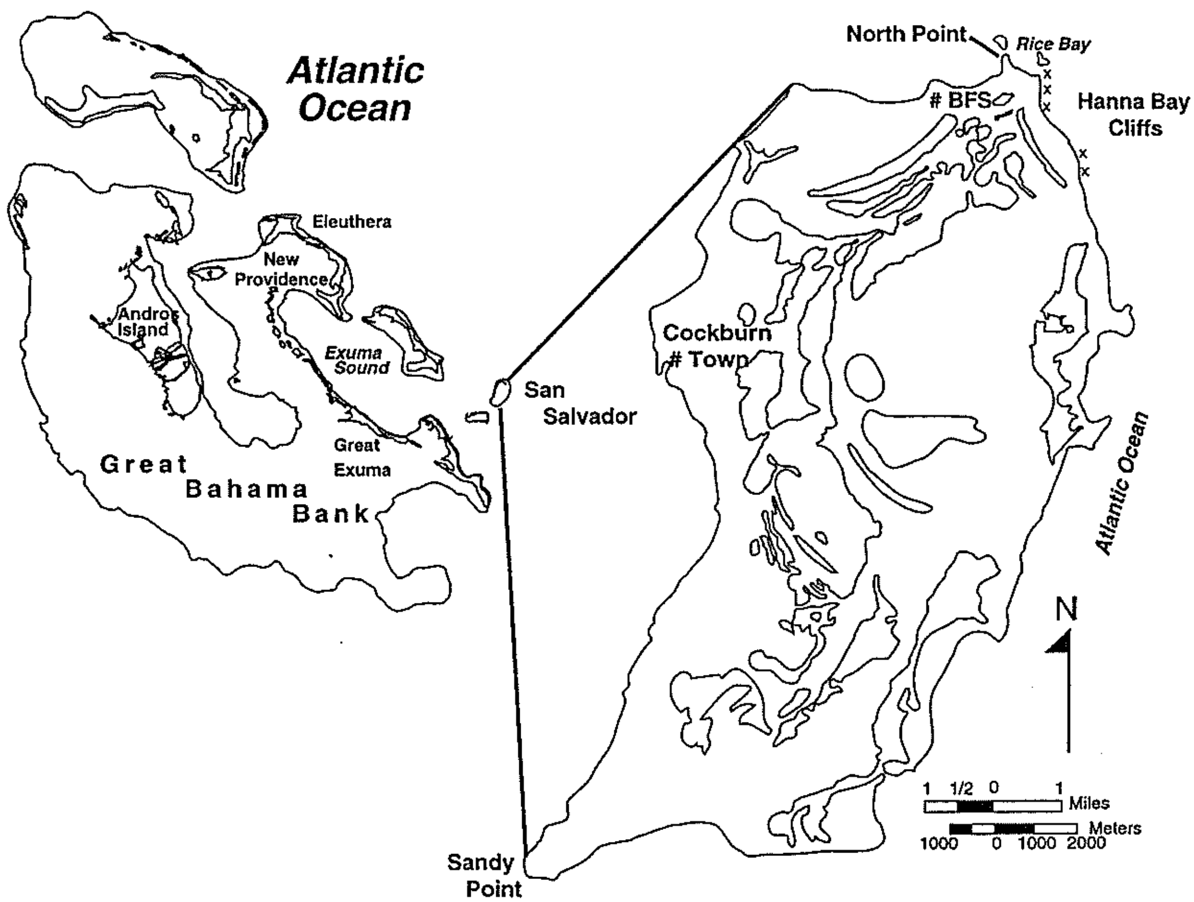

Figure1. Location of San Salvador Island within the Bahama Archipelago and the study sites for the Rice Bay Formation at North Point (North Point Member) and along the Hanna Bay cliffs (Hanna Bay Member). Small xxxs mark approximate location of Hanna Bay Member exposures used in this study.

can contain a distinctive assemblage(s) of trace fossils generated by plants and the burrowing activities of invertebrates. This trace fossil assemblage previously has been described and interpreted in some detail (Curran and White, 1987, 1991; Curran, 1994).

In this paper, we will review briefly the characteristics of the mesoscale physical sedimentary structures found in the carbonate eolianite exposures at North Point; a more detailed description and analysis was given by White and Curran (1988). The paper's emphasis will be on the ichnology of the eolianites exposed in the Hanna Bay cliffs. Characteristics of the previously described trace fossils of the dune environment ichnocoenosis will be reviewed and findings from more recent research will be presented, particularly regarding description and interpretation of the trace fossils attributed to the burrowing activity of bees. The major goal of the paper is to highlight the ichnologic features of Holocene Bahamian eolianites so that they may become better known and put into use as criteria for the recognition of pre-Quaternary carbonate eolianites.

THE GEOLOGIC SETTING

The physical sedimentary structures and trace fossils described in this paper occur in carbonate eolianites of sea-cliff exposures along Hanna Bay and at North Point and Cut Cay along Rice Bay, on the northeastern coastal area of San Salvador (Fig. 1). These Holocene rocks were assigned to the Rice Bay Formation by Carew and Mylroie (1995 and earlier papers) and were subdivided into two parts, the older North Point Member and the somewhat younger Hanna Bay Member (Fig. 2). The general characteristics of the rocks of these members have been described in some detail by Carew and Mylroie (1995, p. 21-22). Both members are well represented by equivalent eolianites on other Bahamian islands, as indicated by references cited in Carew and Mylroie (1995, 1997). Field localities for study of features of the North Point Member and Hanna Bay Member rocks discussed in this paper have been described in chapters written by us for various geology field guides available from the Bahamian Field Station (most recently in Curran, 1997).

The North Point Member eolianites are generally fine-grained sands, mostly pelsparites with some ooids and skeletal fragments. The sediments comprising these eolianites were deposited under transgressive-sea conditions beginning about 6,000 years before present, as the sea flooded the San Salvador shelf (sea-level curve of Boardman, et al., 1989; dates from Carew and Mylroie, 1995). Peak deposition of these eolian sediments occurred around 5,000 years before present. The sediments of the eolianites that form the present North Point were deposited as lobate, parabolic dunes that coa-

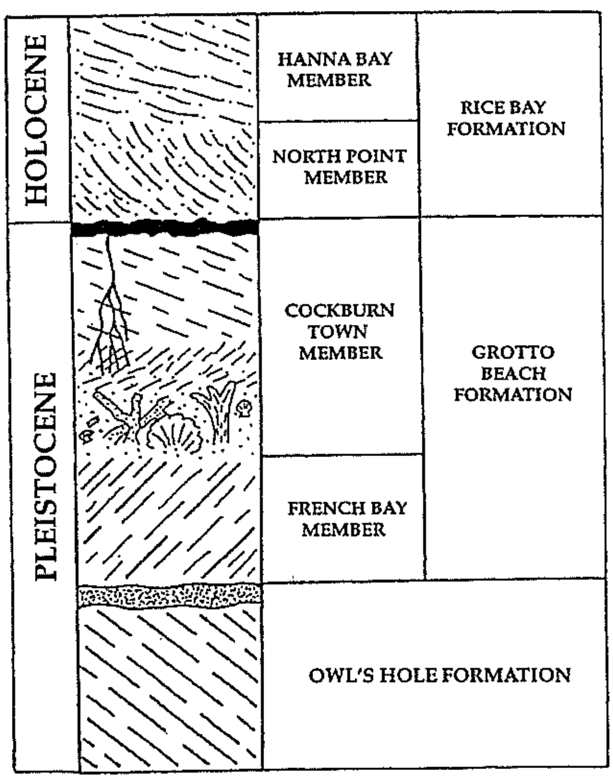

Figure 2. Physical stratigraphic column for San Salvador and other Bahama islands. Note that a well-developed terra rosa paleosol separates the latest Pleistocene unit from the Holocene Rice Bay Formation. From Carew and Mylroie (1995).

lesced to form an elongate dune ridge perpendicular to the prevailing easterly trade winds direction.

The eolianites of the Hanna Bay Member were interpreted as having been deposited essentially in equilibrium with modern sea level, between about 3,200 to 300 years before present. Most such deposits in the Bahamas are younger than 2,500 years before present (Carew and Mylroie, 1995). In the cliffs in the vicinity of the member's type section at Hanna Bay, the lower-most rocks have bedding nearly parallel with present sea level. The sediments of these rocks were deposited in a beach backshore environment (Fig. 3; Curran and White, 1987, 1991), and they consist of generally coarse-grained biopelsparites and pelbiosparites. Moving up the section (Fig. 3), grain size decreases but composition remains essentially the same. The backshore bedding quickly gives way to more complex patterns of wedge-planar cross-stratification, indicative of an eolian environment. Particular care should be taken in examining the exposures of Hanna Bay Member rocks in the field, as the cliffs are steep and the rocks only poorly lithified and commonly slick from sea spray.

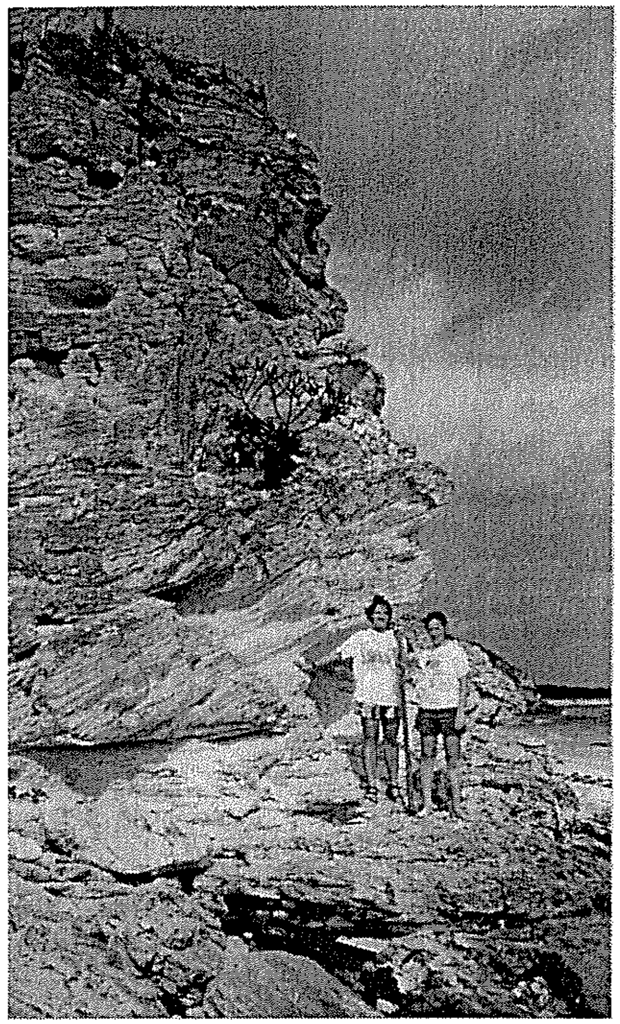

Figure 3. Cliff exposure of the Hanna Bay Member of the Rice Bay Formation at Hanna Bay. Students are standing on backshore beds that quickly grade upward to protodune and dunal beds (carbonate eolianites).

THE PHYSICAL SEDIMENTARY STRUCTURES

Both the North Point Member and Hanna Bay Member eolianites display well-preserved physical sedimentary structures. We have studied these structures in detail, primarily along the windward coast of North Point (White and Curran, 1988). In that paper, we particularly emphasized the description and analysis of the mesoscale physical sedimentary structures found in these rocks. We thought that better descriptions and understanding of these characteristic, small-scale structures would provide useful criteria for the recognition of more ancient carbonate eolianites, particularly in core samples where the larger-scale aspects of dunal structure are not visible. Similar physical sedimentary structures to those described here likely are widespread in Holocene carbonate eolianite deposits throughout the Bahamas. Certainly that was the case with Holocene strata that we studied on Lee Stocking Island in the Exuma Cays (White and Curran, 1993).

Large-scale cross-stratification structures do dominate one's initial view of these dunal deposits, particularly for the exposures on the west (lee) side of North Point (White and Curran, 1988, Fig. 3; and the cover of this volume). Closer examination of the stratification of these rocks reveals that distinctive fine/coarse-grain couplets characterize these deposits. These couplets were formed by the migration of wind ripples (climbing wind ripples). Greater than 90% of these eolianite strata reflect reworking and redeposition of previously accumulated wind-deposited sands by climbing wind ripple activity. These migrating and accreting ripples produced millimeter-scale, fine (migrating trough)-coarse (migrating crest) couplets which form the distinctive laminations visible in outcrop, hand sample, and thin section (White and Curran, 1988, Figs. 6,7).

Other distinctive structures include centimeter-scale grainfall layers of homogenous, unlaminated sands deposited from suspension on sheltered lee-side slopes of the dunes. In some cases, these grainfall deposits avalanched down lee slopes to produce distinctive lenticular structures a few centimeters across (White and Curran, 1988, Figs. 8,9). In addition, micrite crusts and associated plant trace fossils (as described briefly below) are common in the eolianite beds of the Rice Bay Formation (White and Curran, 1988, Fig. 10). These crusts formed quickly, during short-lived breaks in sediment accumulation as the dunes developed. White and Curran (1988, p. 175) suggested that these crusts are a distinctive aspect of transgressive carbonate dune strata. Further criteria for the recognition of transgressive versus still-stand versus regressive carbonate dune deposits have been carefully tabulated and discussed by Carew and Mylroie (1997, 1998).

THE DUNAL ICHNOCOENOSIS

Background

The carbonate eolianites of the Rice Bay Formation contain a distinctive and surprisingly diverse assemblage of plant and animal trace fossils. This assemblage clearly qualifies as an ichnocoenosis; namely, as defined by Bromley (1996), it represents an ecologically pure assemblage of trace fossils resulting from the activities of a single community of organisms. In other words, these organisms, both plants and animals were living together within the dunal environment and performing their trace-making activities at essentially the same time. The dunal zone ichnocoenosis is illustrated in Fig. 4. Undoubtedly there were sub-environments within the dunal zone, and these environments likely hosted their own sub-ichnocoenoses of trace-making organisms. For instance, we suspect that some of the trace fossils most commonly occur in dune lee slope areas owing to the requirement of the trace-making organisms for protection from the wind, requirements for moisture, etc., as discussed below. The ichnology of the Rice Bay Formation strata previously has been described and discussed in detail by Curran and White (1987, 1991), White and Curran (1988), and in Curran (1997), so the following discussions of each element of the dunal ichnocoenosis will be brief. Recent work on the rocks of the Hanna Bay Member has revealed the common occurrence of burrows attributable to the activity of bees, so those trace fossils will receive greatest attention.

Plant Trace Fossils

Structures attributable to the activities of plants, exhibiting a variety of morphologies, likely formed by various parts of plants and un-

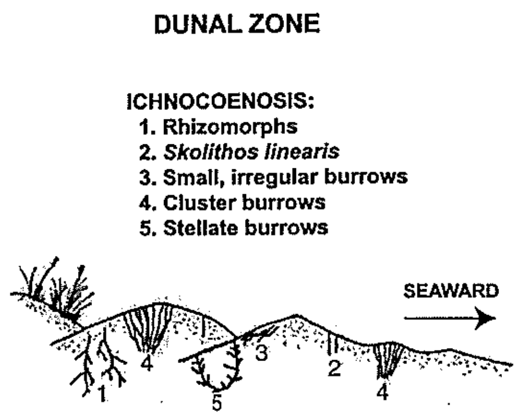

Figure 4. Model of the dunal ichnocoenosis characteristic of Holocene carbonate eolianites in the Bahamas.

der differing circumstances, can be found in virtually all facies of Quaternary Bahamian limestones. Nonetheless, such structures are most common in eolianites.

Initially the term rhizomorph, introduced by Northrop (1890), was used to describe the cylindrical root-like masses found in Bahamian limestones. This term has a bit of a checkered past in that it has been modified, rejected, replaced, and reintroduced in the literature over the years. A lengthy discussion of the history of usage of the term rhizomorph was given by White and Curran (1997) in the context of presenting a classification scheme for all types of plant-related features found in Bahamian Quaternary rocks. Carew and Mylroie (1995) pointed out that not all fossilized plant features represent roots; other vegetative parts also can be preserved in Bahamian rocks in some fashion. They proposed the term vegemorph and suggested that it replace all previously used terms having rhizo as a prefix. Given that "rhizo" structures truly are a common component of Quaternary Bahamian limestones and that they exhibit a range of distinctive morphologies, we felt compelled to offer a new classification scheme for such structures (White and Curran, 1997). In the past, we have favored use of the term rhizomorph, as in Fig. 4 herein.

Probably the most common types of plant trace fossils found in Bahamian rocks, particularly those of late Pleistocene age, are those formed by plant roots. Following the White-Curran classification scheme, such structures are rhizo-ichnomorphs (Fig. 5A). Rhizo-ichnomorphs are present in the Holocene rocks of the Rice Bay Formation, but they are of secondary importance to the horizontally-oriented structures formed by plants, as described below.

Plants with runners extending for several meters across the surfaces of modern sand dunes are abundant on San Salvador, for example the railroad vine (*Ipomoea pes-caprae*) and the bay geranium (*Ambrosia hispida*). These runners can induce lithification, resulting in distinctive, preservable structures, as discussed by White and Curran (1988, 1997). We have termed these structures thallo-ichnomorphs (Fig. 5B). Such thallo-ichnomorphs are common on the numerous micritic crusts of the North Point Member, as exposed along the coast of Rice Bay, and their occurrence on the crusts indicates that they developed contemporaneously with the accumulation of sediments in the ancient dunal environment. The presence of such thallo-ichnomorphs thus can serve as another specific criterion for the recognition of eolian deposition.

Animal Trace Fossils

<u>*Skolithos linearis*.</u>

Skolithos linearis burrows (Fig. 5C) are common in the eolianite beds of the Hanna Bay Member, as exposed in the Hanna Bay cliffs. These burrows consist of simple, lined, unbranched shafts typically 2 to 4 mm in diameter and sometimes up to 45 cm in length. This occurrence of *S. linearis* and its significance was discussed at some length by Curran and White (1987, 1991) and White and Curran (1988). These were dwelling burrows, likely formed by insects, arachnids, or both.

Recently, we made a survey of a 120-meter long section of the Hanna Bay cliffs, counting, identifying, and measuring all burrows in the eolianites section of the cliffs, from the base of the exposures to upward arms-reach level. The data for *S. linearis* burrow diameters were plotted as a histogram (Fig. 6). Although not conclusive, the data suggest two size-classes for these burrows, supporting the idea of more than one tracemaker invertebrate for the burrows.

<u>Small, irregular burrows.</u>

These burrows are the most abundant animal trace fossils in the Rice Bay Formation, and they are particularly common in the North Point Member in exposures on North Point and

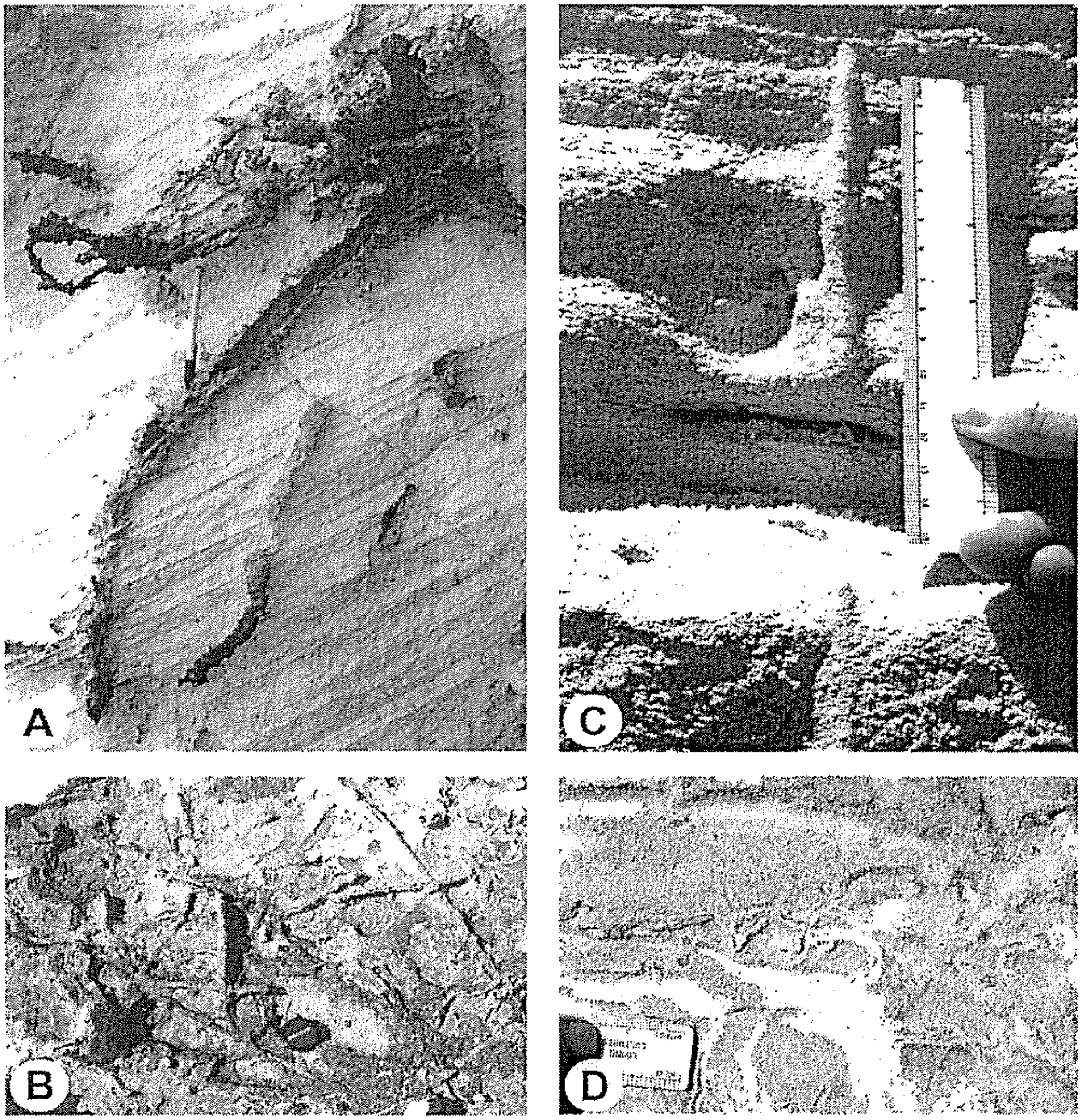

Figure 5. A) Typical rhizo-ichnomorph produced by the biogeochemical action of plant roots that also modified the original sedimentary structures in late Pleistocene eolianites, The Gulf, San Salvador Island. Pen = 15 cm. B) Thallo-ichnomorphs developed on the surface of a micritic crust on beds of the North Point Member of the Rice Bay Formation, North Point. Lens cap = 5.5 cm. C) Typical specimen of Skolithos linearis in eolianite beds of the Hanna Bay Member, Hanna Bay. D) Typical small, irregular burrows on upper surface of sandflow strata, North Point Member, North Point.

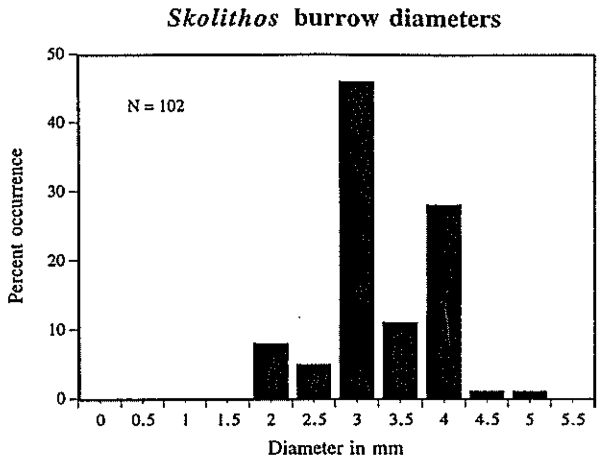

Figure 6. Histogram of Skolithos linearis burrow diameters measured from eolianite exposures of the Hanna Bay Member of the Rice Bay Formation, Hanna Bay.

Cut Cay. The burrows are easily visible on the upper surfaces of the eolianite strata where they irregularly meander (Fig. 5D). They have a uniform diameter of 3 to 4 mm along their length, which commonly exceeds 20 cm. The burrows have an outer wall that is paler than the enclosing sediment and a fill that is like the surrounding sediment. No branching has been observed, but crossovers are common.

In vertical exposure, these burrows can extend 2 to 3 cm into the strata and sometimes are in sufficient density to cause burrow mottling, resulting in a distinctive ichnofabric [after Bromley (1996) "all aspects of the texture and internal structure of a sediment that result from bioturbation at all scales"], as was observed in the Holocene eolianites of Lee Stocking Island (White and Curran, 1993, Figs. 6,7). Larval or adult insects were the probable tracemaker organisms, but no specific modern counterpart has yet been identified. These trace fossils are most common in grainfall and sandflow strata in the North Point Member rocks, suggesting that their makers preferentially inhabited sheltered dune lee slopes areas (White and Curran, 1988).

Cluster burrows.

Clusters of unlined, vertical burrows radiating upward from a common area of origin form the largest and most distinctive trace fossils occurring in the Rice Bay Formation. We have informally referred to these impressive burrow systems as cluster burrows and have described them in some detail (Curran and White, 1987, 1991; White and Curran, 1988). These large burrows consist of numerous, straight to gently curved, unlined shafts (average diameter 1.2-1.4 cm); the shafts are closely packed in cross-section, and they can be 1.4 m or more in length. Each cluster consists of tens to hundreds of individual shafts, creating an overall cone-shaped structure that may reach a diameter of 1 m or more (Fig. 7A,B). Curran and White (1987) interpreted the cluster burrow as representing the brooding and hatching activities of a species of burrowing (digger) wasp of the Family Sphecidae, with each shaft being the escape pathway of a young wasp, formed as it moved to the sediment surface.

Previously we had identified at least 15 cluster burrows in the Rice Bay Formation rocks on San Salvador, with most found in the North Point Member beds. This was a very conservative count. Our more recent work on the Hanna Bay Member exposures along the Hanna Bay cliffs has revealed that cluster burrows are more common there than we originally thought; at least 13 clusters occurred in the 120 m stretch of Hanna Bay exposures that we surveyed. In addition, we found cluster burrows to be well-developed and reasonably common in the Holocene eolianites of Lee Stocking Island in the Exuma Cays (White and Curran, 1993, Figs. 11,12), and Curran and Dill (1990) reported cluster burrows in late Pleistocene eolianites within a submarine cave on Norman's Pond Cay, also in the Exumas. The indication is that this spectacular trace fossil is widespread in Bahamian Quaternary eolianites, and similar cluster burrows very likely occur in tropical eolianites elsewhere in the world. As with the small, irregular burrows, cluster burrows can produce a distinctive ichnofabric within the eolianites where they occur.

<u>Stellate burrows</u>.

Several new exposures of Hanna Bay Member beds along the Hanna Bay coast combined with our recent re-examination of these beds with fresh eyes and, possibly, a greater sense of ichno-awareness has led to our recognition of large, well-formed burrows that we have informally termed stellate burrows for the stellate pattern formed by obliquely-oriented shafts that radiate out and upward from a large central shaft (Figs. 8, 9A,B). A well-developed stellate burrow has a U-shaped main shaft to which literally hundreds of smaller burrows connect (Fig. 8). Stellate burrows are patchy in distribution in the Hanna Bay eolianites. They seem to occur most commonly in the lower half of the eolianite sequence. We found three areas of bedding plane exposure that revealed the abundant presence of the stellate burrow cross-sections and that were sufficiently large in area to permit census measurements (Fig. 9A). Our counts averaged 20 stellate burrow cross-sections per m^2 in these areas.

Typical height of the main shaft of the stellate burrow is 50 cm or more, with average shaft diameter being 5-7 cm. The smaller, obliquely and mostly upward-oriented, unlined shafts that branch off from the main U-shaft have an average maximum diameter of 1 cm. In full longitudinal view, they are flask-shaped, with the entry to the main shaft noticeably constricted (Fig. 9B). Our interpretation of these burrows is preliminary, but we believe that they represent the nesting activity of bees of the Family Halictidae (sweat bees). Michener (1974) illustrated nests made by modern halictid bees that bear close resemblance to those described here.

From the fossil record, Thackray (1994) described nests attributed to halictids from Miocene paleosols of Kenya that have an overall burrow architecture generally similar to the Ba-

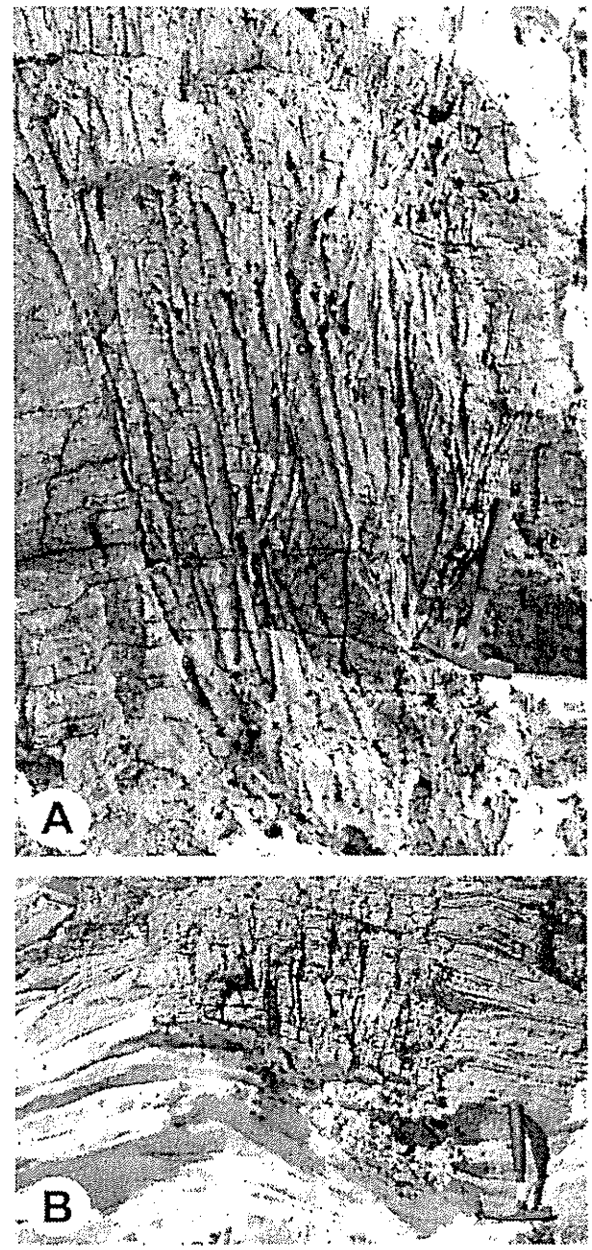

Figure 7. A) Large cluster burrow in vertical dune face exposure, North Point Member of the Rice Bay Formation, North Point. Rock hammer for scale. B) Another cluster burrow in vertical section in eolianite beds, Hanna Bay Member, Hanna Bay. Rock hammer for scale.

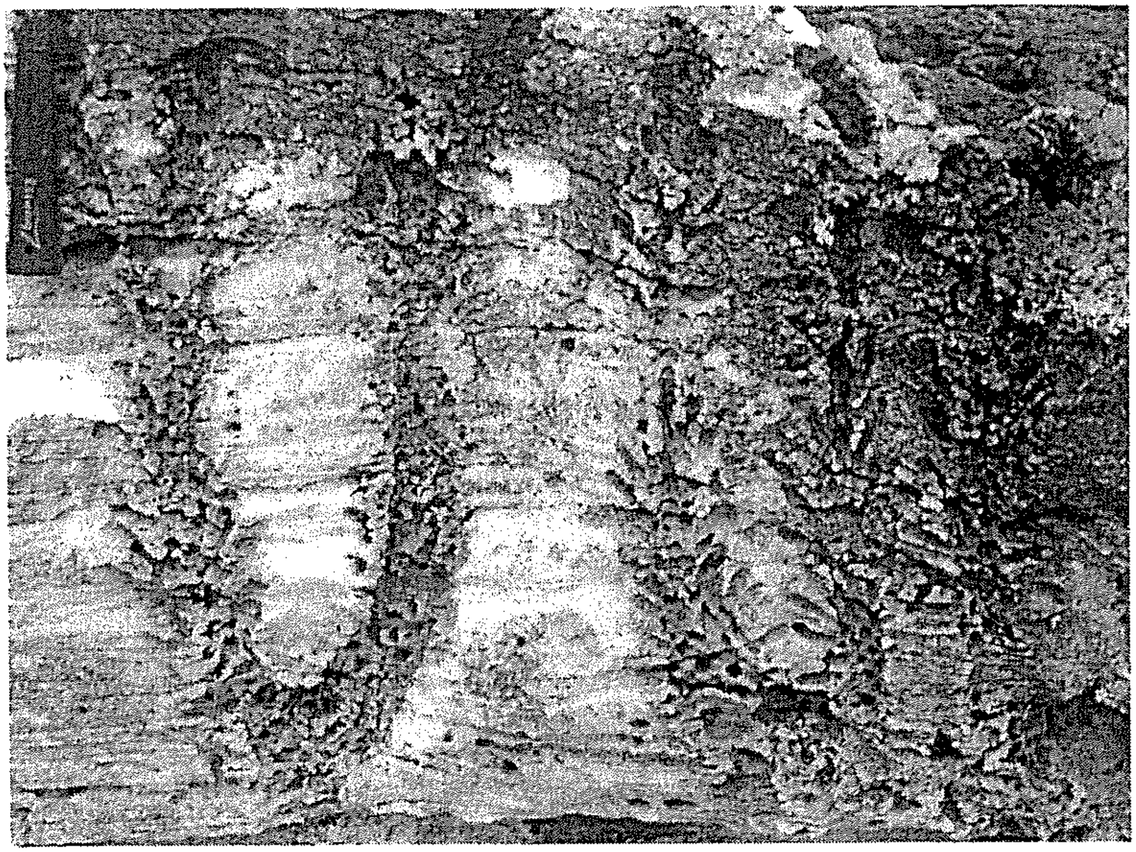

Figure 8. Well-developed stellate burrows in eolianites of the Hanna Bay Member of the Rice Bay Formation, Hanna Bay. Rock hammer handle in upper left = 15 cm.

hamian stellate burrows. More recently, Elliott and Nations (1998) described burrows from the Late Cretaceous Dakota Formation in Arizona that they interpret as halictid nests formed in fluvial channel-bar sands. Although these burrows are smaller in size and differ in overall architecture from the stellate burrows, in cross-section they resemble very closely the stellate form of the Hanna Bay burrows (compare Fig. 9B with Elliott and Nations, Fig. 5A). This is at least somewhat amazing given that the burrows from the Dakota Formation are approximately equivalent in age to the oldest known bee body fossil (Elliott and Nations, 1998).

Both Thackray (1994) and Elliott and Nations (1998) assigned their fossil bee nests to the ichnogenus *Celliforma*. This is a likely taxonomic assignment for the stellate burrows, but, pending further research on our part, we prefer to use the informal name for now. We expect to be able to make new interpretations from these fascinating burrows about the habits of burrowing bees and about sub-environments represented within the Hanna Bay Member eolianites with continued study. Again, these burrows can be sufficiently numerous to impart a signature ichnofabric to the eolianites in which they occur.

Possible ant nesting activity.

Another new observation from the Hanna Bay Member eolianite beds exposed at Hanna Bay is that some cluster burrows show clear evidence of extensive secondary burrowing activity (Fig. 10A,B). During the 4th International Ichnofabric Workshop held on San Salvador in March, 1997, Stephen Hasiotis, an ichnologist specializing in terrestrial burrows, pointed out to the authors that some cluster burrows were infested with

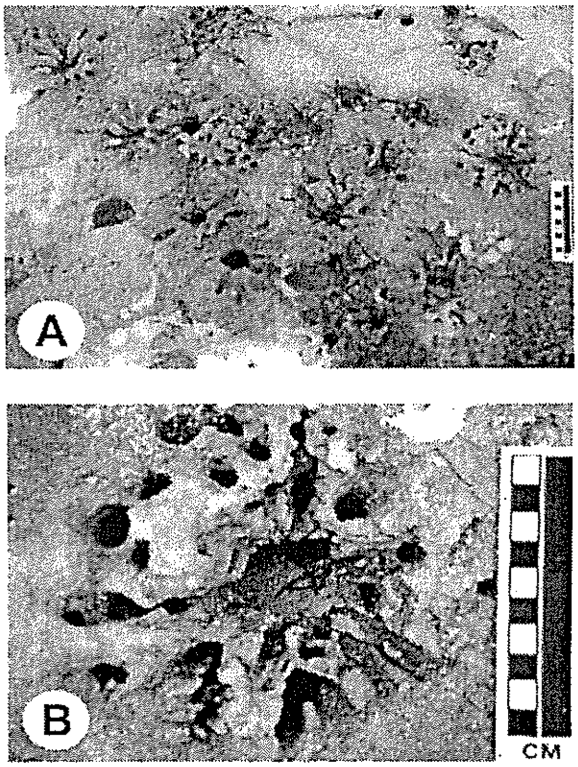

Figure 9. A) Numerous cross-sections of main shafts of the stellate burrow on a near horizontal dune surface, eolianites of the Hanna Bay Member of the Rice Bay Formation, Hanna Bay. Scale = 10 cm. B) Close-up view of a cross-section of the main shaft of a stellate burrow. Note that the smaller, radiating shafts are constricted at their juncture with the main shaft. Same location.

smaller, interconnecting burrows (Fig. 10B). The initial interpretation is that these burrows represent chambers of large ant nests. We are continuing our research on these burrows and expect to have a more complete interpretation in the future. As with the three previously described burrow types, the burrowing represented by this likely ant activity can impart a distinctive ichnofabric to the eolianites it which it occurs.

CONCLUSIONS

From the ichnologic and sedimentologic

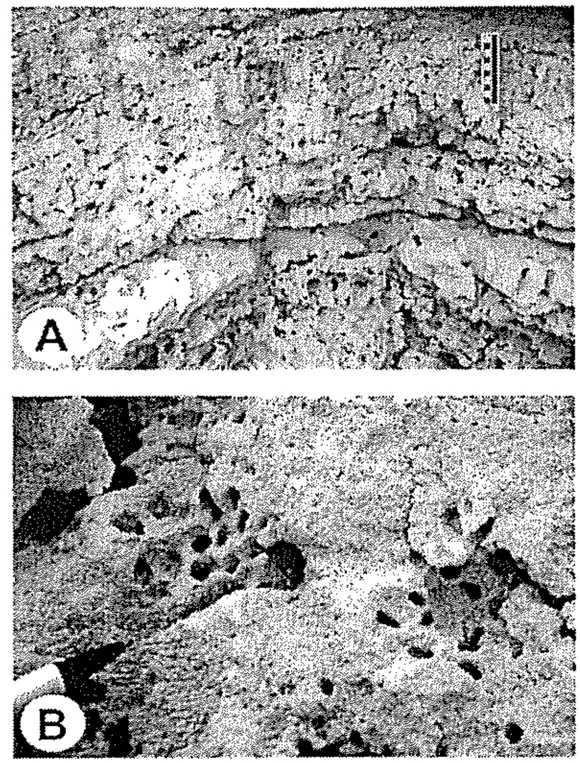

Figure 10. A) Cluster burrow infested by smaller burrows likely formed by ants, eolianites of the Hanna Bay Member of the Rice Bay Formation, Hanna Bay. Scale = 10 cm. B) Close-up view of these smaller burrows, likely the fossil chambers of ants. Same location, pen point for scale.

standpoints, there are several notable aspects of the ichnocoenosis and physical sedimentary structures found in the Holocene carbonate eolianites of the Rice Bay Formation on San Salvador. The first and most obvious point is that these rocks contain a distinctive suite of physical sedimentary structures, particularly at the mesoscale. The inversely graded lamination couplets produced by wind ripples are pervasive and distinctive and should be identifiable in cores and small hand specimens from more ancient carbonate rocks.

Secondly, trace fossils formed by burrowing animals are common in these rocks, thus dispelling earlier views that burrows would be at best rare in carbonate eolianites. Furthermore, burrowing by at least several different types of invertebrates can be sufficiently intense to impart distinctive ichnofabrics to these eolianites.

A third major point is that the diversity of this dunal environment ichnocoenosis is high as compared to the shallow subtidal to intertidal-supratidal ichnocoenoses found in Quaternary carbonates of the Bahamas and other tropical, geologically similar areas (Curran and White, 1991; Curran 1994). Further study of this ichnocoenosis likely will yield much more information about the burrowing activities of a variety of invertebrates in the tropical, carbonate dunal environment; such information will shed light on the habits of similar, more ancient invertebrates, as well as their modern counterparts inhabiting this environment.

Given the above, sedimentary geologists working with more ancient carbonate rocks, particularly with core samples, should not rule out the existence of an eolian environment based on the occurrence of individual burrows or of an ichnofabric. Rather, the occurrence of a suite of animal-generated trace fossils and of different ichnofabrics should be expected in carbonate eolianites, along with trace fossils of plant origin.

ACKNOWLEDGMENTS

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