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Front Cover: Lee-side exposure of a fossil parabolic dune viewed from the Grahams Harbour side (west) of North Point, San Salvador, Bahamas. These Holocene carbonate eolianites have been assigned to the North Point Member of the Rice Bay Formation (Carew and Mylroie, 1995). The eolian cross-stratification dips below present sea level, proving that late Holocene sea-level rise is real. Top of the dune is about 7 meters above the sea surface. Photo by Al Curran.

Back Cover: Dr. Noel P. James of Queen's University, Kingston, Ontario, Canada, keynote speaker for this symposium. Noel is holding a carving of a tropical fish created by a local artist and presented to him at the end of the symposium. Photo by Al Curran.

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FOSSIL UPOGEBIID BURROWS AND THEIR GEOLOGIC SIGNIFICANCE: GROTTO BEACH FORMATION (PLEISTOCENE), SAN SALVADOR, BAHAMAS

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ABSTRACT

Although burrows made by the upogebiid shrimp Upogebia *vasquezi* (Ngoc-Ho 1989) are common in shallow-marine environments of the Bahamas, their trace fossil equivalents have only been documented through a few fragmentary burrow fills on San Salvador, Bahamas. In this report, trace fossils of upogebiid burrows are interpreted from three different localities on San Salvador in the Pleistocene Grotto Beach Formation. Most burrows were discovered on the Bahamian Field Station Nature Trail (GPS location: N 24° 06.8', W 74° 27.9') but two specimens were found at North Pigeon Creek Quarry (Quarry "E") and one was in a displaced boulder associated with expansion of the San Salvador airport.

Trace fossils in the Grotto Beach Formation are nearly identical to modern upogebiid burrows in Pigeon Creek lagoon of San Salvador, as described by Curran and Williams (1997). Burrows have thick walls of 2-4.5 cm diameter and a nodose exterior is evident in some specimens. Internal geometry of some specimens shows criss-crossing U-burrows and other interconnections are clearly demonstrated in places. Burrow diameters range from 2-10 mm, averaging 7 mm ± 3 mm (n = 64). Distances between paired burrow openings averaged slightly more than 2 cm with a range of 2-5 cm. Burrows are preserved in a muddy calcarenite composed of sediments similar to those deposited presently in Pigeon Creek. Although these probable upogebiid burrows may constitute a new ichnogenus because of the combination of their unique geometry and wall structure, no specimen shows the complete criss-crossing, double-U burrow geometry of the modern forms, hence naming of a new ichnogenus is not currently advised.

The most abundant occurrence of these trace fossils is directly below a terra rossa paleosol on the Nature Trail, thus suggesting that their preservation in that area was enhanced by a sea-level stillstand and regression associated with a Pleistocene glaciation. This stratigraphic occurrence points toward potential use of these trace fossils as both paleoenvironmental and sea-level indicators in future studies of Bahamian geology.

INTRODUCTION AND OBJECTIVES

San Salvador Island of the Bahamas is well known for its ichnologic diversity in both its modern environments and relatively young rock record, providing a natural laboratory for a uniformitarian approach in the study of its biota and their traces (Curran, 1984, 1994, 1997; Curran and White, 1991; Curran and Williams, 1997). Of particular focus for study are burrows made by infaunal organisms in shallow marine sediments, which include some of the most industrious burrowers known in the marine invertebrate realm, thalassinidean shrimp (both callianassid and upogebiid), which live in shallow marine environments worldwide (Tudhope and Scoffin, 1984; Swinbanks and Luternauer, 1987; Griffis and Suchanek, 1991; Dumbauld *et al.*, 1996; Astall *et al.*, 1997a; Hughes and Atkinson, 1997; Atkinson *et al.*, 1998; Nates and Felder, 1998). Numerous fossil examples of callianassid burrows (*Ophiomorpha* isp.) are in the Pleistocene Cockburn Town fossil reef complex of San Salvador, which allows for their easy comparison to burrows made by extant callianassid species in the shallow shelf environments around San Salvador and within Pigeon Creek lagoon (Curran, 1984; Curran and Williams, 1997). However, despite the well-described burrow architectures of modern upogebiid shrimp from the Bahamas and elsewhere (Griffis and Suchanek, 1991; Nickell and Atkinson, 1995; Astall *et al.*, 1997b; Curran and Williams, 1997), fragmentary fossil examples of their burrows have been recognized only from San Salvador (Noble *et al.*, 1995) and nowhere else in the world.

The primary objective of this report is to expand considerably on the work of Noble and others (1995) by providing more detailed descriptions and interpretations of fossil upogebiid shrimp burrows, which occur abundantly in the Grotto Beach Formation (Pleistocene) of San Salvador Island, Bahamas. These trace fossils are nearly identical in morphology to burrows formed by modern upogebiid shrimp on San Salvador in Pigeon Creek, as described by Curran and Williams (1997). The potential utility of these fossil burrows toward better understanding the geological development of San Salvador Island is also outlined, particularly in relation to how stratigraphic zones containing such burrows might indicate intertidal environments and sequence boundaries associated with glacioeustatic sea-level fluctuations.

GEOLOGIC SETTING AND LOCALITIES OF FOSSIL BURROWS

The trace fossils are preserved in muddy calcarenites (packstones) of the Grotto Beach Formation, in accordance with the stratigraphic nomenclature of Carew and Mylroie (1995). The most abundant occurrence of the burrows is immediately below a terra rossa paleosol on the Bahamian Field Station Nature Trail in the northeastern part of San Salvador (GPS location: N 24° 06.8', W 74° 27.9'; Fig. 1). The terra rossa likely marks the boundary between the Cockburn Town Member of the Grotto Beach Formation and the overlying North Point Member of the Holocene Rice Bay Formation in this area. Another locality for the burrows, where two specimens were recovered, is North Pigeon Creek Quarry (Quarry "E"), in east-central San Salvador (GPS location: N 24° 00.80', W 74° 28.0'). A single specimen was also found in a displaced boulder associated with the San Salvador Airport expansion project, west-central

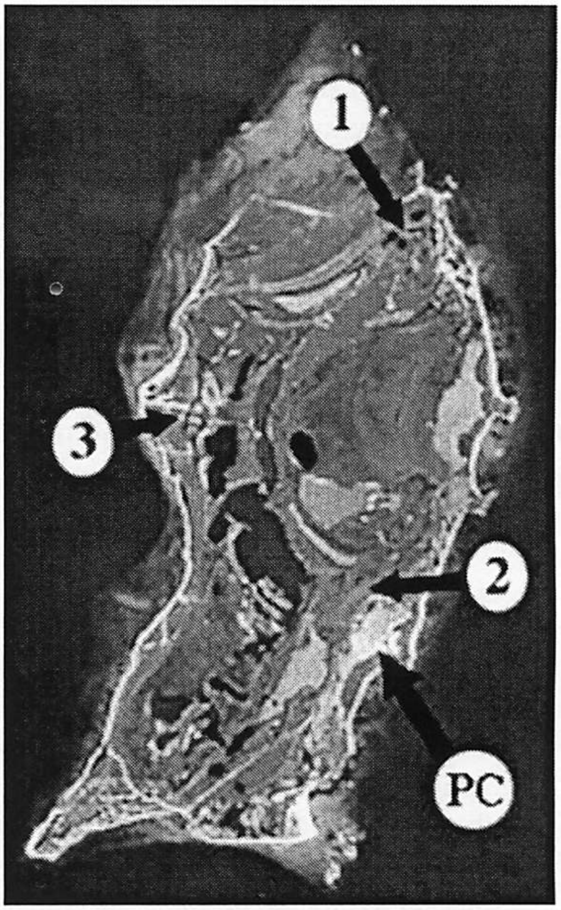

Figure 1. Locality map for fossil upogebiid burrows, San Salvador, Bahamas. 1 = Bahamian Field Station (BFS) Nature Trail, 2 = North Pigeon Creek Quarry, 3 = Airport expansion area, PC = Pigeon Creek.

San Salvador (no GPS reading available). The latter two localities are presumed to represent the Grotto Beach Formation on the basis of closely associated outcrops, but otherwise exact stratigraphic positions for their trace fossils is unknown.

MODERN AND FOSSIL UPOGEBIID SHRIMP BURROWS

Modern Upogebiid Burrows and Their Environmental Setting

Upogebiid shrimp are represented on San Salvador by *Upogebia vasquezi* (Ngoc-Ho 1989), as identified by Williams (1993), and are most abundant and easily observed in Pigeon Creek, a lagoon in the southeastern part of the island with distinctive carbonate subfacies, tidal exchange, and typical salinities of 36-38 ppt (Mitchell, 1987; Teeter, 1989; Boardman and Carney, 1992; Cummins *et al.*, 1995; Curran and Williams, 1997). Subfacies include subtidal channel deposits containing sandy and shelly deposits (including concentrations of the bivalve *Codakia*), whereas intensely bioturbated intertidal muddy sandflats are more common toward the edges of the lagoon (Mitchell, 1987; Cummins *et al.*, 1995; Noble *et al.*, 1995). Meadows of the seagrass *Thalassia testudinium* are common throughout the lagoon and aid in sediment baffling, whereas sediment binding is largely caused by microbial mats that develop on the sandflats (Curran, 1997). Pigeon Creek is bordered by extensive thickets of red mangroves that help to stabilize sediments on its periphery.

Common infaunal decapods in Pigeon Creek other than *Upogebia* include *Glypterus acanthochirus*, a callianassid shrimp, and *Uca major*, a fiddler crab. Callianassids are primarily responsible for the surface topography of Pigeon Creek, where their deep burrowing and biodeposition have caused numerous coalescing low-relief (about 30 cm high) mounds that are clearly evident at low tide (Curran and Williams, 1997; Curran, 1997). Upogebiid burrows commonly occur on sediment mounds formed by callianassids and thus cross-cut (post-date) development of those features. *Uca* burrows are generally more common in the mangrove areas but some cohabit the same areas as the upogebiid burrows. Callianassids occupy the deepest tier and are in the deepest parts of the lagoon, whereas upogebiids and fiddler crabs are relatively shallow-tier infauna and mostly live in intertidal zones.

Upogebiid shrimp are primarily suspension feeders and will construct permanent dwelling burrows to facilitate this behavior (MacGinitie, 1930; Thompson and Pritchard, 1969; Astall *et al.,* 1997). Upogebiid burrows are similar in morphology worldwide, although depth of burrowing for different species varies considerably; most occupy shallow tiers, but some will burrow to as much as 1.5 m (Ott *et al.,* 1976). Burrows are open, vertically to obliquely oriented, Y- or U-shaped with some end shafts branching from the main structure, and reinforced by both mucous and mud pellets, which can impart an outwardly knobby appearance to the burrow walls (Stevens, 1927; MacGinitie, 1930; Frey and Howard, 1975; Swinbanks and Luternauer, 1987).

Similarly, *Upogebia vasquezi* burrows, as described by Curran and Williams (1997) from Pigeon Creek (Fig. 2), consist of: (1) vertically oriented U-shaped burrows that in some cases criss-cross and have small end shafts branching from the U part of the burrows; (2) paired openings to the U burrows that are 2-3 cm apart; (3) other pairs 2-5 cm away from these openings; (4) opening diameters of 2-6 mm, although some expand to 6-10 mm diameter below the sediment-water interface; (5) reinforced burrow walls, 3-5 cm thick, with nodose and pelleted exteriors; (6) burrowing depths of 10-15 cm; and (7) occurrence in fine-grained carbonate sediment (mud mixed with very fine to fine sand). Curran and Williams (1997) postulated that fossil examples of these burrows should have had a high probability of preserva-

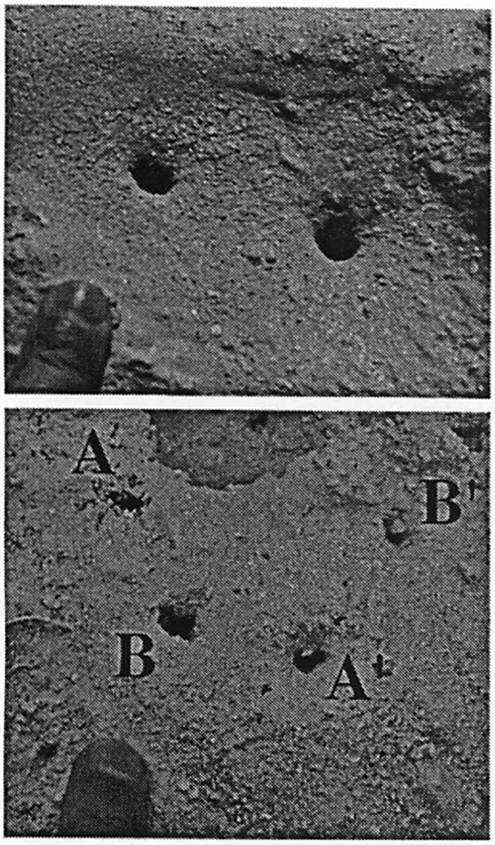

Figure 2. Modern upogebiid shrimp (Upogebia vasquezi) burrows, Pigeon Creek, San Salvador. Top - One pair of openings of double-U burrow structure. Bottom - Two pairs of openings representing criss-crossing U burrows. (A-A' represents paired openings to one U, B-B' is paired openings to another U).

tion, especially in consideration of their thick walls and abundance. However, they also noted that the most likely paleoenvironmental conditions favoring preservation of these shallow-tier traces would have been a combination of a sea-level stillstand followed by a regression; their shallow-tier origin means that they could have been easily erased by bioturbation of deeper-burrowing callianassids, which might have accompanied the increased sedimentation associated with a rise in sea-level. Consequently, application of such a predictive model means that fossil examples should occur just below a sequence boundary showing evidence of a sea-level low (perhaps marked by a paleosol) overlain by transgressive facies, such as transgressive eolianites, as outlined in a depositional scenario for the Bahamas (Carew and Mylroie, 1995).

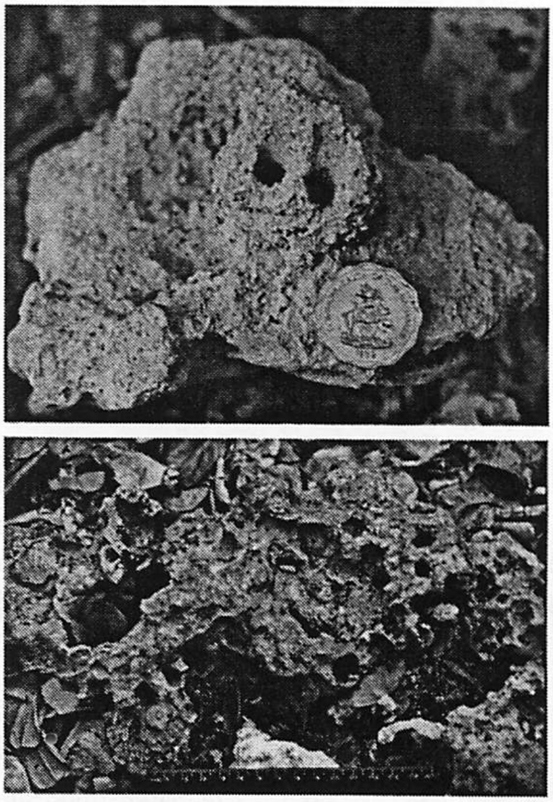

Figure 3. Fossil upogebiid burrows, BFS Nature Trail. Top - First clue to fossil burrows, found by author in March, 1997. Reinforced wall structure and paired openings (although more closely spaced than modern examples) led to looking for similar structures on a subsequent visit in January, 1998. Bottom - "Moonscape" surface of bedrock, BFS Nature Trail, immediately north of Oyster Pond. Surface characterized by 0.2-1.1 cm diameter holes rimmed by 2-4 cm thick linings; scale (black ruler at bottom) = 15 cm.

Fossil Upogebiid Shrimp Burrows, Grotto Beach Formation

The irregular topography of bedrock cropping out along part of the BFS Nature Trail has been noted by some previous workers and nicknamed "moonscape" (Godfrey *et al.*, 1994). Immediately north of Oyster Pond on the trail is an outcrop of this "moonscape" that shows numerous open holes with thickened, cemented rims, some of which show close enough spacing to suggest pairing (Fig. 3). My initial examination of these structures lead me to hypothesize that these are fossil examples of the upogebiid burrows seen in nearby Pigeon Creek, a hypothesis that was tested by numerous measurements, qualitative descriptions, and subsequent analyses. Three other structures found at North Pigeon Creek Quarry and the airport expansion area also bear a resemblance to the structures occurring on the BFS Nature Trail.

A morphological comparison of the structures with modern upogebiid burrows on San Salvador reveal a striking resemblance (Figs. 3-4). The structures found on the BFS Nature Trail and elsewhere show the following characteristics: (1) vertically oriented U-shaped burrows that in some cases have double U's criss-cross and small end shafts branching from the U part of the burrows; (2) paired openings mostly 2-4 cm apart; (3) other pairs 1-5 cm away from these openings; (4) burrow openings of 2-10 mm diameter; (5) reinforced burrow walls, 2-5 cm thick, some with evident nodose and pelleted (irregular) exteriors; (6) burrow depths of as much as 11 cm; and (7) preservation through cementation of fine-grained carbonate (mud and sand) sediment. Additionally, some structures show more than two openings and have complex geometries, which may indicate several generations of burrowing or the contributions of several burrowers, a condition that might not be readily apparent in modern ex-

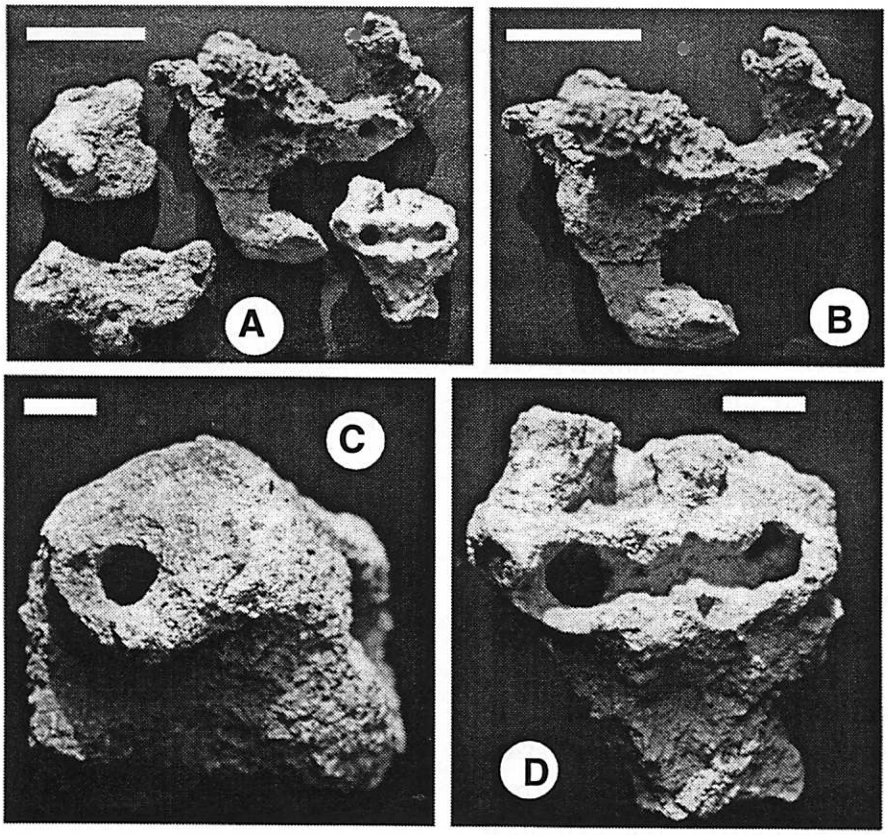

Figure 4. Fossil upogebiid burrows, BFS Nature Trail. A) Variations in morphology of fossil burrows from the BFS trail, showing numerous holes, well-cemented walls, and complexity of structure; scale bar = 5 cm. B) Close-up of burrow structure showing slightly nodose exterior, branching partial U structures (toward top), and probable end tunnel; scale bar = 5 cm. C) Single opening to burrow showing reinforced lining; scale bar = 1 cm. D) Open basal part of a U burrow, showing both openings to both shafts; scale bar = 1 cm.

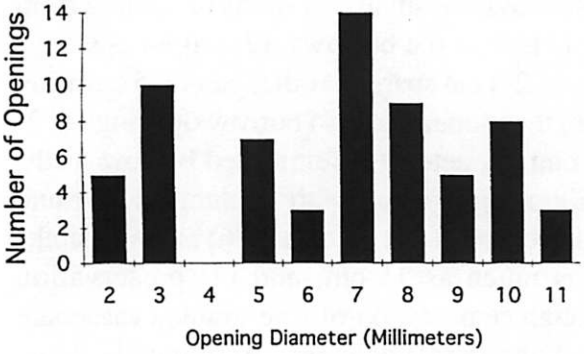

Figure 5. Size distribution of openings in fossil upogebiid burrows, combining data from all three localities (n = 64); majority (61) are from BFS Nature Trail.

amples but should be expected in fossil ones. Nevertheless, because of the close similarity between these structures and modern upogebiid burrows, I am proposing that they are fossil examples of those burrows.

A statistical analysis of openings in the structures corroborated initial impressions of conformity of their sizes with openings in previously described modern upogebiid burrows. Mean opening diameter is 7 ± 3 mm (n = 64); the median and mode are identical to the mean. However, the distribution of sizes is polymodal, with secondary peaks in the 3, 8, and 10 mm categories (Fig. 5). Additionally, although the spacing between some paired openings were nearly identical to those of modern burrows, other pairs were closer spaced than those seen in modern examples (Figs. 6-7).

Explanations offered for these data are based on various scenarios. First, smaller-sized openings may represent the originally narrow openings of upogebiid burrows that expanded downward, thus the variety of sizes is reflective of preservation of both types of openings. Second, smaller holes could have been made by juvenile upogebiid shrimp and the distribution may be approximately representative of a population structure for the trace-making species. Third, an unknown tracemaker was possibly responsible for superimposing its burrows onto the larger, cemented burrows. Finally, multiple episodes of burrowing may have occurred, which would have resulted in closely spaced openings that actually are unrelated to one another. However, a combination of all of the preceding scenarios is also likely considering the unknown aspects of physical and biogenic reworking of the original burrows, upogebiid reproduction, and other organisms that might have cohabited or later occupied the burrows during their potentially long history.

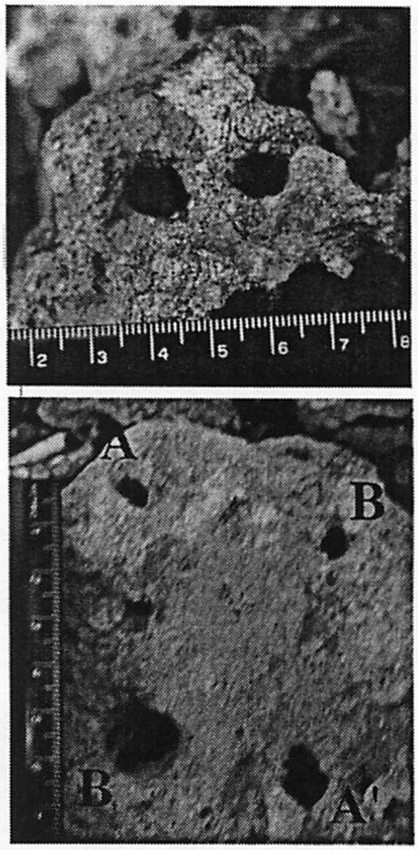

Figure 6. Fossil upogebiid burrows showing paired openings, BFS Nature Trail. Top - Paired openings accompanied by thick linings. Bottom - Two pairs of openings (compare with Figure 2). Errant fifth opening (between two openings on the left) may represent opening from unrelated burrow structure.

Probably the best specimen exhibiting the most diagnostic characteristics of a modern upogebiid burrow was found at the North Pigeon Creek Quarry (Fig. 8). The specimen is composed of a muddy calcareous sand, is thick-walled with a nodose exterior, and shows openings on opposite sides of cross-sections that lead to intersecting U's within the structure. If a new ichnogenus was named for this trace fossil, this specimen would be an excellent candidate for a holotype. However, the difficulties of distinguishing the external morphology of this trace fossil from the similarly nodose *Ophiomorpha*, as well as the lack of a specimen showing the entire double-U geometry, argues against the naming of a new ichnogenus as yet. Perhaps the addition of more material will better define an identifiable morphology that would warrant an ichnotaxonomic designation, but until then it should simply be recognized on the basis of some or most of the characteristics that ally it with its modern analogue.

GEOLOGIC SIGNIFICANCE OF FOSSIL UPOGEBIID BURROWS

The fossil burrows described here, like most relatively recent trace fossils in the Bahamas, are easily connected to their paleoenvironments through comparison with traces made by extant species in the Bahamas. In this case, the burrows are sensitive indicators of intertidal and lagoonal conditions, the norm for upogebiid shrimp in the Bahamas, and thus can be used in conjunction with other ichnologic and sedimentologic criteria for interpreting such paleoenvironments. Although the limited exposure of the burrows described here provides little other paleoenvironmental information, I expect that further recognition of such burrows on San Salvador and in other parts of the Bahamas will be accompanied by an association with other trace fossils that reflect intertidal and lagoonal facies, as well as sediment textures, physical sedimentary structures, and body fossils. For example, a more representative trace fossil assemblage would include intensely to completely bioturbated muddy calcarenites containing the upogebiid burrows described here, discrete *Ophiomorpha*, and possibly the still-unknown fossil equivalents of fiddler crab bur-

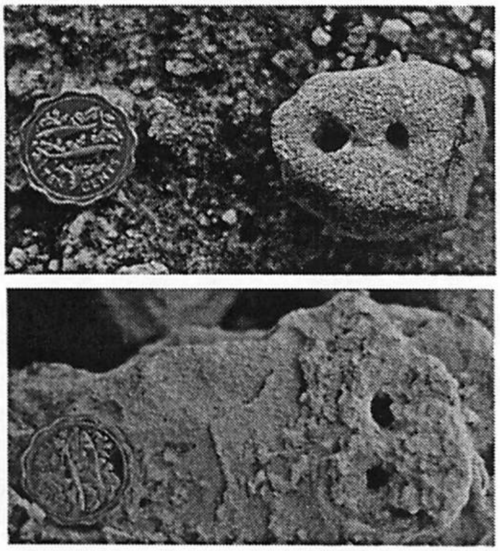

Figure 7. Specimens with paired openings and thick lining from localities other than BFS Nature Trail. Top - Specimen from North Pigeon Creek Quarry. Bottom - Specimen from boulder in San Salvador Airport expansion area.

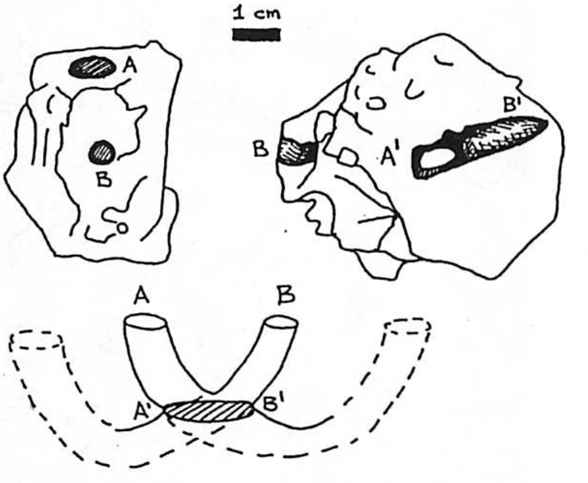

Figure 8. Sketch of fossil upogebiid burrow showing evidence of criss-crossing double-U structure, North Pigeon Creek Quarry, with interpretation of internal structure as shown by interconnections of openings. A-A' corresponds to connection of holes from one limb of a U, whereas B-B' is connection of holes from one limb of another U.

rows, although the latter have lower preservation potential (Curran and Williams, 1997). Complete reworking of sediments by burrowers may have erased physical sedimentary structures in such facies, but any preserved structures should show evidence of tidal fluctuations. Additionally, *Codakia* beds, which are common in outcrops of the Grotto Beach Formation underlying the burrowed zone in the vicinity of the BFS Nature Trail, likely represent analogues of laterally adjacent channel subfacies seen in present-day Pigeon Creek (Godfrey *et al.*, 1994; Noble *et al.*, 1995), thus their stratigraphic co-occurrence is supportive evidence of their paleoenvironmental association.

Larger-scale applications of the trace fossils include their use in studying sea-level fluctuations in combination with known marker horizons, such as terra rossa paleosols (Fig. 9). Terra rossa paleosols on San Salvador and in other parts of the Bahamas likely denote drops in sea level caused by glaciation during the Pleistocene (Carew and Mylroie, 1995). Because the burrows are most abundant directly below such a horizon on the BFS Nature Trail, they are probably associated with a sea-level stillstand and a subsequent regression. This particular paleosol most likely separates the marine-related facies of the Pleistocene Grotto Beach Formation from the beach and eolian (transgressive dune) facies of the Holocene Rice Bay Formation, thus representing a bounding discontinuity (sequence boundary). Trace fossil assemblages have been used for better delineation of sequence boundaries in clastic rocks (e.g., Pemberton *et al.*, 1992) but relatively little similar work has been done using trace fossils in carbonates, especially in the Bahamas. Further testing of the co-occurrence of these and other trace fossils with paleosols may supplement other information used for defining such sequence boundaries in the Bahamas, which will lead to a broader understanding of the geologic history of the Bahamas platform.

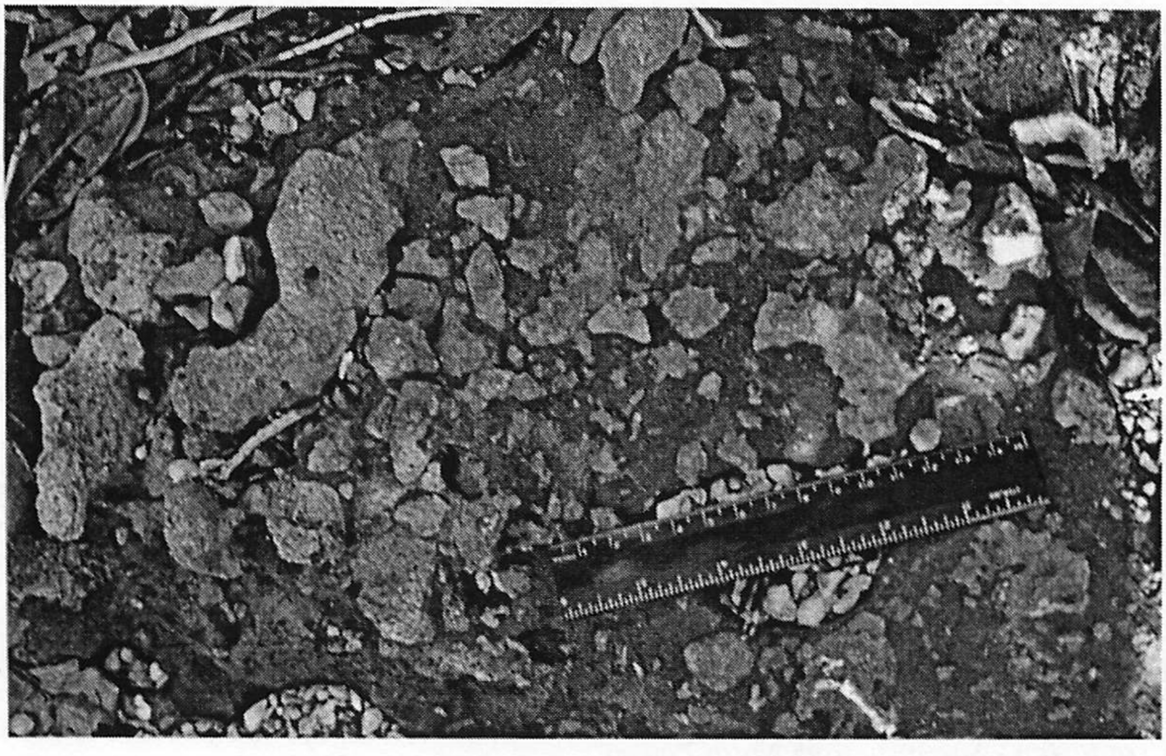

Figure 9. Terra rossa horizon representing paleosol within Grotto Beach Formation (Pleistocene), BFS Nature Trail; scale ruler = 15 cm.

CONCLUSIONS

1. Fossil upogebiid shrimp burrows in the Grotto Beach Formation (Pleistocene) of San Salvador Island occur most abundantly on the Bahamian Field Station Nature Trail, but a few examples were also found at North Pigeon Creek Quarry and the area associated with the new airport expansion on the western side of the island.

2. The trace fossils are nearly identical morphologically to those made by modern upogebiid shrimp *Upogebia vasquezi* (Ngoc-Ho 1989) on San Salvador in Pigeon Creek lagoon, thus they were likely made by the same species or a very similar species of upogebiid shrimp in a similar environment. Variations in trace fossil morphology are likely attributable to factors such as different tracemakers modifying the burrows or multiple episodes of burrowing. Variations and incompleteness of the total morphology of the burrows argue against the naming of a new ichnogenus for them unless more material is found to corroborate the current interpretation.

3. The trace fossils are most abundantly represented directly below a terra rossa (paleosol) horizon on the Bahamian Field Station Nature Trail, thus suggesting their link to a sea-level stillstand and regression associated with a Pleistocene glaciation and pointing out their potential use as both paleoenvironmental and sea-level indicators in future studies of Bahamian geology.

ACKNOWLEDGMENTS

Many thanks go to many people who helped this project come to fruition. First and foremost of these people is Al Curran, who first gave me a "grand tour" of the ichnologic richness of San Salvador in January, 1996, introduced me to the problem of previously undiscovered fossil upogebiid burrows, and encouraged me to publish the results of this study. He and John Mylroie are recognized for their editing acumen, which made this Symposium volume a reality. Also deserving praise is Ken Buchan, director of the Bahamian Field Station, and his entire staff for putting me up (or putting up with me) for the brief but necessary duration of time required for the field work on this project and arranging for me to give a presentation on it *in absentia* at the Ninth Geology of the Bahamas Symposium. The students of my Geosciences 171 (Modern and Ancient Tropical Environments Field Course) of Emory University also are commended; of that group, Keana Taylor discovered one of the burrows at North Pigeon Creek Quarry in between the pioneering reblazing by other students of "Hard Bargain Trail" (now renamed by me as "Emory Estrogen Trail") to Six-Pack Pond (now renamed by me as "Kegger Pond") in January, 1998. Stephen Henderson of Oxford College in Georgia, who assisted me in the Emory field course, and Andy Rindsberg of the Alabama Geological Survey both provided excellent feedback on my initial hypotheses about the burrows. Last but not least, accolades go to Carl Froede of the U. S. Environmental Protection Agency in Atlanta, Georgia, who transported my poster presentation to San Salvador for me so that it could be part of the Symposium while I was bodily in the country responsible for the European discovery and naming of San Salvador: Spain. What goes around comes around.

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