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Sinuous Rhizoliths Mimic Invertebrate Trace Fossils on Upper Pleistocene Caliche Surfaces, San Salvador Island, Bahamas

H. Allen Curran
Smith College, acurran@smith.edu

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H.A. Curran

Department of Geosciences, Smith College, Northampton, Massachusetts 01063, USA

E-mail: acurran@smith.edu

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ABSTRACT

The Pleistocene–Holocene boundary on islands of the Bahama Archipelago is typically marked by a calichified paleosol horizon that formed on exposed limestone surfaces during lowered sea level of the Last Glacial. On the north coast of San Salvador, an extensive laminar caliche surface is present west of Singer Bar Point. Formed on Upper Pleistocene (Eemian) carbonate eolianite and overlain by Holocene eolianite, this surface bears numerous and distinctive large, sinuous structures typically preserved in half relief, and with sharp, parallel ridge-like edges that slope inward to form a smooth, medial 'trough' having widths mostly between 1 and 3 cm. Individual structures can commonly be traced for lengths of several metres and exhibit complex patterns, with branching only occasionally present. Three hypotheses for the origin of these structures are presented and discussed: physical processes, invertebrate trails similar to the ichnogenus Archaeonassa*, and formation by plant roots. The last hypothesis is favoured. Similar structures have been found on Upper Pleistocene laminar caliche surfaces at other coastal locations on San Salvador, and they likely are present on similar surfaces throughout the Bahamas and beyond. This suggests that structures of this origin may be far more common and widespread on the surfaces of Quaternary and older carbonate facies elsewhere than previously recognized.*

INTRODUCTION

One of the more difficult everyday tasks confronting ichnologists is the consistent identification of ichnotaxa. There are many reasons for this, including but not limited to: commonly inadequate original taxonomic descriptions and illustrations; the fact that specific tracemakers can make multiple trace forms and different tracemaker organisms can generate similar forms; and that some trace fossil taxa are highly complex so that preserved individual trace fossil segments can not, or have not, been recognized as parts of the whole. This study provides an example of the above with respect to sinuous, horizontally oriented structures most probably created by plant roots on laminar caliche surfaces of Bahamian carbonates that mimic trace fossils generated by herbivorous gastropods.

Biogenic sedimentary structures are a common and important component of the Quaternary grainstones and packstones that cap the islands of the Bahama Archipelago. Physical and biogenic structures, including ichnocoenoses of invertebrate and plant trace fossils, have been used to characterize the facies of these rocks, ranging from shallow subtidal to beach to dune paleoenvironments (Curran and White, 2001; Curran, 2007; Knaust *et al.*, 2012, and earlier studies). These overview papers established an ichnologic framework for Bahamian lithofacies and similar tropical carbonate settings elsewhere, but there are numerous subfacies and bedrock surfaces manifested in Bahamian carbonates that have yet to be documented with respect to their ichnological characteristics. This paper describes in detail large, heretofore enigmatic structures that occur on laminar caliche surfaces around San Salvador Island. Hypotheses for the origin of these structures are presented, and the implications of the favoured hypothesis of formation by plant roots are discussed.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The primary locality of this study is along the mostly rocky north coast of San Salvador Island to the west of Singer Bar Point (Fig. 1). Access to this reach of coast is via a small boat-launch ramp on the north side of the island's main road (N24º07.122'; W74º28.711'). Here a prominent laminar caliche paleosol surface caps the underlying bedrock. Throughout the Bahama Archipelago, such laminar caliche paleosol surfaces mark Quaternary disconformities between interglacial deposits and the glacial intervals during which the caliche surfaces formed. In this case, the laminar caliche paleosol separates eolianites of the Grotto Bay Formation (Upper Pleistocene - MIS 5e, Eemian, or Last Interglacial) and Holocene eolianites of the Rice Bay Formation on San Salvador (stratigraphy of Carew and Mylroie, 1995; Mylroie and Carew, 2008).

As pointed out in the introduction to the edited volume titled *Calcretes* by Wright and Tucker (1991), the terms caliche and calcrete are synonymous in current usage, with caliche favoured by most authors of papers on Bahamian geology. Laminar caliche consists of microcrystalline carbonate material and refers to indurated sheets of carbonate, typically undulose, and usually forming over hardpans or indurated rock substrates (Wright and Tucker, 1991, p. 3). Surfaces of laminar caliche marking the Pleistocene–Holocene disconformity occur along the coast at multiple areas on all sides of San Salvador and can be recognized by their distinctive rusty red colouration owing to the elevated oxidized iron content of the microcrystalline caliche material. Similar surfaces are widespread throughout the Bahamas. Previous studies of laminar caliche and paleosols on San Salvador and elsewhere in the Bahamas were directed primarily to the petrographical, geochemical, and stratigraphical aspects of Bahamian caliches (Beier, 1987; Boardman *et al.*, 1995). Surface megascopic structures of caliches have not been investigated in detail prior to this study.

The distinctive structures in question are best displayed on high intertidal to supra-tidal surfaces of laminar caliche located west of Singer Bar Point (Fig. 2A; most concentrated area of occurrence at N24º07.168'; W74º28.520'). A few metres west of the boat landing entry point to the coast, rocks of the Rice Bay Formation are well exposed above the Pleistocene–Holocene disconformity marked by the laminar caliche surface (Fig. 2B). Further reconnaissance study of the rocky coast area of San Salvador has revealed the presence of similar structures on other laminar caliche surfaces, particularly on the surface west of The Gulf on the island's south coast and on surfaces along Fernandez Bay and near the Club Med Marina, all on the west coast (Fig. 1). It is highly likely that similar structures will be found on Upper Pleistocene–Holocene laminar caliche discontinuity surfaces throughout the Bahama Archipelago and beyond. A prime example from Rum Cay, the closest island southwest of San Salvador, is highlighted later in this paper.

DESCRIPTION OF THE STRUCTURES

Structures found on the laminar caliche surfaces in the Singer Bar Point area consist of sinuous, trough-like forms typically preserved in half relief. Sharp and parallel, ridge-like edges slope inward to form a smooth, medial trough (Fig. 3A–C). Width of the structures measured from ridge edge-to-edge ranges from 1 to 5 cm, and a median of 2 to 2.5 cm (Fig. 4). Individual structures can be traced for considerable lengths, up to 5.5 m in one case, and complex forms are present, including at least one near-circular example (Fig. 3C and D).

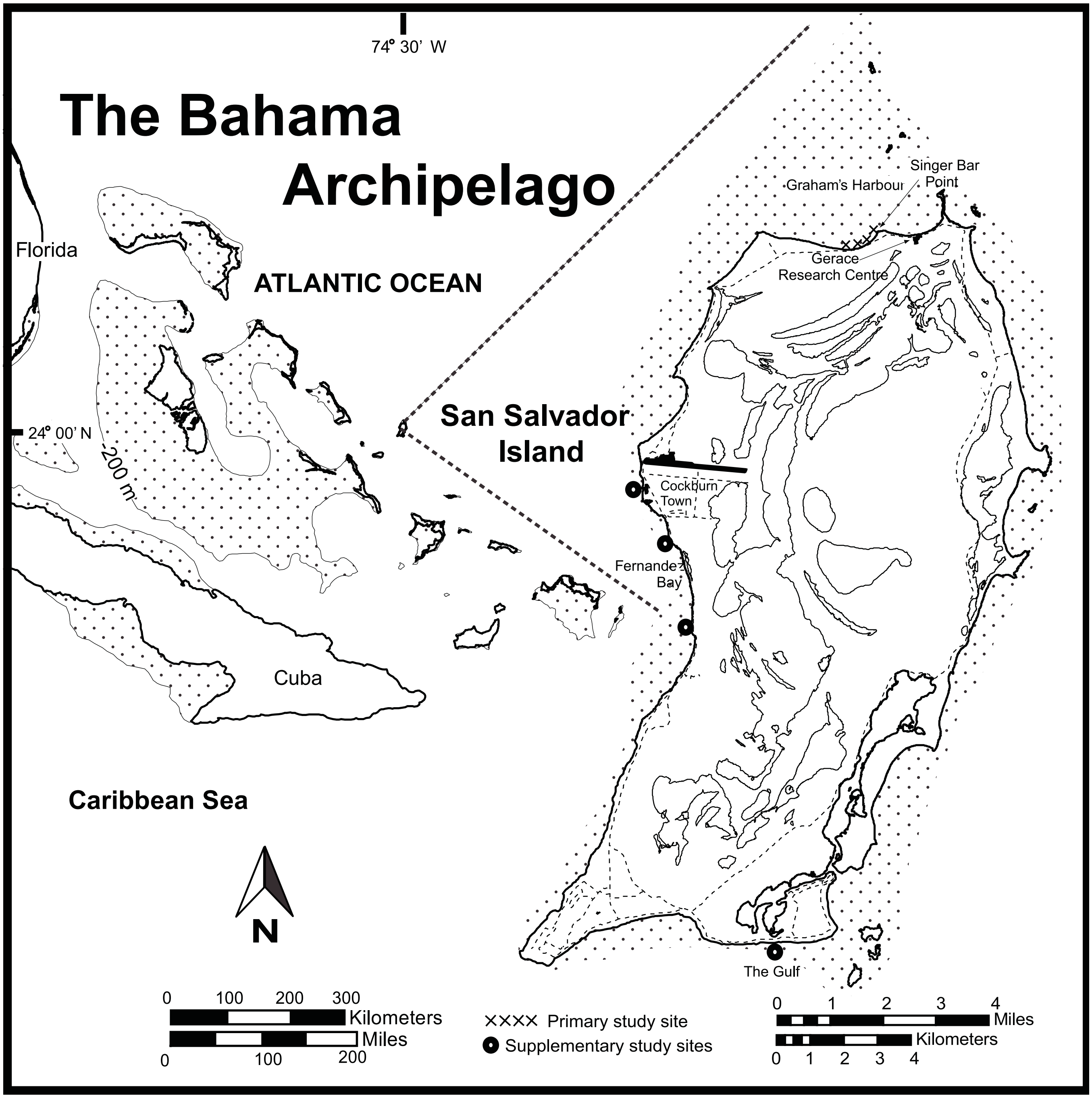

Figure 1. *Index map to the Bahama Archipelago and study sites on San Salvador Island. The principal study site, marked by Xs, is along the north coast, just west of the Gerace Research Centre and Singer Bar Point. Supplementary sites (marked by bullseye circles) are on the laminar caliche surface of the island's south coast, a short distance west of The Gulf, and along Fernandez Bay on the island's west coast; the surface marked by the northernmost bullseye is immediately north of the entrance to Club Med Marina.*

Larger structures branch only rarely, but crossover intersections are common and sometimes complex (Fig. 3D and E). Neritid snails representing several species are present on these intertidal, laminar caliche surfaces. Interestingly, individual snails appear to show preference for movement along the smooth, highway-like troughs of the structures (Fig. 3B). Snail trails are common and distinct in areas where a thin cover of moist sand is present, and these trough-like trails commonly pass over the fossil troughs, leaving a form suggestive of origin for the latter (Fig. 3F).

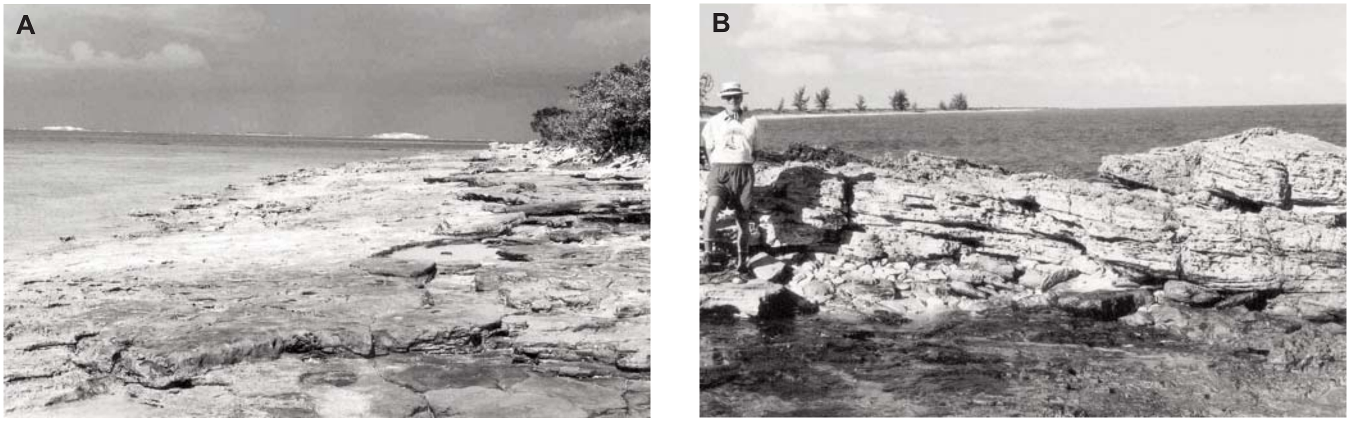

Figure 2. A) *View of laminar caliche surface looking east toward Singer Bar Point from location just east of boat ramp entry to the coast;* **B)** *outcrop of Holocene Rice Bay Formation overlying the laminar caliche surface and Upper Pleistocene eolianite of the Grotto Beach Formation; photo taken a short distance west of entry point; author for scale.*

At first view, one is taken with the large, trough-like forms and their complex meandering and crossover patterns. However, more careful observation reveals the presence of a variety of forms beyond the half-relief troughs. Smaller, less obvious forms are preserved as partial or complete tubes of laminar caliche, and branching is present. Some areas reveal exposures of small-diameter rhizoliths that resemble fossil root mats (Fig. 5).

The calcarenite beds beneath the thin, laminar caliche layer at Singer Bar Point consist of very fine to fine skeletal sand, with individual grains tending to be rounded. For the most part, the beds are gently seaward dipping and dunal bedforms are not obvious, but the absence of shell layers and the overall fine-grained texture of the rock suggest eolian deposition. It is extremely difficult to sample the actual trough structures, and no thin sections have been made, but several rock samples were cut to reveal trough structures in cross section. The rust-coloured laminar caliche layers are extremely thin, discontinuous, and inter-layered with fine sand grains. In short, it was surprising to find just how thin the veneer of laminar caliche actually is. This holds true for the other laminar caliche areas around San Salvador that were surveyed in this study.

HYPOTHESES FOR ORIGIN OF THE ENIGMATIC STRUCTURES

Three hypotheses, representing physical, invertebrate, and plant themes, are considered herein to explain the origin of the sinuous structures found on laminar caliche surfaces around San Salvador Island.

A PHYSICAL ORIGIN?

Structures of obvious inorganic origin are present and sometimes common on Bahamian laminar caliche surfaces. Typical are caliche-filled fractures (Fig. 6) that bear superficial resemblance to the sinuous, trough-shaped forms at Singer Bar Point and elsewhere. These inorganic structures differ from those found at Singer Bar Point in that they exhibit irregular, zig-zag patterns in the horizontal plane, not smooth, sinuous forms, and there is no true trough development. In addition, caliche-filled fractures branch frequently (Fig. 6), and do not commonly reach the widths of the trough-shaped structures. Vertical sections reveal that caliche-filled fractures can extend for decimetres below the horizontal, laminar caliche surfaces.

AN INVERTEBRATE ORIGIN?

The modern herbivorous snails that move over intertidal sandy and smooth rock substrates that have a thin cover of moist sand make trails that bear striking resemblance to the trough-shaped structures found at Singer Bar Point and elsewhere. In the Bahamas, these trails are commonly made by neritids (Fig. 3F). A typical higher latitude, temperate climate example would be the intertidal zone of siliciclastic-sand beaches of Cape Cod Bay, Massachusetts. Here littorinid snails are common, and at low tide, their abundant, long, meandering trails with trail crossover intersections are

Figure 3. (opposite) *Views of the large, sinuous structures exposed on laminar caliche surface a short distance west of Singer Bar Point:* **A)** *typical structure exhibiting parallel, ridge-like edges with a smooth 'trough' in the middle;* **B)** *parallel structures with a live neritid snail in trough of the lower specimen; pen = 15 cm;* **C)** *overview of several large, sinuous structures; hammer = 26 cm;* **D)** *structure with roughly circular form; note several crossovers and that a pre-existing structure underlies the circle;* **E)** *close-up of complex intersecting of structures;* **F)** *neritid snail crossing over a fossil structure and leaving a trail of similar form; snail diameter = 2 cm.*

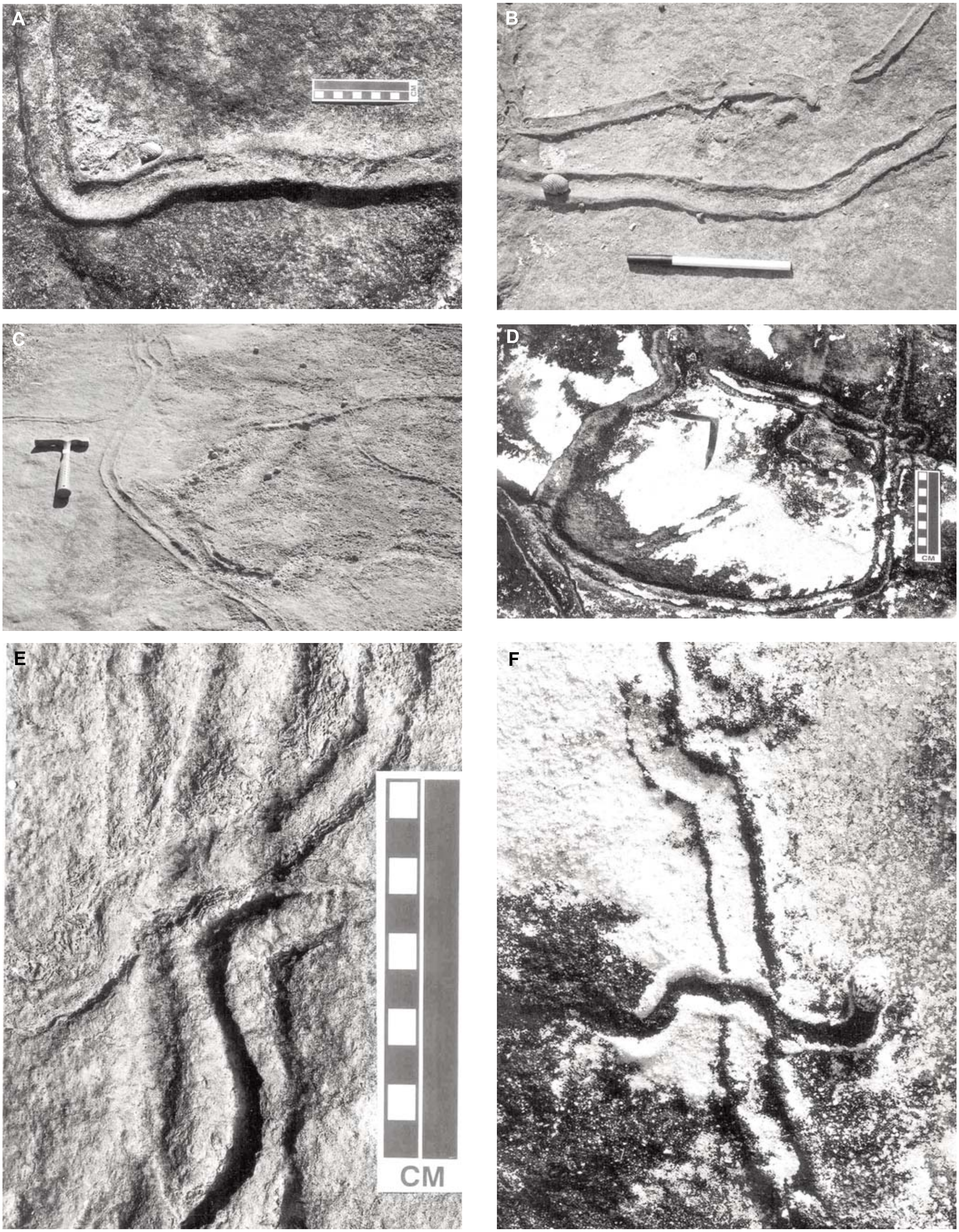

Figure 3. *Caption on opposite page.*

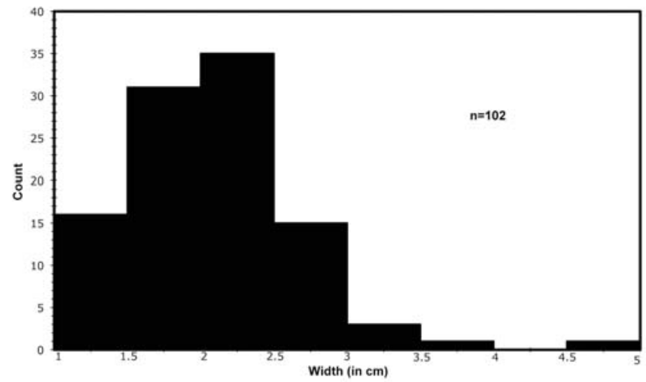

Figure 4. *Histogram plot of maximum widths of structures measured at Singer Bar Point study area.*

Figure 5. *Horizontal surface in Singer Bar Point study area with numerous small rhizoliths forming what appears to be a fossil root mat.*

revealed (Fig. 7A and B), with forms very much like the Bahamian trough-shaped structures. Such trails are known from the fossil record and are most commonly assigned to the ichnogenus *Archaeonassa*, although several other, similar ichnotaxa also are recognized (Buckman, 1994; Buatois

Figure 6. *Caliche-filled fractures weathered out in positive relief bear superficial resemblance to the sinuous structures; this example from The Gulf study area; pen = 15 cm.*

and Mángano, 2011, Fig, 11.6 d). Similar modern *Archeonassa*-like trails can also be formed by polychaete worms foraging in intertidal sands (Fig. 7C). This emphasizes the point that many trace fossil ichnotaxa can have multiple tracemaker origins.

This hypothesis for origin of the sinuous fossil structures is appealing, but is rejected for at least three reasons: 1) Herbivorous gastropod trails typically do not branch; rather, the snails forage by moving ahead, and do not back up and move in another direction. Although not common for the sinuous, trough-shaped structures, branching does occur and is present in examples from laminar caliche surfaces on San Salvador beyond Singer Bar Point, as discussed below. 2) Snail trails always manifest in semi-relief, whereas examples of trough-shaped forms morphing to a tubular form can be cited from Singer Bar Point and elsewhere, again as discussed below. 3) Finally, the character of the underlying rocks at the Singer Bar Point locality and other, similar localities on San Salvador do not support the possibility of a snail origin for these structures. The laminar caliche surfaces at Singer Bar Point formed on eolianites, not sediments deposited in an intertidal zone. Furthermore, the caliche surface, upon which the structures were formed, developed in a fully terrestrial environment during the Last Glacial when sea level was significantly lower than at present.

A PLANT ROOT ORIGIN

Root structures have usually been called rhizomorphs, rhizocretions, or vegemorphs in Bahamian literature (*see* White and Curran, 1997, for a comprehensive review of terminology). Rhizolith is used here because this term today is more universally recognized. Rhizoliths are a common feature of Bahamian eolianites and can occur in virtually all Bahamian lithofacies. The root origin hypothesis for the sin-

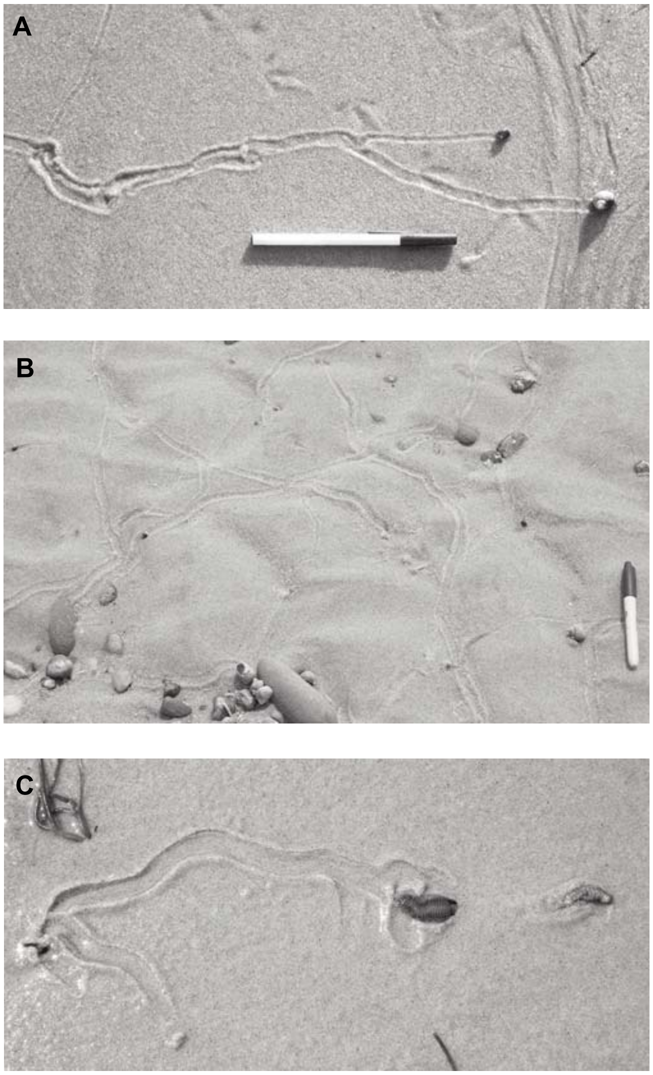

Figure 7. *Intertidal zone of siliciclastic sand beach at Duck Harbor, Wellfleet, Cape Cod Bay, Massachusetts, USA:* **A)** *littorinid snail trails; these trails bear close morphologic similarity to form of the sinuous structures; pen = 15 cm;* **B)** *snail trails everywhere! Marker = 14 cm;* **C)** *foraging polychaete worm ('blood worm') generating a similar trail; width of trail = 1.2 cm.*

uous, trough-shaped structures at Singer Bar Point, and beyond, is that such structures represent root tubules in the sense of Klappa (1980). Tubules are preserved in half relief, with the upper half of tubules having been eroded away with subaerial exposure of the laminar caliche surfaces on which they occur.

The tubules presumably formed by partial dissolution and re-precipitation of calcitic materials around roots as they penetrated downward through overlying sediment cover and then moved laterally along hard, laminar caliche surfaces (*see* Klappa, 1980, p. 625-628, for a review of rhizolith-formation geochemistry). One can reasonably assume that gravity played a role with fluids generating a thicker rind of calcitic material on the lower half of a given tubule, thus making the trough form thicker and more readily preserved with exposure and surface erosion of the laminar caliche surfaces. A few specimens at Singer Bar Point are suggestive of complete tubule formation, as per the excellent example of a root tubule present on a Pleistocene sloping laminar caliche surface on Rum Cay (Fig. 8). The upper part of this specimen is a complete tubule, but this tubule was preserved only in half relief on the fully exposed lower part of the slope.

With this interpretation of the trough-shaped structures at Singer Bar Point and elsewhere as half-relief root tubules, such structures can be considered trace fossils, as they record plant activity. However, the timing of their formation is not easily determined. It is tempting to think that the structures had a Holocene origin, with formation by plant roots penetrating down through the overlying eolianites of the Rice Bay Formation and moving laterally over the impenetrable laminar caliche surface and forming tubular rhizoliths. With rising sea level, this surface then was exposed by coastal erosion stripping away the weakly lithified Holocene beds and exposing the tubules that then were bevelled to half relief. However, it also is possible that the tubular rhizoliths formed along a well-indurated horizon under sediment/soil cover that developed during the long expanse of the Last Glacial

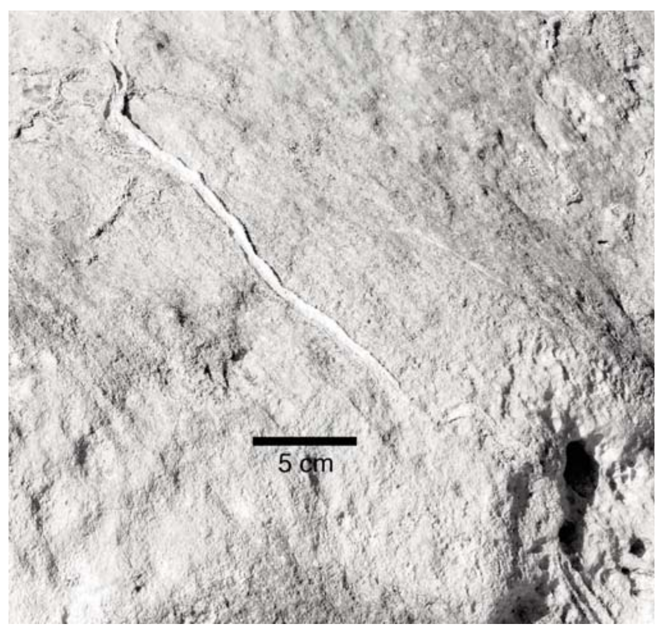

Figure 8. *Lengthy structure on a sloping laminar caliche surface, north coast of Rum Cay, Bahamas. Upper end of structure is tubular, whereas the lower two-thirds are trough-shaped. Presumably the upper half of this tubule was eroded away downslope. This form would be termed a root tubule following the classification of rhizoliths by Klappa (1980).*

and were then exposed by later coastal erosion. Thus an answer to the question of precise timing of tubular rhizolith formation cannot be easily determined.

Additional evidence for a plant-root origin for the structures in question is the fact that patchy surfaces with closely spaced, mat-like masses of rhizoliths are present at Singer Bar Point (Fig. 5) and at places along the south coast of San Salvador. Such masses are rare and not extensive, but they do give solid evidence of ancient plant root activity on and just below the laminar caliche surface.

DISCUSSION, AND EVIDENCE FROM OTHER LOCALITIES

A tubular rhizolith origin is favoured for the structures at Singer Bar Point and similar examples elsewhere. However, a prime argument against this hypothesis might be the lack of branching. Roots typically branch, and the sinuous, trough-shaped structures can extend for considerable distances over laminar caliche surfaces without branching. The limiting factor, at present, is lack of knowledge about the specifics of root geometries for most of the larger plant species of the Bahamas. One potential candidate for formation of the fossil structures is the roots of the sea grape (*Coccoloba uvifera*). Sea grape is common along the coasts of the islands of the Bahamas. Its roots typically are smooth, have diameters within the range of diameters for the trough-shaped structures, and branching, while present, can be infrequent, as might be expected for roots advancing along a hard surface with minimal available nutrients, and even moisture.

The reconnaissance study of other areas of coastal laminar caliche exposure on San Salvador revealed that sinuous structures similar to those at Singer Bar Point are present on an extensive caliche surface west of The Gulf. Scattered structures also are present on the laminar caliche surfaces bordering Fernandez Bay and along the coast just north of the entrance to the Club Med Marina (Fig. 1).

Structures on the Fernandez Bay surfaces are less common, occur in low relief, and have widths less than the median at Singer Bar Point (Fig. 9A). A relatively flat caliche surface caps the high cliffs of Upper Pleistocene eolianite along the south coast of San Salvador between The Gulf and the coastal reentrant feature to the west informally referred to as 'The Cut'. Here sinuous, trough-shaped structures are common (Fig. 9B), although not as large and well formed as those at Singer Bar Point. Nonetheless, these sites indicate that such structures are likely present on similar surfaces well

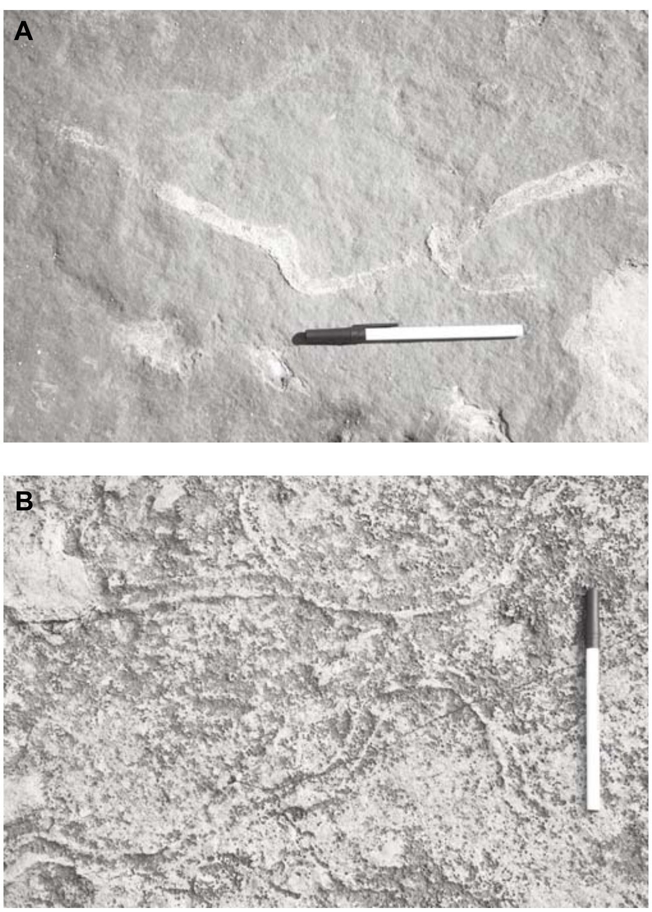

Figure 9. *More sinuous structures:* **A)** *example from laminar caliche surface at south end of Fernandez Bay;* **B)** *intersecting structures from surface of The Gulf study area;* **C)** *branching root tubule from the same surface. Pen = 15 cm.*

beyond San Salvador. A branching root tubule specimen preserved in full relief (Fig. 9C) from the south coast of San Salvador clearly demonstrates that branching plant roots once were present on these laminar caliche surfaces and supports the hypothesis that all of the sinuous, trough-shaped structures had a root origin.

Recently, a large, sinuous structure was discovered on the laminar caliche surface present on the coast just north of the Club Med Marina (Fig. 10). This is one of the longest and most intricate structures recorded to date. It does not have the raised half-relief edges typical of the Singer Bar Point specimens, probably owing to a higher degree of surface scouring by wave action at this location, but in all other respects it is identical to previously described specimens.

CONCLUSIONS

Large, highly distinctive, sinuous, trough-shaped structures that superficially resemble the trace fossil *Archaeonassa*, a trail attributed to the grazing activity of intertidal herbivorous gastropods, occur commonly on the laminar caliche surface near Singer Bar Point and other similar coastal localities on San Salvador Island. Physical sedimentary structure and invertebrate origin hypotheses for these structures are rejected; a plant-root origin is favoured and supported by several lines of evidence indicating that these structure are root tubules, following the classification of Klappa (1980), eroded to half-relief form or less by coastal wave-erosion processes. Nonetheless, important questions remain, such as why branching is so infrequently observed with most of these structures, and just what kind(s) of plant roots might have been responsible for their formation.

Figure 10. *Large, complex sinuous structure from a laminar caliche surface on coast just north of channel entrance to Club Med Marina. A thin, branching rhizolith is present in the upper left-centre of image; scale = 10 cm.*

Sinuous, trough-shaped structures formed by plant roots likely are widespread on coastal laminar caliche surfaces throughout the Bahama Archipelago and on tropical carbonate coasts well beyond. This Bahamian example offers a cautionary note to ichnologists working on bedding plane exposures of older carbonate rocks. Sinuous root structures preserved in half relief can mimic invertebrate trace fossils. Furthermore, the time of origin for such structures can be highly disconnected from the geological ages of the rocks and the bedding plane or caliche surfaces on which they formed. In the absence of preserved organic material, a plant root origin might not be considered and recognized, thus leading to trace fossil misidentifications.

ACKNOWLEDGMENTS

This paper is dedicated to the memory of Jordi Maria de Gibert, a friend and colleague whose creative research was valued by all in the ichnological community. Jordi visited San Salvador Island twice, and he contributed useful insights to ichnological investigations there, including the field sites of this study. I am indebted to Jim Carew (College of Charleston) for originally directing my attention to the enigmatic structures present at Singer Bar Point. My thanks to the editorial team at Memorial University of Newfoundland for their assistance with editing of the original manuscript and for their excellent work in production of this volume. Anna Dustira (Smith College) conducted a preliminary study of the structures at Singer Bar Point, and Jane Curran assisted greatly with field investigations. Fieldwork was funded, in part, by the Smith College Committee for Faculty Compensation and Development and the Department of Geosciences, and I am grateful to the staff of the Gerace Research Centre for full logistical support of my research on San Salvador Island and elsewhere in the Bahamas.

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