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Sedimentology and Ichnology of Holocene Dune and Backshore Deposits, Lee Stocking Island, Bahamas

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ABSTRACT

Lee Stocking Island is located at the southern end of the Exuma Cays that form the eastern edge of the Great Bahama Bank. Bordered to the east by the deep reentrant of the Exuma Sound, Lee Stocking lies exposed to the prevailing trade winds and the accentuated tides of the sound.

The majority of Holocene limestones on Lee Stocking are eolianites, however, some strata found up to 7 meters above present sea level have the characteristics of backshore deposits. The eolianites consist largely of finely laminated calcarenites that were deposited by climbing wind ripples and some grainfall and lenticular sand flow deposits. The backshore deposits contain sand laminae that are notably coarser than the eolianites and that contain broken marine shells. Generally, the laminae are much flatter lying than those of the eolianites, although they contain some small-scale cross beds that are believed to have formed in runnels on the backshore.

The Holocene limestones on Lee Stocking Island contain a diverse ichnofauna. These trace fossils include large cluster burrows believed to have been formed by the upward migration of the hatchlings of digger wasps. Also present are groups of small, irregular burrows that are common enough in some layers to cause destruction of the eolianite laminations by bioturbation. A trace fossil discovery of especial importance is the presence of *Psilonichnus upsilon*, the fossil burrow formed in beach sediments by the ghost crab *Ocypode quadrata*, in strata interpreted by lithology and sedimentary structures as having formed in the backshore environment. Rhizomorphs produced by plant roots and other traces formed by the vegetative structures of plants occur commonly in the eolianites. Also present and of particular interest are the cylindrical molds of palm trees preserved in growth position and the imprints of palm fronds.

Eolianites were deposited on Lee Stocking Island during the Holocene transgression when carbonate sands formed on the flooded shelf were transported to the beach and thence blown into dunes by the prevailing easterly trade winds. An explanation for the backshore deposits found up to 7 meters above present sea level is less evident. Along modern beaches on Lee Stocking Island there is evidence of wave deposited carbonate sands up to 4 meters above present sea level, presumably as a result of storms and a shoreline configuration that focuses the incoming waves. Whether such circumstances could deposit sands up to 7 meters above sea level is not known. Assuming that there has been no tectonic uplift, the only other explanation is a former sea level during the Holocene 2 to 3 meters above present sea level.

INTRODUCTION

Lee Stocking Island lies a few kilometers northwest of Barraterre, Great Exuma near the southeastern end of the Exuma Cays, a 200 km long chain of islands that extends from northwest to southeast along the eastern margin of the Great Bahama Bank (Fig. 1). To the northeast, Lee Stocking Island is separated from the deep waters of Exuma Sound by a narrow shelf 1.5 to 3 km wide. Tidal current velocities in the waters adjacent to Lee Stocking Island commonly reach 100 cm/second (Dill, 1991). Lee Stocking Island lies at the windward edge of the Great Bahama Bank where it is exposed to the prevailing easterly trade winds. The island is exposed to storm surge and high waves during the passage of hurricanes, the actual wind directions depending on the position of the storm center and its counterclockwise winds relative to the island.

GEOLOGIC BACKGROUND

Geologically, Lee Stocking Island is best-known for the giant subtidal stromatolites that occur in tidal channels to the northwest and north of the island (Dill, *et al.*, 1986; Dill and Shinn, 1986; Dill, 1991). Little has been written about the geology of the island itself. Kindler (1991) suggested that the island, which hither

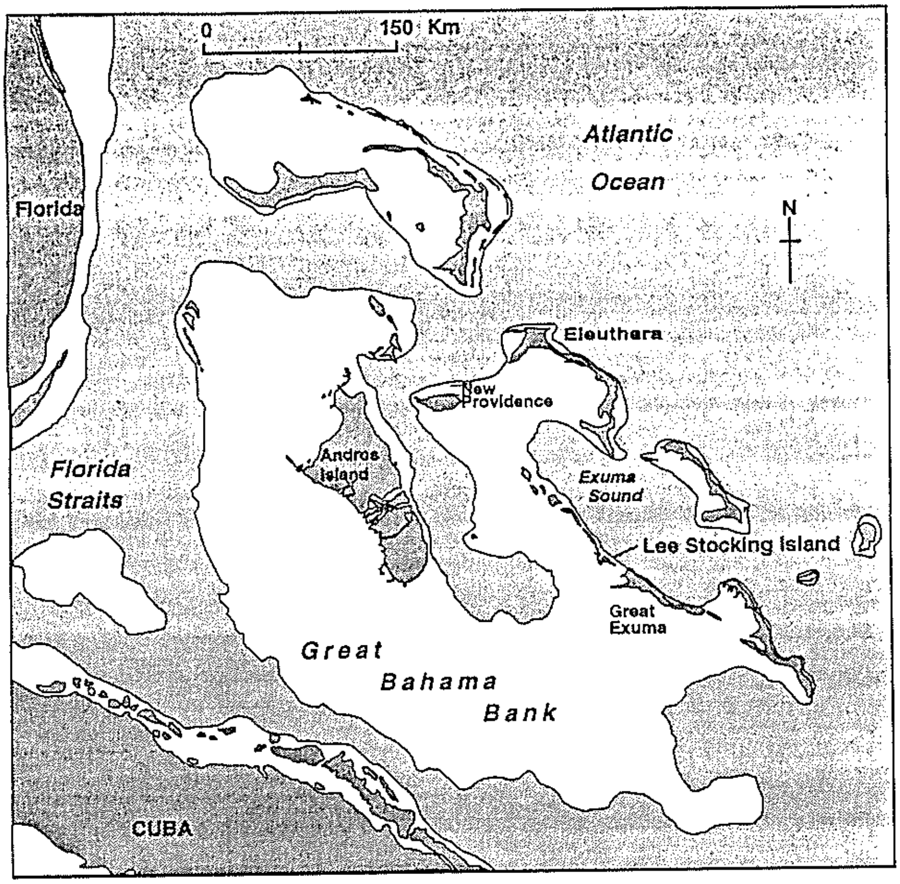

Fig. 1. Location of Lee Stocking Island.

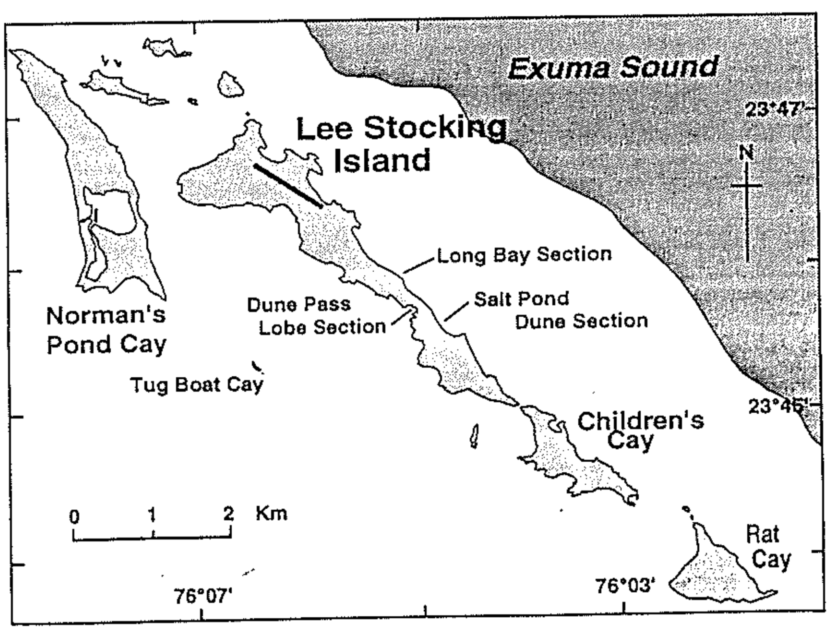

Fig. 2. Field localities on Lee Stocking Island.

to had been regarded as consisting of Pleistocene limestones, is made up largely of Holocene rocks that rest on a Pleistocene substratum. He divided the Holocene limestones into two units and compared them with the Rice Bay Formation of San Salvador Island, Bahamas. According to Kindler, a lower unit has a radiocarbon age of 5170±60 YBP and consists of eolianites deposited when Holocene sea level was lower than present. He records an upper unit that was deposited in dune and upper beach environments when sea level was close to present elevation. Observations on the Pleistocene stratigraphy and ichnofossils revealed in a submarine cave on nearby Norman's Pond Cay were made by Curran and Dill (1990, 1991) . A summary of the observations reported here was presented by White and Curran (1992).

HOLOCENE LIMESTONES

Introduction

Although we have explored much of the Holocene exposed on Lee Stocking Island, in this report we will focus on observations made of three measured sections, informally called Dune Pass Lobe, Salt Pond Dune, and Long Bay, located as shown in Fig. 2. The palm tree molds occur in sea cliffs bordering Long Bay, although we did not measure a stratigraphic section at that specific locality.

Dune Pass Lobe Section

Eolianites with distinctive sedimentary features and some trace fossils are well displayed at the readily accessible Dune Pass Lobe location. The sequence is shown in Fig. 3 and the measured stratigraphic section is illustrated by Fig. 4. Finely laminated limestones make up most of the section and these show millimeter scale fine-coarse couplets typical of carbonate

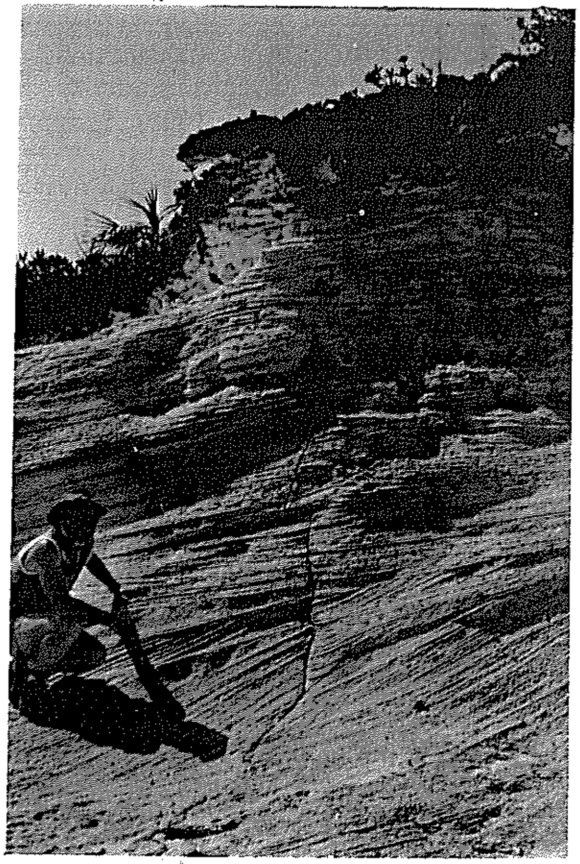

Fig. 3. Eolianite outcrop at the Dune Pass Lobe locality.

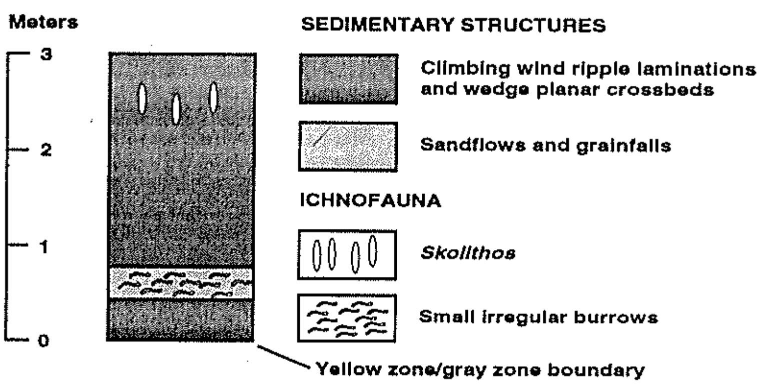

Fig. 4. Stratigraphic sequence at the Dune Pass Lobe locality.

Fig. 5. Climbing wind ripple laminations and lee-side sandflow deposits in eolianites at the Dune Pass Lobe locality. Hand lens for scale.

meter scale fine-coarse couplets typical of carbonate sands deposited by climbing wind ripples (White and Curran, 1988). Also present are lenticular sandflows representing sediment accumulation by dry sand avalanching down lee slopes. These structures are identical to those described from Holocene eolianites of San Salvador Island (White and Curran, 1985, 1988). Sedimentary features characteristic of eolianites found at the Dune Pass Lobe locality are shown in Fig. 5.

Animal trace fossils are quite common in some strata at this locality, especially a form known informally as the small, irregular burrow that is also widespread in the Holocene eolianites of San Salvador Island (White and Curran, 1985, 1988; Curran and White, 1987, 1991). These are revealed on the upper surface of strata as meandering burrows 3 to 4 mm in diameter. The burrows are unbranched and have a pale outer wall. The burrows also extend 1 to 2 cm into the strata (Fig. 6) and in some instances they are sufficiently numerous to cause burrow mottling of the sediments (Fig. 7). Scarce *Skolithos* burrows are present in the section at Dune Pass Lobe (Fig. 8). *Skolithos* has been reported from several localities of Pleistocene and Holocene carbonate eolianites, and in

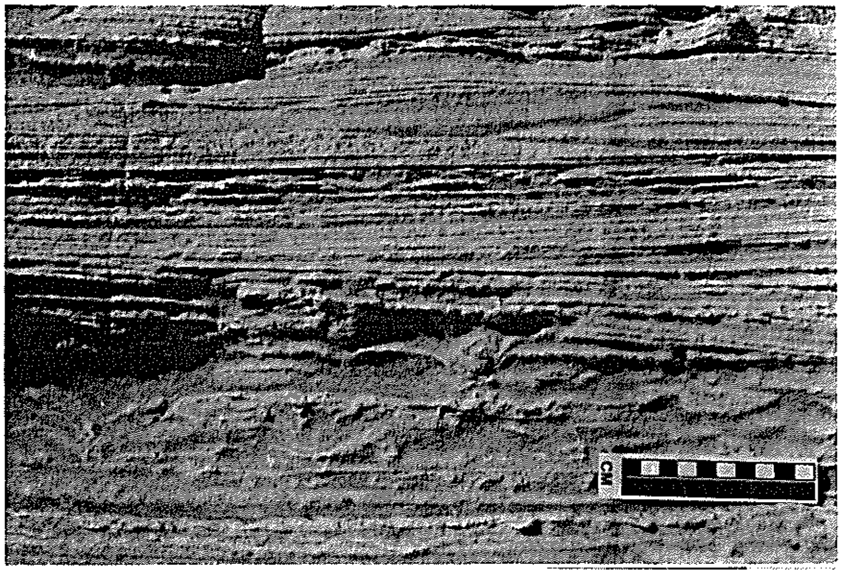

Fig. 6. Climbing wind ripple laminations and layers with small, irregular burrows in eolianites at the Dune Pass Lobe locality. Note prominent bioturbation to the left of the scale.

these rocks they are thought to have been produced by insects or arachnids, or both (Curran and White, 1991).

Salt Pond Dune

The sequence of eolianites exposed in sea cliffs on the coast east of a salt pond consists of three overlapping dunes (Fig. 9). Eolianites commonly form along the coast of Bahamian islands as small parabolic dunes that have their axes approximately parallel to the prevailing easterly trade winds. Such dunes coalesce by overlapping of adjacent dune flanks to form a series of hummocky dunes lying perpendicular to the trade wind direction (White and Curran, 1985, 1988). This is the case on Lee Stocking Island, and the Salt Pond Dune locality provides a clear example. Climbing wind ripple lamination and sandflow lens as described above are present at this locality. There also are good examples of grainfall deposits (Fig. 10) and small, irregular burrows. A remarkable feature of this locality is the presence of a number of closely-spaced trace fossils known informally as cluster burrows (Fig. 11, 12). These large, complex trace fossils are similar to those first described from San Salvador Island (Curran and White, 1987, 1991; White and Curran, 1985, 1988).

Fig. 7. Bioturbation of eolianites by small, irregular burrows at the Dune Pass Lobe locality. Arrows point to examples of burrows with pale walls. Compare with the well preserved laminations and lee-side structures shown in Fig. 5.

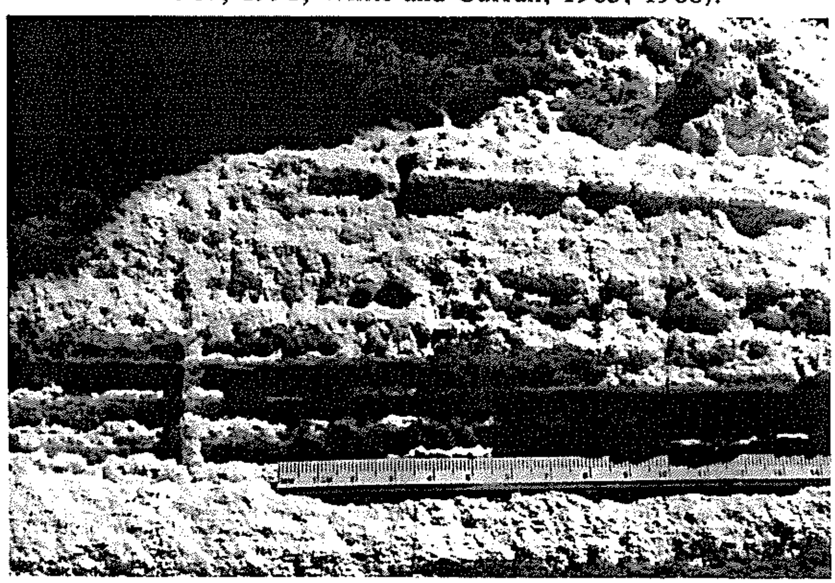

Fig. 8. *Skolithos* in eolianites (to the left of the scale) at the Dune Pass Lobe locality. Scale in centimeters.

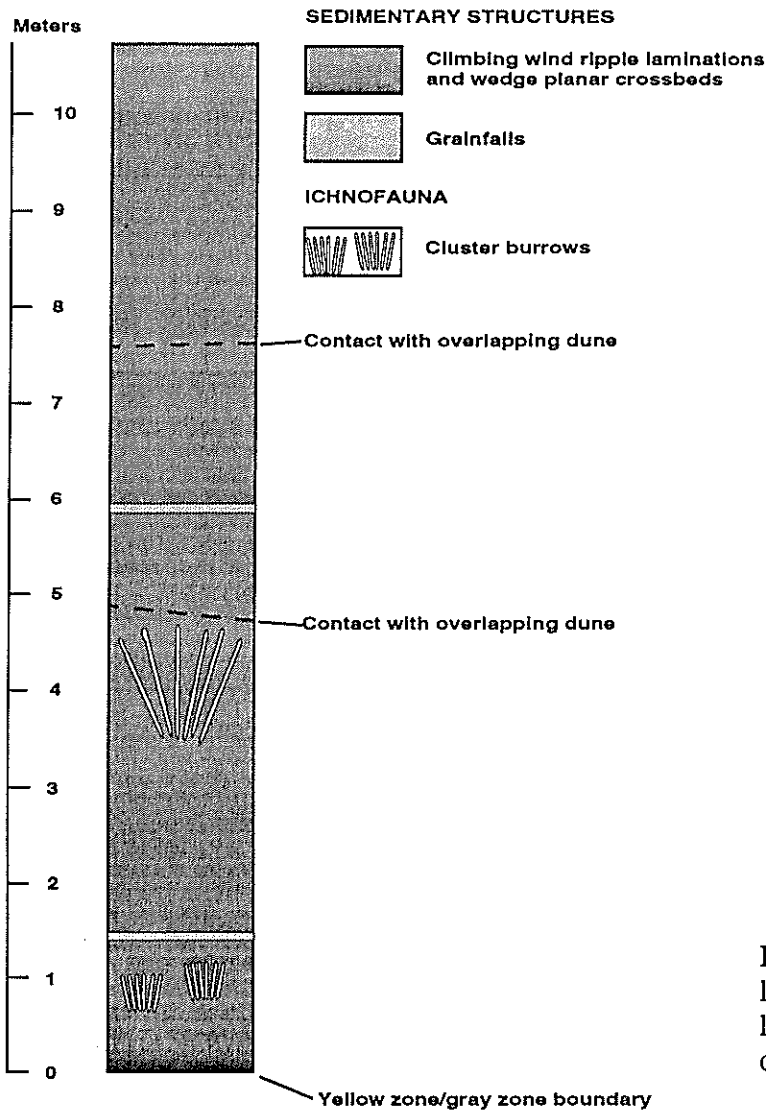

Fig. 9. Stratigraphic sequence at the Salt Pond Dune locality.

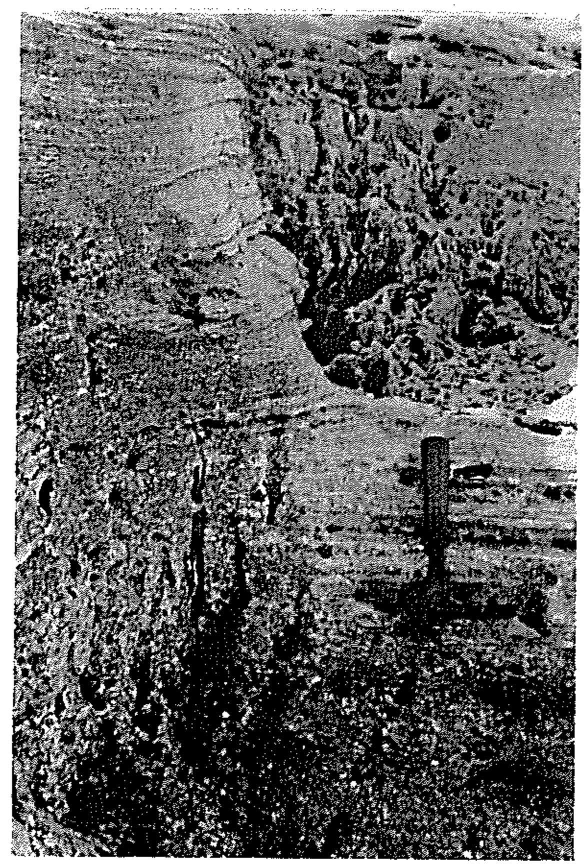

Fig. 11. Two examples of cluster burrows in the lower part of the sequence at the Salt Pond Dune locality. One cluster to the left of the hammer the other one above it.

Fig. 10. A layer of grainfall deposits between climbing wind ripple laminations at the Salt Pond Dune locality. Scale in centimeters.

and Curran, 1985, 1988). Curran and White (1987, 1991) have interpreted this trace fossil as being produced by the escape of juveniles of a species of burrowing wasp of the Family Sphecidae. The female wasp lays eggs a meter or more below the eolian sand surface and provisions the egg chamber with food for the hatchlings. Eventually, the young wasps make their way to the surface leaving a trace of their passage as the cluster burrows. The same origin is suggested for the formation of the cluster burrows found at the Salt Pond Dune locality. A similar trace fossil has been described from Pleistocene eolianites exposed in the walls of a

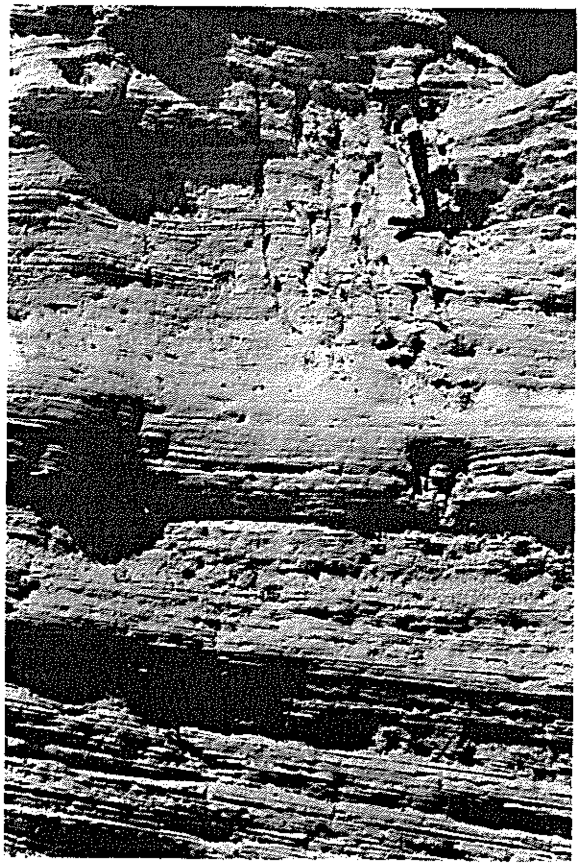

Fig. 12. An example of a cluster burrow (to the left of the hammer) in the upper part of the sequence at the Salt Pond Dune locality.

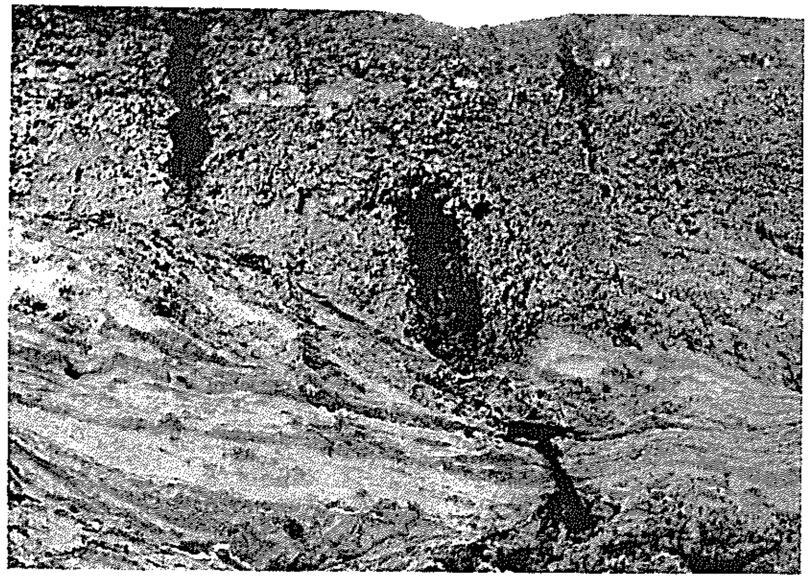

Fig. 14. Close-up of two tree molds (to the left and above the hammer) in eolianites at the Long Bay locality.

Fig. 13. Sea cliffs adjacent to Long Bay showing a cluster of tree molds preserved in growth position in the upper layers of eolianites.

submarine cave located on Norman's Pond Cay approximately 7 km northwest of the Salt Pond Dune (Curran and Dill, 1990, 1991).

Palm Tree Molds

A number of vertical, cylindrical molds are grouped in an exposure high in the Holocene eolianite sea cliffs fronting Long Bay (Fig. 13). The cylinders range up to 2 m in height and 15 cm in diameter (Fig. 14). These molds are believed to represent palm trees that were buried by migrating eolian sand while still in growth position. Early meteoric diagenesis caused lithification of the enclosing eolianites prior to decay of the organic matter of the palms and allowed preservation of the form of their trunks. A similar mode of preservation of palm trees was observed by the authors in eolianites of the Sangamon-age Southampton Formation on Bermuda. Further support for this interpretation is provided by the discovery of palm frond imprints in eolianite blocks forming talus below the mold-bearing sea cliffs on

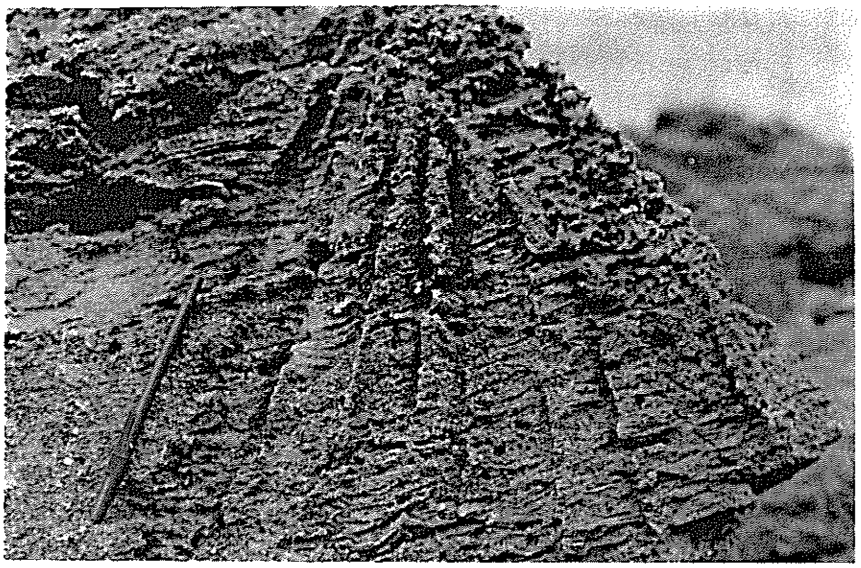

Fig. 15. Palm frond imprint in talus block beneath the cliff outcrops shown in Figure 13.

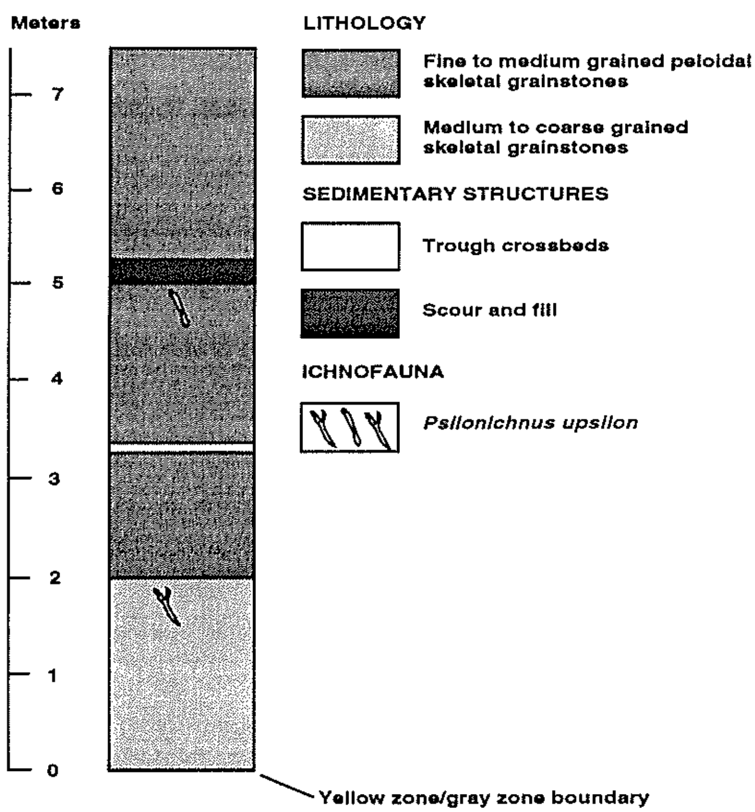

Fig. 16. Stratigraphic sequence at the Long Bay locality.

Lee Stocking Island (Fig. 15). Palm frond imprints have been found on Bermuda on the lee side of Southampton Formation eolianite dunes. They are believed to indicate early cementation of the dune sands (Bretz, 1960) and were used as one of several criteria to distinguish eolian limestones from marine limestones (Land, *et al.*, 1967). Similar palm frond molds were discovered in eolianites of early Sangamon age 2 to 3 m below sea level in a submarine cave on Norman's Pond Cay (Curran and Dill, 1991). These Late Pleistocene frond imprints were interpreted as resulting from the burial by wind-blown sand of fronds of palms such as silver thatch palm (*Coccothrinax argentata*). The same preservation mechanism is believed to have formed the imprints found in the Holocene eolianites of Lee Stocking Island.

Long Bay Section

At the Long Bay section (Fig. 16), a recent rockfall has created a large, fresh exposure of rocks that do not have the sedimentary structures and trace fossils that characterize the Holocene eolianites as described above for Lee Stocking Island and as seen on San Salvador Island (White and Curran, 1988, 1989). The limestones of this locality are somewhat coarser grained than eolianites and contain many layers with broken shells of marine invertebrates. They do not show the distinctive fine-coarse millimeter couplets typical of eolianite climbing wind ripple lamination nor any grainfall or sandflow deposits. Most of the strata consist of gently dipping to almost horizontal laminations that extend several meters across the cliff face (Fig. 17). These are interrupted by beds up to 15 cm thick that contain small-scale tabular planar cross-beds and scour-and-fill structures.

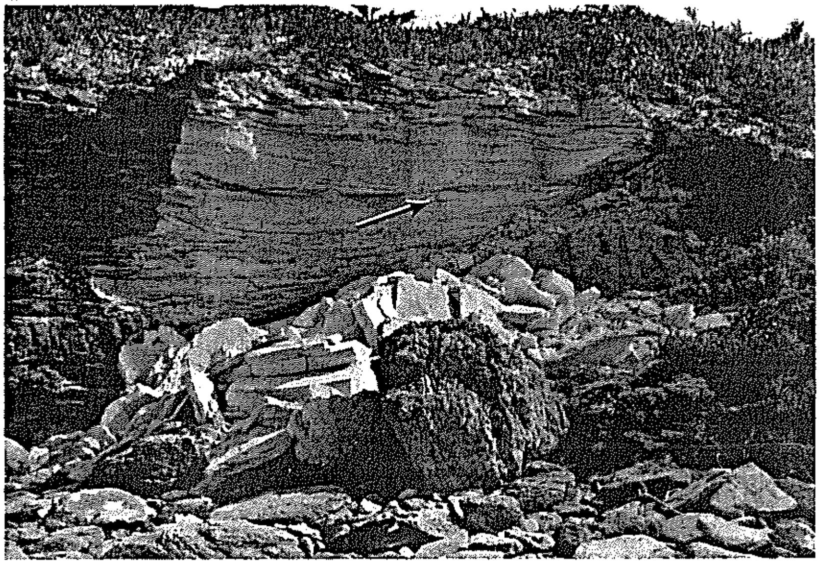

Fig. 17. Outcrop of backshore deposits exposed by recent rockfall in cliffs adjacent to Long Bay. Arrow points to the location of *Psilonichnus upsilon* shown in Figure 18.

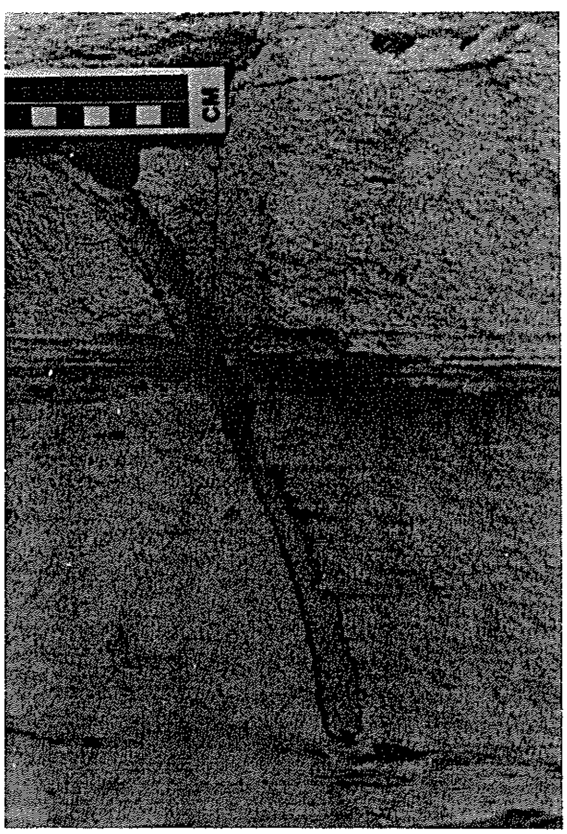

Fig. 18. *Psilonichnus upsilon* from backshore deposits of the Long Bay locality. Position in sequence is shown in Figure 17.

These strata also contain good specimens of *Psilonichnus upsilon* (Fig. 18), the trace fossil produced by the burrowing activities of the ghost crab *Ocypode quadrata*. In the Bahamas, the ghost crab is confined to a narrow ecological zone and provides a useful indicator of deposition of the enclosing sediments in a backshore beach environment (Curran and White, 1987, 1991; Frey, *et al.*, 1984). Thus, the sedimentary structures, lithology, and the trace fossils are unlike those of eolianites and indicate formation in a backshore environment.

DISCUSSION

Eolianites

The Holocene eolianites of Lee Stocking Island contain a suite of sedimentary features and ichnofossils that are distinctive indicators of wind deposition of carbonate sands and the formation of coastal dunes that were colonized by plants and inhabited by various animals, probably including insects and spiders. The dunes were formed during the Holocene transgression when the shallow shelf bordering the eastern shore of the Pleistocene core of Lee Stocking Island was drowned by the rising marine waters resulting from the melting of Wisconsinan glaciers and the thermal expansion of the oceans. Biogenic carbonate grains produced by shallow water marine invertebrates and calcareous algae were swept by waves on to the beach. The beach sediments were winnowed by the prevailing easterly trade winds and blown landward to form small parabolic dunes that eventually overlapped their neighbours and coalesced to form a line of dunes lying approximately parallel to the general trend of the coast. The dune sands were reworked by the shifting winds and the bulk of the eolianites were deposited as the result of accretion during the migration of climbing wind ripples. In some cases, however, lee-side deposits were preserved without being reworked and they are seen as scarce grainfall and sandflow lens.

There is ample evidence that some, at least, of the dunes were vegetated, in some cases by small palm trees. This vegetation may have helped to stabilize the dunes and prevent them from advancing very far inland from the beach from which they were derived, as was suggested for Pleistocene coastal dunes on Bermuda (Vacher, 1973). Modern carbonate dunes are inhabited by a broad range of animals including birds, crabs, lizards, and a wide variety of insects, which produce an array of tracks, trails, and burrows. Evidence for the activity of some of these is preserved in the Lee Stocking eolianites in the form of small vertical dwelling tubes, burrow mottling, small irregular burrows, and the very large cluster burrows probably formed by digger wasps. It has been suggested that early meteoric diagenesis partly cemented coastal eolianites on Bermuda and helped to stabilize them close to where they were formed (Bretz, 1960, Land, *et al.*, 1967). The presence of traces of vegetation in the Lee Stocking eolianites indicates that there was sufficient fresh water available from rainfall to allow their survival. Slightly acidic rain falling on the carbonate sands would dissolve some of the metastable aragonite and high Mg calcite components. Subsequent drying would cause the dissolved calcium carbonate to precipitate as a cement to begin the process of lithification. In places, at least, the sand acquired a consistency that allowed digger wasps to penetrate for up to a meter into the subsurface without collapsing the sand and being buried by it.

Backshore Deposits

The limestones measured in the stratigraphic section at Long Bay differ in lithology, sedimentary structures, and ichnofossils from the distinctive eolianites described from the sections at Dune Pass Lobe and Salt Pond Dune and observed elsewhere on Lee Stocking Island. The rock characteristics point to an origin in a backshore environment inhabited by the ghost crab, *Ocypode quadrata,* that produced the distinctive ichnofossil, *Psilonichnus upsilon.* The strata containing trough crossbeds and scour-and-fill structures are thought to have been formed by currents flowing into runnels that developed from time to time on the backshore. The sequence is similar to strata belonging to the Hanna Bay Member of the Rice Bay Formation on San Salvador Island from where the type specimen of *Psilonichnus upsilon* was described (Frey, *et al.*, 1984).

The most difficult feature to explain about these strata is their relationship to present sea level and the usual description of sea-level elevations during the Holocene transgression (see for example Boardman, *et al.*, 1989). Specimens of *Psilonichnus upsilon* occur at least 5 meters above present sea level and the enclosing strata with backshore deposit characteristics reach 2 meters higher. Layers of strata with different sedimentary structures and the presence of *Psilonichnus upsilon* at several horizons suggest that deposition occurred over a significant amount of time and not as a result of some single, extraordinary event. We have observed on the windward shore of Lee Stocking Island not far from the Long Bay section wave-deposited sand and flotsam as much as 4 meters above present sea level. These deposits formed a ramp that extended up into the dunes and sloped steeply seaward. We speculate that this deposition occurred during a storm and that waves were focused and raised by a particular confluence of bay and headland morphology and direction of wave approach. While this occurrence demonstrates that waves can carry sand several meters above sea level, it does not serve as a complete model for the Long Bay sequence. It would require storm waves to carry sand over some high, berm-like feature and deposit it on a surface that was close to horizontal or sloped gently landward. This process would need to be repeated many times to produce the sequence of strata observed in the Long Bay section.

The most obvious explanation for the deposits invokes a sea level several meters higher than present in the vicinity of Lee Stocking Island. As mentioned above, the main difficulty with such an explanation is that there is no evidence known to the authors that supports such a radical change in the generally accepted Holocene sea-level curve. Surely, deposits from such an elevated sea level would not be confined to one section of the coast of Lee Stocking Island as numerous islands in the Bahamas would have been affected by such a high stand.

CONCLUSIONS

1. Most of the Holocene strata exposed on Lee Stocking Island are eolianites deposited initially by the prevailing easterly trade winds that transported beach sands a short distance inland. This occurred during the Holocene transgression when sea water flooded the shelf around a core of Pleistocene limestones that formed proto-Lee Stocking Island. Biogenic grains that were produced on the newly flooded shelf were deposited along beaches that provided the source for the eolian dunes.

2. The sand was largely reworked by winds of variable direction and ultimately deposited as climbing

wind ripples. In some instances, grainfall and sandflow deposits represent deposition of sand in the lee of small dunes without subsequent reworking by wind.

3. The dunes were vegetated and the plant growth may have helped to stabilize the dunes and slow their landward migration. The dunes were inhabited also by a variety of animals that produced a suite of trace fossils and locally caused bioturbation of the eolian strata.

4. A distinctly different sequence of strata containing structures and trace fossils characteristic of backshore environments is exposed in sea cliffs along Long Bay. These represent a significant anomaly as the strata extend as high as 7 meters above present sea level. Although there is evidence on Lee Stocking Island that waves can deposit sand up to 4 meters above present sea level, no really satisfactory model has yet been devised to explain these strata. Invoking a sea-level stand 3 or 4 meters higher than the present during the Holocene could explain these deposits but creates problems outside the immediate context of the backshore deposits as there is no published evidence to support such a high stand from adjacent areas in the Bahamas. For the moment, at least, these strata must remain an enigma.

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