

10-1991

Trace Fossils of Shallow Subtidal to Dunal Ichnofacies in Bahamian Quaternary Carbonates

H. Allen Curran

Smith College, acurran@smith.edu

Brian White

Smith College

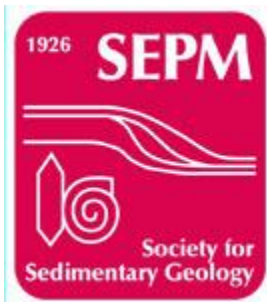
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Author(s): H. Allen Curran and Brian White

Source: *PALAIOS*, Vol. 6, No. 5 (Oct., 1991), pp. 498-510

Published by: SEPM Society for Sedimentary Geology

Stable URL: <http://www.jstor.org/stable/3514987>

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Trace Fossils of Shallow Subtidal to Dunal Ichnofacies in Bahamian Quaternary Carbonates

H. ALLEN CURRAN and BRIAN WHITE

Department of Geology, Smith College, Northampton, MA 01063

PALAIOS, 1991, V. 6, p. 498–510

Pleistocene and Holocene carbonate grainstones or calcarenites capping the islands of the Bahamas commonly contain distinctive animal and/or plant trace fossils. Three ichnocoenoses within the Skolithos and Psilonichnus ichnofacies are recognized in the transition from sediments deposited in the shallow shelf environment, commonly associated with coral reefs, to sediments of the coastal dune environment. Analog relationships between the trace fossils and modern tracemakers can be established in many cases, and this correspondence strengthens the interpretive model. Ophiomorpha and Skolithos linearis characterize beds deposited in shallow shelf settings. Psilonichnus upsiloides, the fossil burrow of the ghost crab Ocypode quadrata, marks beds deposited in the upper foreshore-backshore environment and has particular utility as an indicator of sea-level position. A diverse ichnocoenosis consisting of Skolithos linearis, a large cluster burrow, small, irregular burrows, and plant trace fossils formed along bedding planes characterizes beds of the dunal environment. The ichnologic model developed herein for recognition of depositional zones in the transition from shallow subtidal to dune environments in the tropical, carbonate coastal settings of the Bahamas should be applicable to other geologically similar settings around the world.

INTRODUCTION

The carbonate grainstones of Pleistocene and Holocene age that cap the islands of the Bahama Archipelago can be subdivided into lithofacies reflecting a spectrum of paleodepositional environments, ranging from bank-barrier coral reefs to terrestrial dunes. Trace fossils formed by both animals and plants are common components of these grainstones, and ichnocoenoses readily assignable to either the *Skolithos* or the *Psilonichnus* ichnofacies can be rec-

ognized. When used in concert with primary sedimentary structures, a given ichnocoenosis can be useful in characterizing a calcarenite facies and its depositional paleoenvironment (Curran, 1984; Curran and White, 1987). Traces and trace makers in modern Bahamian environments can be identified as analogues for most of the trace fossils, further strengthening the interpretive ichnologic model.

The purpose of this project was to examine ichnocoenoses representing shallow subtidal to dunal environments that are likely to occur in Pleistocene and Holocene calcarenites of the Bahamas. Our findings are based principally on field studies on San Salvador and Great Inagua islands (Fig. 1), with supplementary information from the Exumas, Rum Cay, and Sand Cay (Turks and Caicos). Specifically, we examine herein the transition from shallow subtidal to beach to dune environments as they might occur in a tropical, windward to leeward, carbonate sand coastal setting. Lithofacies representing more protected environments, such as in or marginal to a large coastal bay, lagoon, or tidal creek, are not directly considered here. Nonetheless, modern environments of these types in the Bahamas and elsewhere have numerous tracemaking organisms, and comparable rock record lithofacies undoubtedly bear distinctive ichnocoenoses (e.g., the lagoonal assemblages from Pleistocene strata in the Cayman Islands described by Jones and Pemberton, 1989).

In the Bahamian setting of islands atop isolated platforms and surrounded by narrow shelves, the overriding control on environments, depositional patterns, and the distribution of infaunal animals and terrestrial plants is sea-level position. The ichnocoenosis representing the backshore zone allows precise definition of former sea-level positions in these calcarenite sequences. This ichnocoenosis is given particular emphasis in this paper, as its occurrence should be equally valuable in other, similar geologic settings. Additional environmental controls to be discussed that are particularly important in determining the distribution patterns of the Bahamian ichnocoenoses include substrate stability with respect to hydrodynamic and wind energy and density of terrestrial plant cover.

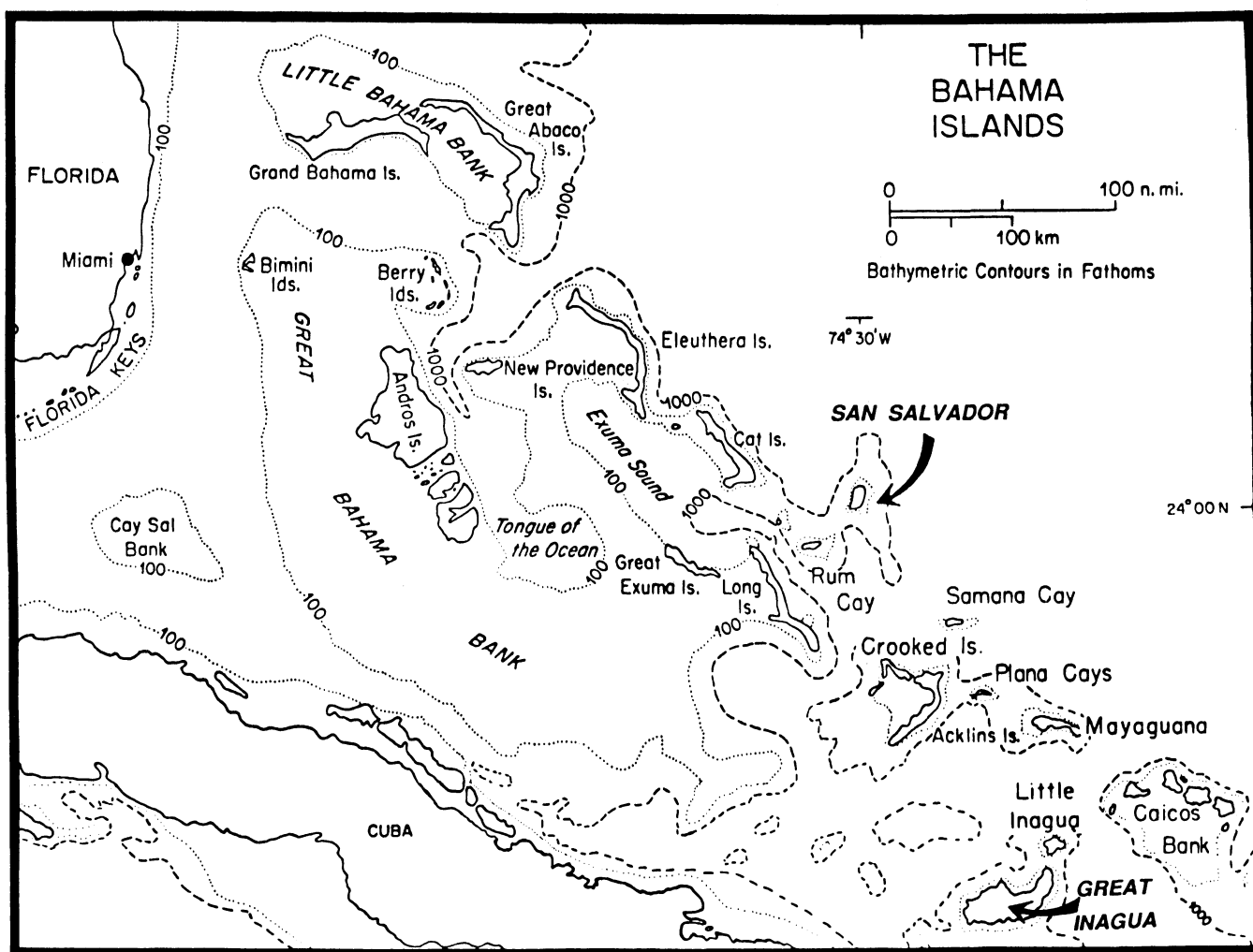


FIGURE 1—Islands of the Bahama Archipelago. The principal study areas are on San Salvador and Great Inagua islands.

THE GEOLOGIC SETTING

The Bahama Archipelago is an arcuate chain of tectonically stable carbonate platforms, many of which are capped by low islands (Fig. 1). Water depths on the banks normally are less than 10 m, but the banks are separated by inter- or intra-platform, deep-water basins and troughs (Curran, 1989).

San Salvador and Great Inagua islands sit atop isolated platforms rising from the deep ocean floor. In a real sense, these islands can be viewed as sea-level gauges. The Pleistocene and Holocene lithofacies that cap the islands tend to have limited areal extent and sharp contacts in vertical section. These lithofacies have recorded in some detail at least the latter part of the Quaternary history of glacial and interglacial eustatic sea-level change (Carew and Mylroie, 1987).

All trace fossils of subtidal origin illustrated in this paper occur in Pleistocene beds associated with substantial bank-barrier coral reefs on San Salvador and Great Inagua. On

San Salvador, trace fossils are found in the Cockburn Town Member of the Grotto Beach Formation, named by Carew and Mylroie (1985), in the area of the Cockburn Town fossil coral reef, near the village of Cockburn Town on the western coast of the island. This fossil reef and its associated strata were described in detail (White et al., 1984; Curran and White, 1985, 1989). Trace fossils also occur in the Devil's Point reef complex on Great Inagua (White and Curran, 1987). Both reefs are of Sangamon age, and a substantial number of fossil corals from both sites recently have been dated using advanced U-Th series age-dating techniques (Chen et al., 1991).

The remainder of the trace fossils illustrated in this paper are found in rocks of the sea cliff exposures of Hanna Bay and North Point along Rice Bay, on the northeastern coast of San Salvador Island. These rocks have been assigned to the Rice Bay Formation and radiometrically dated as Holocene in age (Carew and Mylroie, 1985). Carew and Mylroie subdivided the Rice Bay Formation into two parts, the North Point Member and the Hanna Bay Member.

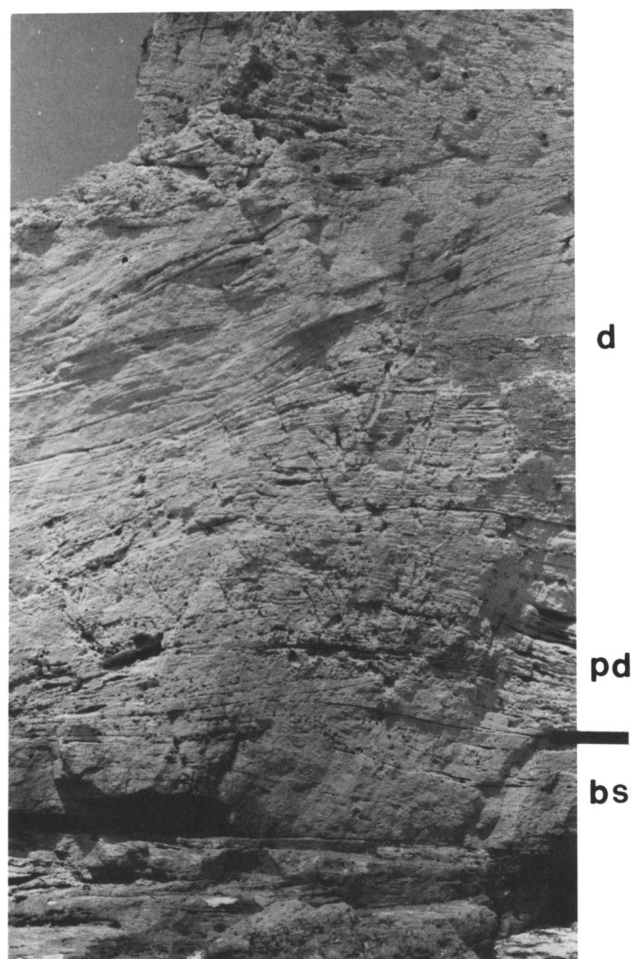


FIGURE 2—The sea cliffs at Hanna Bay on San Salvador Island showing Holocene exposures of the Hanna Bay Member of the Rice Bay Formation. Cliffs are about 6 m high; bs = backshore beds, pd = proto-dunal beds with gradual transition to d = dunal beds. Narrow beach and Atlantic Ocean are to the right of photo.

The North Point member consists entirely of carbonate eolianites. Radiocarbon whole-rock samples yielded dates of about 5300 years for these rocks (Carew and Mylroie, 1985, 1987). The sediments of this member were deposited as lobate, parabolic-like dunes that coalesced to form an elongate, transverse dune ridge perpendicular to the prevailing easterly wind direction during Holocene sea transgression. The primary sedimentary structures and trace fossil occurrences in these eolianites were described by White and Curran (1988).

The sediments of the Hanna Bay Member apparently were deposited in equilibrium with modern sea level (Carew and Mylroie, 1985). In the cliffs of the section at Hanna Bay, the lower-most rocks exhibit near horizontal bedding. Higher in the section, the sediments show a decrease in grain size (Carew and Mylroie, 1985), and gently seaward dipping bedding gives way to more complex patterns of

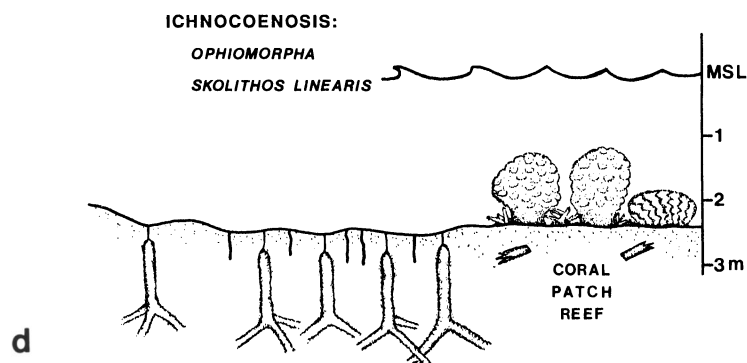


FIGURE 3—Model ichnocoenosis of the shallow shelf subtidal zone.

wedge-planar cross bedding. From cliff bottom to top, the paleodepositional environments represent foreshore to backshore to proto-dune and dunal rocks (Fig. 2). Radiocarbon whole-rock sample dating yielded an age of about 3200 years for these rocks (Carew and Mylroie, 1987).

THE ICHNOCOENOSSES

In this paper, we follow the definitions of ichnocoenosis as given by Ekdale et al. (1984) and Bromley (1990), namely that an ichnocoenosis is an ecologically pure association of traces or trace fossils derived from the activities of a single endobenthic community. As Bromley (1990) pointed out, the term paleoichnocoenosis is technically more correct for such fossil associations, but we have followed the more accepted usage of ichnocoenosis for both modern and fossil associations.

By contrast, the term trace fossil assemblage is more general (Bromley, 1990) and can refer to activities recorded in the substrate by one or more benthic communities, possibly at different times. This is a particularly important point to consider in the Bahamian context because rhizomorphs, in addition to being an integral part of certain terrestrial ichnocoenoses, also can be formed by plant roots in any Bahamian lithofacies during periods of subaerial exposure and lowered sea level. Similarly, a marine borings ichnocoenosis could be developed on the rock surfaces of any Bahamian lithofacies during an interval of high sea stand. An ichnocoenosis from Bahamian rocks must be reconstructed with care; non-contemporaneous rhizomorphs and/or borings must be subtracted out of a given suite of trace fossils to equal the true ichnocoenosis.

Over the past two decades, ichnologists have recognized recurring associations of trace fossils that are thought normally to represent specific benthic environments (i.e., the "Seilacherian" ichnofacies of Bromley, 1990). Such associations have been given formal names such as *Skolithos* ichnofacies or *Cruziana* ichnofacies (see Frey and Pemberton, 1984, 1985, and Frey et al., 1990, for tables listing formally described ichnofacies). A given ichnofacies may involve the occurrence of one or more ichnocoenoses. For example, Pemberton and Jones (1988) recognized several

assemblages of trace fossils (ichnocoenoses) in Pleistocene calcarenites on Grand Cayman. All clearly are part of the *Skolithos* ichnofacies. Thus, for a formally recognized ichnofacies, one or more ichnocoenoses may be involved temporally, and many ichnocoenoses certainly could be present through time.

The Bahamian ichnocoenoses described herein are placed within the broader context of the universal ichnofacies. However, the Bahamian ichnocoenoses typically represent narrower and more specific paleoenvironmental zones than that of an ichnofacies.

Subtidal Ichnocoenosis

Curran (1984) described the trace fossils that form an ichnocoenosis characteristic of the sandy, shallow shelf subtidal zone (Fig. 3) as preserved in marine calcarenites of the Bahamas. The characteristic trace fossils of this ichnocoenosis are *Ophiomorpha* and *Skolithos linearis*, attributed to the burrowing activities of callianassid shrimp and polychaetes, respectively. This ichnocoenosis was shown to occur in Pleistocene calcarenite facies that interfinger with coral rubblestones at the Cockburn Town fossil reef site on San Salvador (Curran, 1984) and in similar, reef-associated facies and shallow subtidal marine facies landward of the Devil's Point fossil reef complex on Great Inagua (White and Curran, 1987).

Based on numerous observations of the modern, shallow subtidal zone off Bahamian beaches, Curran (1984) noted that callianassid shrimp normally are not found burrowing in Bahamian open shelf sands at a water depth of less than about one meter and that callianassid burrows are not found on beach lower foreshores. This situation contrasts markedly with siliciclastic beaches of the southeastern United States where the burrows of *Callianassa major* are common in the lower foreshore (Frey and Mayou, 1971; Frey and Pemberton, 1987). Bahamian beaches tend to be narrow and steep, with shifting substrate conditions in the swash and surf zones. Such conditions largely prohibit burrowing activity, and the result is that the lower foreshore-uppermost shoreface zone of Bahamian beaches largely is devoid of preservable traces. By analogy, trace fossils may be expected to be absent to rare in the sediments of Pleistocene rocks that were deposited in this environment. The possible exception would be a protected shoreline situation where a low-gradient beach could develop with relatively firm substrate conditions; however, such beach conditions are not common in the Bahamas today.

The Bahamian shallow subtidal ichnocoenosis clearly fits within the *Skolithos* ichnofacies, as conceived by Frey and Pemberton (1984, 1985) and Frey et al. (1990). It should be noted that in tropical, carbonate sand, shallow subtidal environments, the ichnocoenosis frequently occurs in close association with coral reefs and reefal sediments (Curran, 1984). Indeed, we have found the ichnocoenosis preserved in pockets of sediment surrounded by lithified coral rubble and, occasionally, isolated shafts of *Ophiomorpha* occur within the coral rubble.

Ophiomorpha

In our experience, *Ophiomorpha* is widespread and common in Pleistocene shallow subtidal calcarenites of the Bahamas, except in calcarenites that formed from mobile sediments in the very shallow environment of the beach swash zone. Occurrences range from isolated but robust shafts in tidal delta deposits (Curran, 1984, fig. 3D) to densely packed (ichnofabric index 4 of Droser and Bottjer, 1989), irregular boxworks of shafts and tunnels associated with reefal facies (Curran, 1984; White and Curran, 1987; and Fig. 4A, B herein). Similar widespread occurrence of *Ophiomorpha*, commonly with *Skolithos*, has been reported from the Pleistocene marine calcarenites of the Cayman Islands (Pemberton and Jones, 1988; Jones and Pemberton, 1989).

Ichnospecies of *Ophiomorpha* are defined principally on the basis of differences in the burrow wall and its pellet form or pattern (Frey et al., 1978). Pemberton and Jones (1988) recognized two ichnospecies from the calcarenites of the Cayman Islands, *O. boorneensis* and *O. nodosa*. The pellet forms of Bahamian *Ophiomorpha* specimens range from well-formed single pellets (Curran, 1984, fig. 3D), to elongate pellets imparting a rugose appearance to the outer burrow wall (Curran, 1984, fig. 3A), to somewhat spikey pellets, possibly resulting from diagenetic changes in the outer wall surface. This variability of pellet form and exterior wall appearance, coupled with variation in the overall burrow configuration, makes it difficult to designate ichnospecies of *Ophiomorpha*. As Curran (1984) noted, numerous species of burrowing thalassinidean shrimp inhabit the tropical, shallow marine environments of the Bahamas and South Florida, and several of these species are capable of making *Ophiomorpha* or *Ophiomorpha*-like burrows. Until more becomes known about these modern burrows and the full range of the possible fossil counterparts, we prefer to refrain from making ichnospecies designations for *Ophiomorpha* in Bahamian rocks.

In Bahamian calcarenites derived from shelf environments and associated with reefal facies, *Ophiomorpha* commonly occurs in a pattern of irregular boxworks of interconnecting shafts and tunnels (Fig. 4A). An ichnofabric index (following Droser and Bottjer, 1989) of 3 to 4 or even 5 is estimated for calcarenite pockets of the Cockburn Town fossil reef complex on San Salvador Island. *Ophiomorpha* burrow walls typically are robust, having a thickness of 1–3 mm (Fig. 4B) of micritic material, with smooth interior surfaces and distinctly mammillated to unevenly rugose exterior surfaces. Tubes have outside diameters of 1–5 cm; maze juncture points can be particularly broad (Fig. 4B). In reefal facies, *Ophiomorpha* tubes easily can be confused with rhizomorphs (=rhizocretions) and/or weathered branching coral specimens. Criteria for differentiating *Ophiomorpha* from these other forms were offered by Curran (1984).

Frequently, the carbonate sand filling *Ophiomorpha* tubes is well-lithified. Exposures of shallow subtidal, Pleistocene calcarenites on Great Inagua Island, deposited seaward of the swash and surf zone but landward of the Devil's

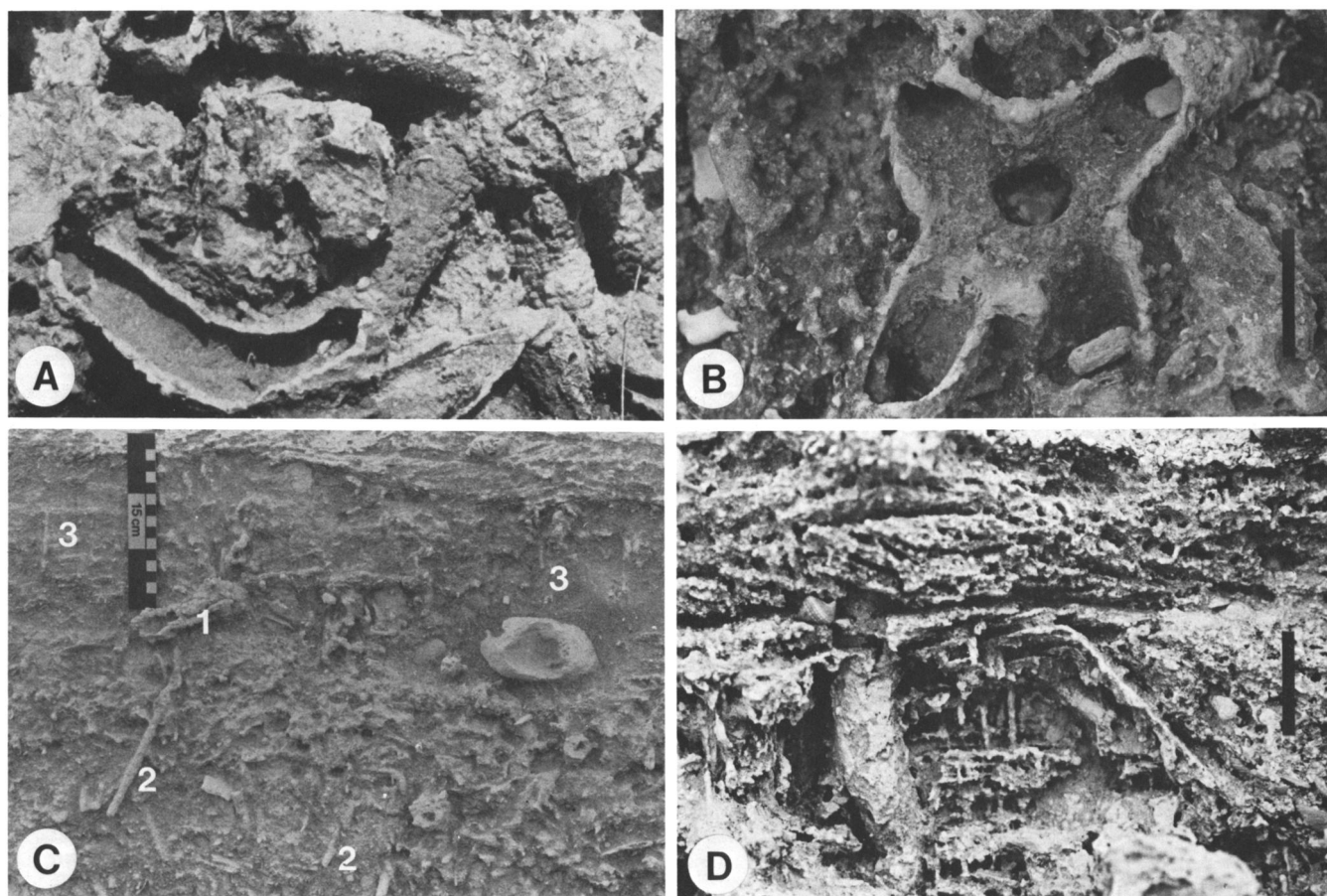


FIGURE 4—**A**) *Ophiomorpha* in Pleistocene rocks of the Cockburn Town Member, Grotto Beach Formation on San Salvador; note smooth interior surface of the broken tunnel wall; tunnel diameter = 2 cm. **B**) Large maze juncture point of *Ophiomorpha* in Pleistocene coral rubblestone on Great Inagua; bar scale = 2 cm. **C**) *Ophiomorpha* burrow walls (1) and lithified burrow fills (2), *Skolithos linearis* (3), and beachrock clasts in a Pleistocene shallow subtidal sand facies on Great Inagua. **D**) Close-up of *Skolithos linearis* amidst an irregular boxwork of *Ophiomorpha*, Cockburn Town Member, San Salvador; bar scale = 3 cm.

Point fossil reef complex (White and Curran, 1987), are intensely burrowed (ichnofabric index = 3). Mostly shafts and tunnels of lithified fill material are present (Fig. 4C), the original wall material having been eroded away. However, the occurrence of some shafts and tunnels having micritic walls and a knobby exterior surface confirmed an *Ophiomorpha* identification for all of the larger burrows.

Skolithos linearis

Specimens of *Skolithos linearis* (Fig. 4C, D) are widespread in Bahamian shallow subtidal calcarenites, and most are found with, but are decidedly subordinate to, *Ophiomorpha*. These *S. linearis* burrows are straight to somewhat sinuous, unbranched shafts, typically oriented perpendicular to bedding. *S. linearis* specimens of marine lithofacies in the Bahamas are lined with fine- to medium-sized carbonate sand and are small in size; outside diameters are 2–4 mm and measurable lengths are less than 15

cm. Such burrows were interpreted as the dwelling tubes of polychaetes by Curran (1984).

Beach Ichnocoenosis

As stated previously, the lower foreshore zone of modern Bahamian beaches and the Pleistocene strata that formed in this zone largely are devoid of traces and trace fossils, respectively. However, this changes for the upper foreshore and backshore zone, which is characterized by burrows of the ghost crab *Ocypode quadrata* and, in the rock record, by the trace fossil *Psilonichnus upsilon* (Fig. 5). Adams (1989) showed that modern carbonate beaches in the Bahamas can be burrowed by beetles (patchy distribution), by oligochaete worms (possibly pervasive), and, in some instances, by polychaetes (in the foreshore only). These animals are not known to form distinctive traces, but their burrowing activity may result in significant bioturbation of beach sediments. In sediments at the landward edge of

the backshore, as it merges with at least partly vegetated proto-dunes, there is a variety of root molds, some of which have distinctive forms. This ichnocoenosis clearly belongs in the *Psilonichnus* ichnofacies, as described by Frey and Pemberton (1987). However, the distributional range of *P. upsilon* is more restricted in tropical, Bahamian carbonates than in the siliciclastic setting of the Georgia coast.

Burrows of *Ocypode quadrata*

Even the casual observer will note that burrow holes are common in the beach upper foreshore and backshore zones of modern Bahamian beaches. These burrow openings (Fig. 6B) range from 1 to 2 cm to about 8 cm in diameter. The burrower is the ghost crab *Ocypode quadrata* (Fig. 6A), which lives on sandy western Atlantic and Caribbean beaches from Rhode Island to Brazil (Williams, 1984). Its burrow is *Psilonichnus upsilon* (Frey et al., 1984).

Ocypode quadrata constructs a variety of burrow forms, ranging from steeply inclined shafts, to J-, U-, and Y-shaped forms (Frey and Mayou, 1971; Hill and Hunter, 1973; Allen and Curran, 1974; Frey and Pemberton, 1987). We have made numerous casts of *O. quadrata* burrows in the beaches of San Salvador, and we find the most common forms to be steeply inclined shaft and U-shapes or Y-shapes (Fig. 6C–E).

On coasts dominated by siliciclastic sands, such as the Georgia and Carolina coasts of the United States, *Ocypode quadrata* ranges well back into the coastal dunes (Frey and Mayou, 1971; Wolcott and Wolcott, 1990). However, large areas of these dunes commonly are unvegetated or only sparsely vegetated. Observations on San Salvador indicate that the situation is not the same for the tropical, carbonate coastal regime, where sandy backshores tend to merge sharply with densely vegetated proto-dunes and dunes. The ghost crab shuns such vegetated areas, possibly because dense, low-lying vegetation impedes its mobility. The crabs are predators, and they remain largely on the beach to seek their prey (Wolcott and Wolcott, 1990). The common land crab, *Gecarcinus lateralis*, is the well-established burrower in vegetated dunal areas in the Bahamas.

Ocypode quadrata probably would burrow in carbonate dunal areas if such areas were largely unvegetated. However, since this normally is not the case, *O. quadrata* and its burrows are confined largely to the upper foreshore and backshore zones. Very similar burrows and a similar distribution pattern of burrowing were reported for the crabs *O. cordimanus* and *O. ceratophthalma* in the Seychelles (Braithwaite and Talbot, 1972) and *O. ceratophthalma* on Heron Island, Australia (Förster and Barthel, 1978).

Psilonichnus upsilon

The ichnospecies *Psilonichnus upsilon* was described by Frey et al. (1984). The type specimen occurs in the lower beds of the Hanna Bay Member in the cliffs at Hanna Bay (Fig. 2) on the northeastern coast of San Salvador Island. Here burrows are unlined, unbranched to Y-shaped

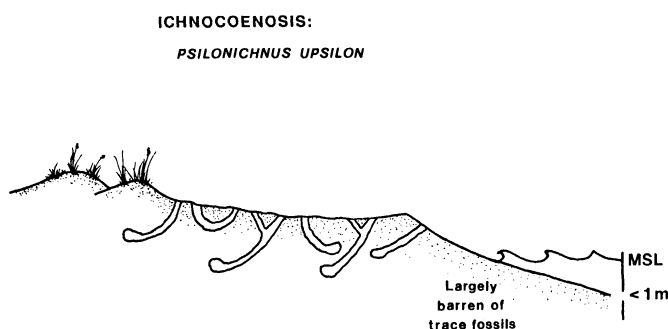


FIGURE 5—Model ichnocoenosis of the upper foreshore-backshore zone.

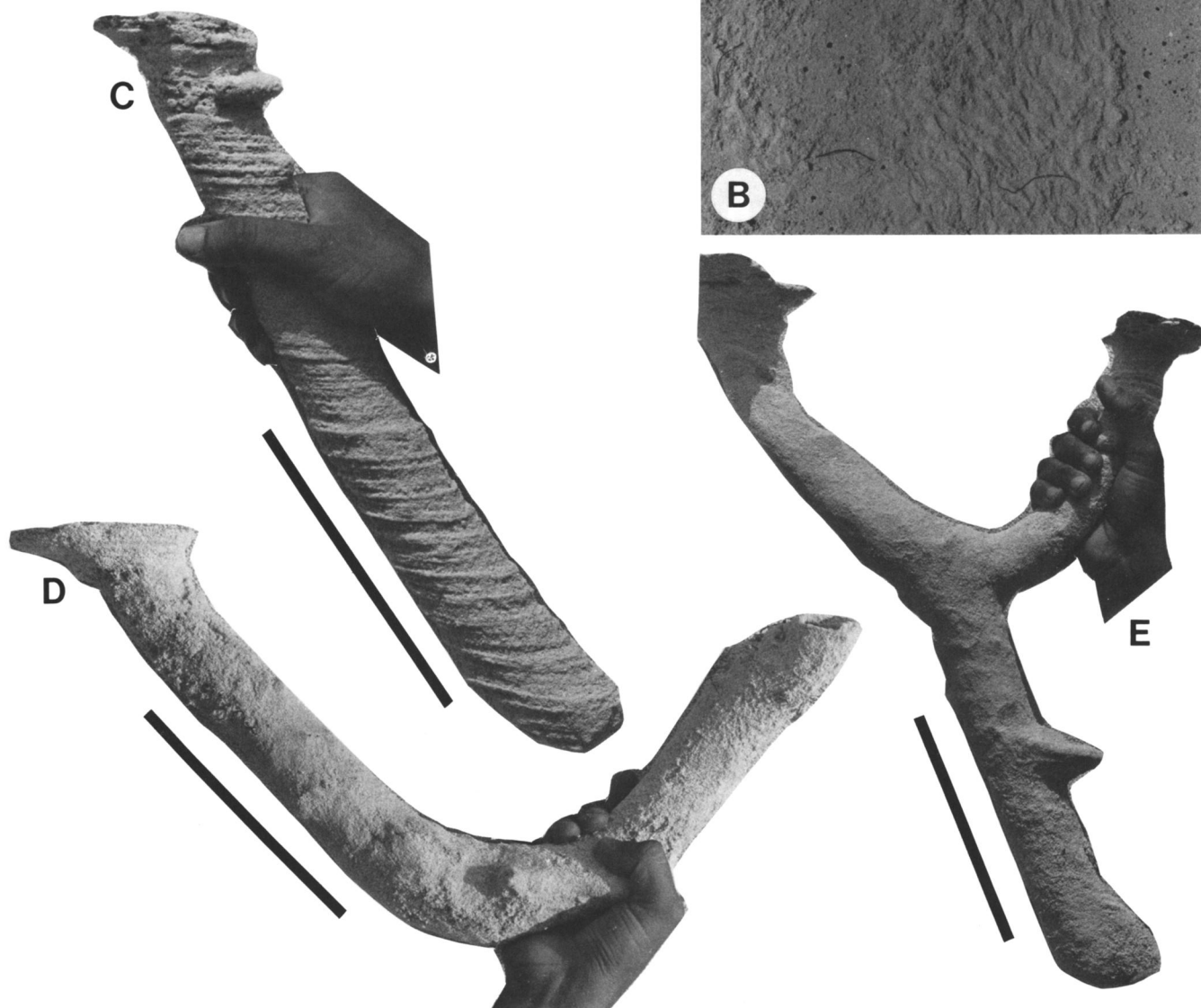
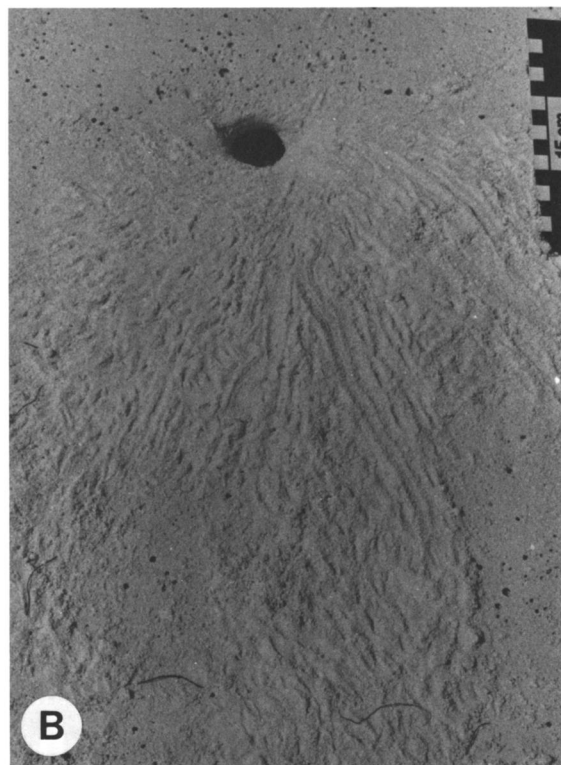
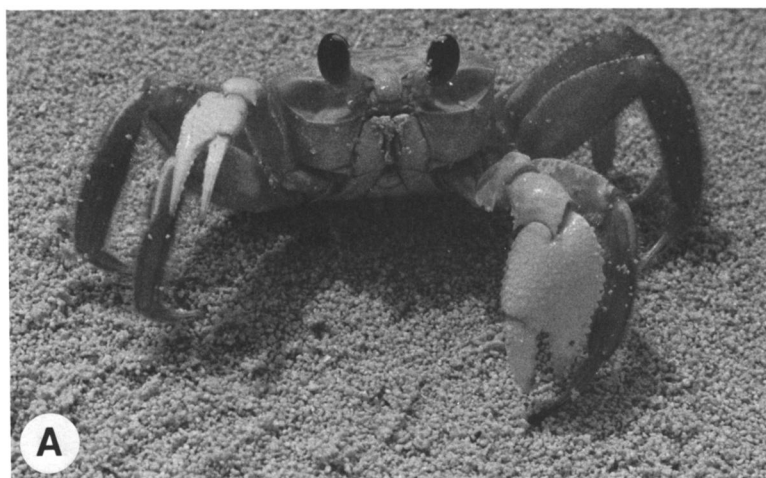
shafts (Fig. 7A) steeply inclined to bedding. The burrows typically are 2.5 to 4.5 cm in diameter, and up to 1.2 m or more in length (Curran, 1984; Frey et al., 1984; Curran and White, 1987). Commonly, specimens of *P. upsilon* occur as segments of shafts (Fig. 7B).

In addition to the Hanna Bay cliffs, *Psilonichnus upsilon* occurs in Holocene rocks of backshore to proto-dune origin in cliffs on Catto Cay and White Cay and to the south of Grotto Beach on San Salvador, in cliffs of Holocene rock on Lee Stocking Island, Bahamas, and in Pleistocene calcarenites of the Belmont Formation on Bermuda (Curran, 1990). In these settings, the well-documented relationship between *P. upsilon* and its tracemaker, *Ocypode quadrata* (Frey et al., 1984), makes the occurrence of the trace fossil particularly useful as a reliable indicator of backshore beds in Bahamian-style carbonate sequences. As such, *P. upsilon* can be used as an indicator of past sea-level position (Curran, 1990). Judging from the burrow casts of *O. ceratophthalma* figured by Braithwaite and Talbot (1972) and by Förster and Barthel (1978) from carbonate backshore beds in the Indo-Pacific, these burrows would be assigned to *P. upsilon* if fossilized, and they would have similar value as sea-level indicators. Indeed, the senior author recently found well-preserved *P. upsilon* specimens in Holocene beach rock on Heron Island, Australia, undoubtedly formed by *O. ceratophthalma*.

Y-shaped Plant Root Molds

External molds of large, commonly Y-shaped plant roots (Fig. 7C) easily could be confused with animal burrows. Such root molds commonly are prominent in proto-dune and dunal Bahamian calcarenites, preserved along bedding plane surfaces. Root molds are common in the Holocene rocks of the Hanna Bay Member of the Rice Bay Formation on San Salvador, and we have seen such structures in similar Holocene beds on other Bahamian islands. These molds have a variety of diameters and shapes. They differ from rhizomorphs in being smooth-sided and having no calichified tubular lining or core, as is characteristic of rhizomorphs.

Root molds as shown in Figure 7C are smooth-sided, can have multiple Y-shaped branches, and diameters of



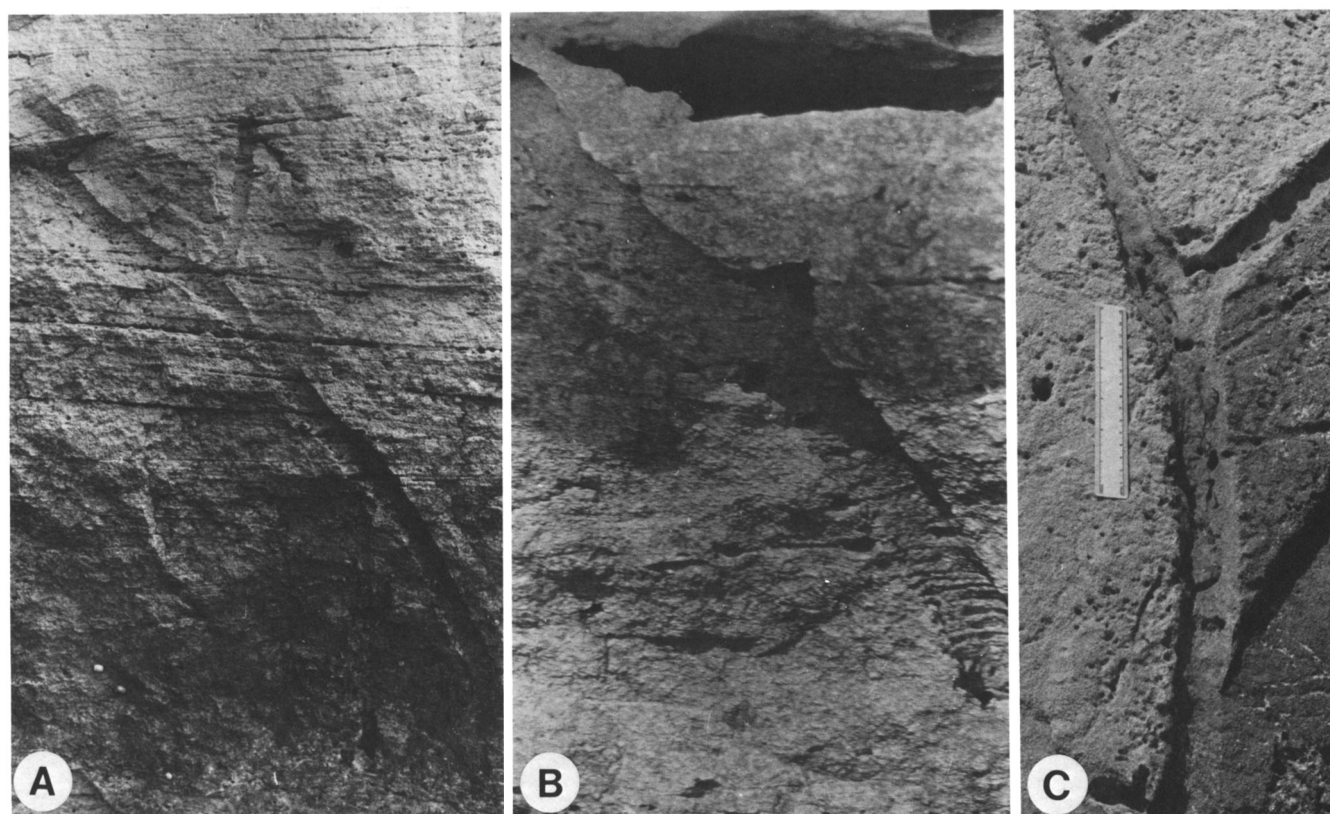


FIGURE 7—*Pylonichnus upsilon* in the Hanna Bay Member of the Rice Bay Formation (Holocene) on San Salvador. **A**) Large, well-preserved specimen of *P. upsilon* (this is the type specimen, see Frey et al., 1984); burrow diameter about 4 cm and burrow length = 1.2 m. **B**) Typical segment of a *P. upsilon* burrow; diameter of shaft = 2.5–3 cm. **C**) Fossil root mold with Y-shaped branching preserved along a bedding plane; scale = 15 cm.

about 1.5 to 6 cm. In the Hanna Bay section on San Salvador, root molds of this type are found in beds that overlap with the upper level of occurrence of *Pylonichnus upsilon*. Comparison of Figures 7A–C will show morphologic similarity between *P. upsilon* and the root mold form, but *P. upsilon* occurs always in vertical section whereas the root molds are found on horizontal bedding plane exposures and commonly show multiple branches.

The form of the root molds in Figure 4C shows close similarity with the roots of *Coccoloba uvifera*, the sea grape. This plant is a common inhabitant of modern proto-dunes and dunes on San Salvador (Smith, 1982). In the Hanna Bay cliffs, the initial presence of root molds may indicate the transition from backshore to proto-dune/dune conditions.

Dune Ichnocoenosis

Recent studies by Curran and White (1987) and White and Curran (1988) have shown that both plant and animal trace fossils are reasonably common in carbonate eolianites. A distinctive ichnocoenosis (Fig. 8) occurs in the Holocene eolianites of the North Point Member of the Rice Bay Formation on San Salvador. Nonetheless, the interpretive value of the trace fossils of the dunal ichnocoenosis is in part limited by the lack of knowledge about trace-maker organisms that inhabit modern carbonate dunes. Ahlbrandt et al. (1978), Ekdale et al. (1984), and Ekdale and Picard (1985) have compiled useful tables listing animals that form traces and trace fossils in dunal environments. However, the effects of animals on and within coast-

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FIGURE 6—**A**) The beach-dwelling ghost crab *Ocypode quadrata* (Fabricus). **B**) Typical ghost crab burrow opening on a Bahamian beach. **C–E**) Resin casts of typical ghost crab burrow forms; bar scales = 15 cm; **C**) steeply inclined shaft; **D**) U-shaped form; **E**) Y-shaped form.

ICHNOCOENOSIS:

1. Cluster burrow
2. Small, irregular burrow
3. *SKOLITHOS LINEARIS*
4. Rhizomorphs

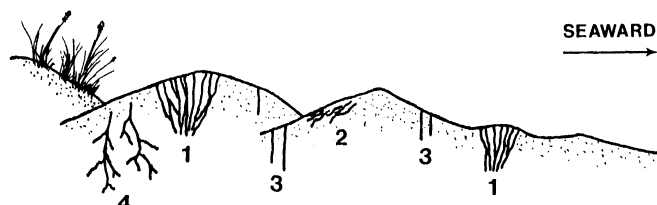


FIGURE 8—Model ichnocoenosis of the dunal zone.

al dune complexes, and particularly carbonate dunes, have received little attention. The modern and Holocene/Pleistocene carbonate dune ichnocoenosis clearly belongs in the *Psilonichnus* ichnofacies (Frey and Pemberton, 1987). The fact that *P. upsilon* is not present in the ichnocoenosis reflects differences between the tropical, carbonate coastal dune setting and temperate, siliciclastic coastal dune conditions.

Skolithos linearis

Skolithos linearis (Fig. 9C, D) can be common in carbonate eolianites, as in the Holocene beds of the Hanna Bay Member (Curran and White, 1987) and, to a lesser extent, in beds of the North Point Member (White and Curran, 1988) of the Rice Bay Formation on San Salvador. These burrows are lined, unbranched shafts, vertical to near vertically oriented, and most commonly 2–4 mm in diameter. Individual specimens can be up to 30 cm long; most specimens are considerably shorter, but the full length of the original tube normally is not preserved. We have observed similar *S. linearis* burrows in Holocene carbonate eolianites in the Yucatan, Mexico, and in Pleistocene eolianites on Sand Cay, Turks and Caicos.

The *Skolithos* tube, most commonly functioning as a dwelling burrow, undoubtedly has been constructed by many different types of invertebrates through its long geologic history (late Precambrian to Recent). The ichnogenus is one of the most typical representatives of the *Skolithos* ichnofacies, which is characteristic of shifting substrates of lower intertidal to shallow subtidal environments (Frey and Pemberton, 1984). Nonetheless, *Skolithos* is known to have a much broader range of environmental occurrence, from floodplain deposits (Ratcliffe and Fagerstrom, 1980) to deep-sea fans (Crimes, 1977). More recently, Frey and Pemberton (1987) reported a variety of *Skolithos*-forming tracemakers from the modern backshore, washover fan, and dune zones of the Georgia coast. Modern burrows of *Skolithos* form, constructed by insects and by arachnids, also were reported as being common by Ahlbrandt et al. (1978) in siliciclastic inland dune fields. Our observations extend the already wide range of *Skolithos* to the carbon-

ate coastal dune environment. By comparison with burrows in modern carbonate dunes on San Salvador and elsewhere, we suggest that the tracemakers were insects or arachnids, or both. The insect/arachnid ichnocoenosis merits considerable further study in this environmental setting.

Cluster Burrows

The largest, most complex, and most distinctive trace fossil found in the Holocene rocks of the Rice Bay Formation consists of a cluster of shafts radiating upward from a common area of origin (Fig. 9A). This trace fossil previously has been referred to by the informal name "cluster burrow" (Curran and White, 1987; White and Curran, 1988). Although the specimen shown in Figure 9A is the largest and best preserved one that we have seen to date, over fifteen other, similar trace fossils, all smaller in overall size, have been observed and measured in the eolianites of the Rice Bay Formation on San Salvador. Recently, Curran and Dill (1990) discovered the cluster burrow in Pleistocene eolianites within a submarine cave on Norman's Pond Cay of the Exuma Cays, and similar forms have been reported from Holocene eolianites on Lee Stocking Island, the Exuma Cays, and from Pleistocene eolianites on New Providence Island (P. Kindler, pers. comm.).

The cluster burrow trace fossil consists of numerous, straight to gently curved, unlined shafts (Fig. 9A). Individual shaft diameters range from 1 to 2 cm (average 1.2 to 1.4 cm); the shafts are closely packed in cross-section (Fig. 9B), and they can be 1.4 m or more in length. In some cases shaft diameters narrow slightly towards their upper ends. A few of the shafts branch upwards, and definite crossovers occur. Each trace fossil consists of a cluster of tens to hundreds of individual shafts that radiate upward from an approximately common point or area of origin, creating a cone-shaped structure that may reach a diameter of 1 m or more.

Curran and White (1987) interpreted this trace fossil as representing the brooding and hatching activities of a species of burrowing (digger) wasp of the Family Sphecidae, with each shaft representing the escape pathway of a young wasp as it made its way to the sediment surface. The sedimentologic setting for the specimens illustrated herein was described in detail by White and Curran (1988).

Small, Irregular Burrows

The most abundant animal trace fossil in the Rice Bay Formation, particularly common in the windward cliff exposures of the North Point Member at North Point and Cut Cay on San Salvador, consists of small, irregular burrows. These are best seen on the upper surfaces of the strata (Fig. 9E), where they are revealed as irregularly meandering burrows having a uniform diameter of 3 to 4 mm along their length, which commonly exceeds 20 cm. The burrows consist of an outer wall that is noticeably paler than the enclosing sediments, and a sediment fill that is like the enclosing matrix. No branching was ob-

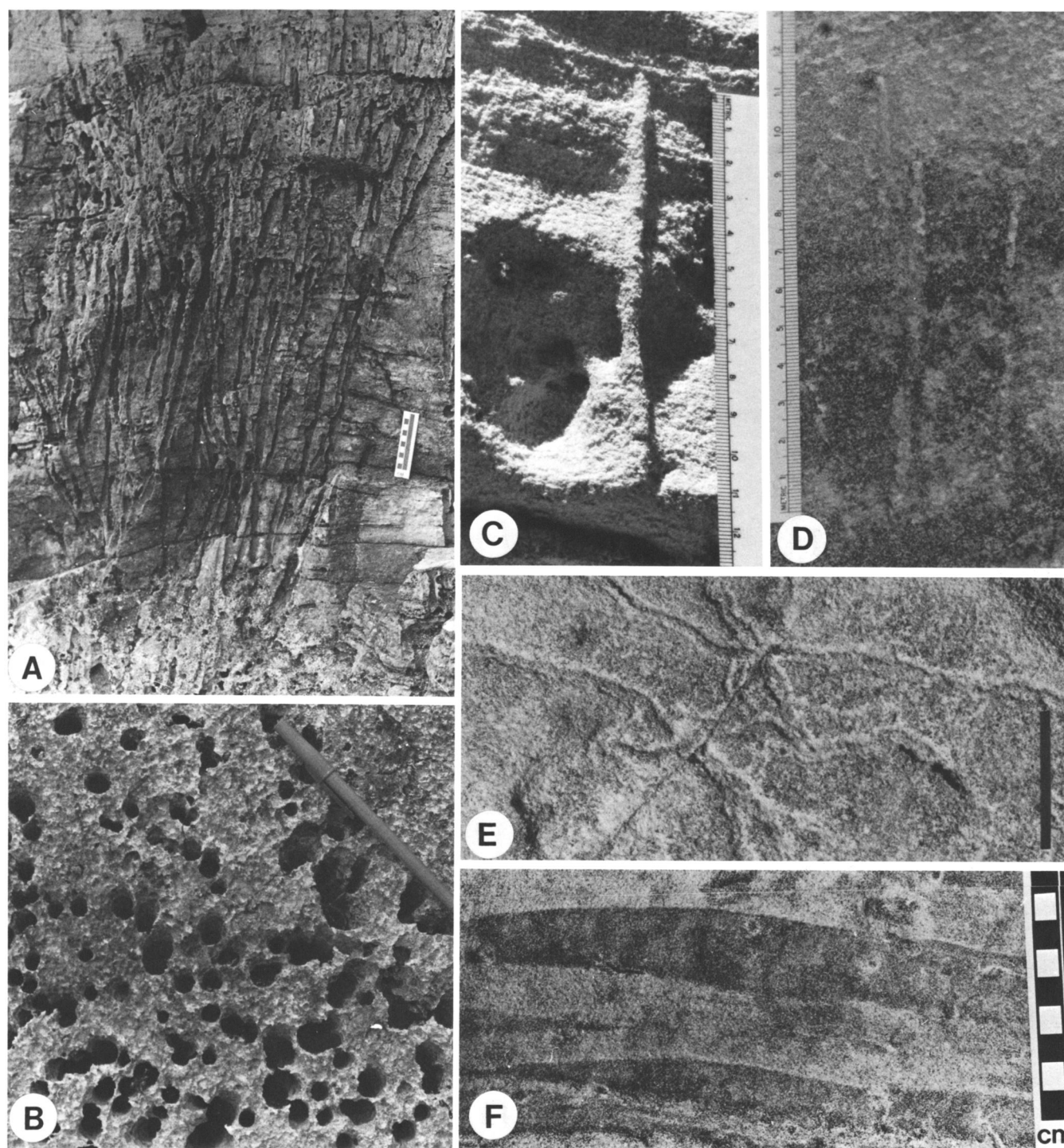


FIGURE 9—Trace fossils in the Rice Bay Formation (Holocene) on San Salvador. **A)** Large cluster burrow in vertical dune face, North Point Member; scale = 10 cm. **B)** Openings of cluster burrow shafts on a horizontal surface, North Point Member; pen = 15 cm. **C, D)** *Skolithos linearis* specimens, Hanna Bay Member. **E)** Small, irregular burrows on upper surface of sandflow strata, showing meandering form and crossovers; North Point Member, bar scale = 2 cm. **F)** Vertical surface of sandflow and grainfall layers showing mottling produced by organisms that formed the small, irregular burrow; North Point Member.

served, but crossovers occur commonly, giving rise to an appearance of a branching and radiate structure. The burrows are exposed most abundantly in vertical profile, where they can be seen to extend 2 to 3 cm into the strata, in some cases with sufficient density to cause burrow mottling



FIGURE 10—Upper surface of micrite crust showing plant trace fossils formed by the creeping, prostrate stems of dune plants. This crossover pattern is much like that of the bay geranium, *Ambrosia hispida*, North Point Member; lens cap = 5.5 cm.

of the sediments (Fig. 9F). These trace fossils have been found only in grainfall and sandflow strata of the North Point Member (White and Curran, 1988). We interpret this to indicate that the tracemakers preferred the shelter of dune lee slopes.

Frey and Pemberton (1987, fig. 21) reported burrows attributed to mole crickets on the surfaces of modern siliclastic sand dunes of the Georgia coast that are similar in their surface pattern to the Bahamian small, irregular burrows. Although it is probable that these fossil burrows were made by insects (either adults or larvae), specific identifications of burrowing insects inhabiting the surfaces of modern Bahamian dunes have not yet been made. However, we have observed a preferential distribution of insects burrowing on the protected lee sides of modern carbonate dunes, as is the case for the distribution of the fossil burrows.

Plant Trace Fossils

In sections of the eolianite outcrops of the North Point Member at North Point on San Salvador, very thin, hard micritic crusts cap bedding planes at intervals of approximately every 10 to 15 cm (White and Curran, 1988, fig. 10). On vertical faces these crusts stand out as thin, resistant layers, whereas their upper surfaces commonly bear plant trace fossils occurring as narrow micritic ridges up to 1 cm high (Fig. 10). Analogous crusts and ridges commonly occur on modern dune surfaces in the Bahamas, and their mode of formation was discussed by White and Curran (1988). Plant trace fossils associated with the mi-

SHALLOW SUBTIDAL — BEACH — DUNE TRANSITION

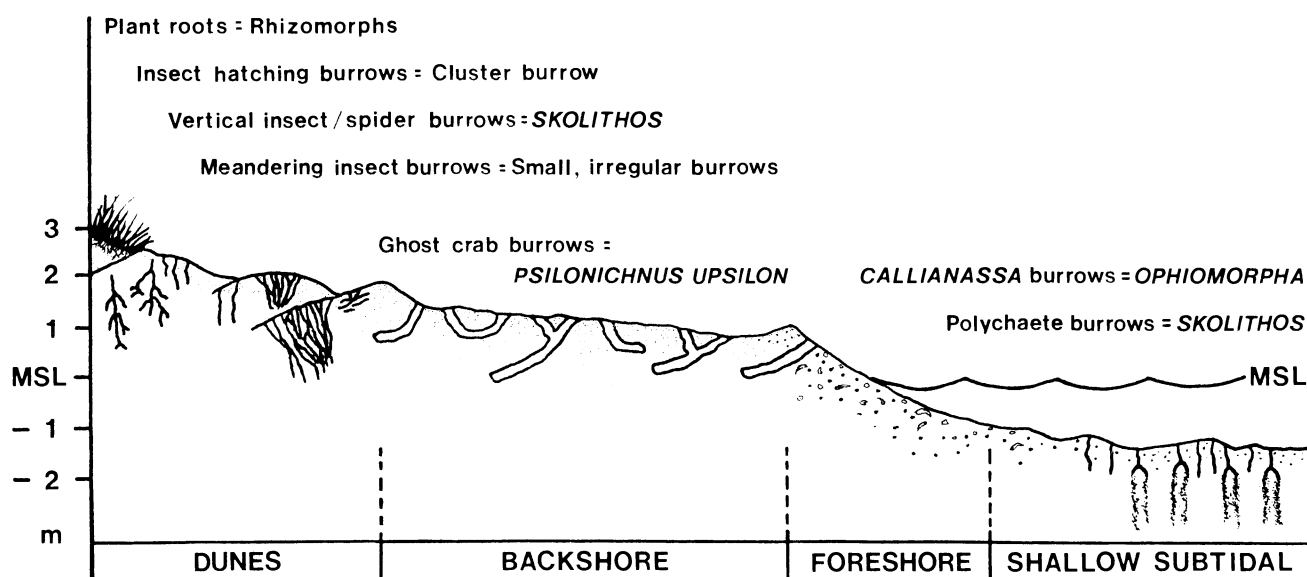


FIGURE 11—Ichnologic model for Bahamian calcarenites showing ichnocoenoses in the transition across an open coast from shallow subtidal to dunal environments.

crite crusts represent the creeping, prostrate stems and branches characteristic of railroad vines (*Ipomoea pes-caprae*) and bay geraniums (*Ambrosia hispida*) that extend, commonly for several meters, across the surfaces of the modern carbonate dunes.

As stated earlier, the presence of rhizomorphs in a Bahamian carbonate rock does not necessarily mean that the encompassing sediments were deposited in a terrestrial environment, only that the strata were subaerially exposed at some time during or after deposition. However, the preservation of plant trace fossils on and in horizontal micritic crusts, as in the North Point Member rocks, does indicate contemporaneous occurrence within a dunal environment. Such trace fossils provide a specific criterion for the recognition of eolian deposition and the past presence of vegetated surfaces.

CONCLUSIONS

Three distinctive ichnocoenoses, characteristic of the shallow subtidal, upper foreshore-backshore, and dunal environments, respectively, can be recognized in the Pleistocene and Holocene calcarenites and in the modern carbonate sands of Bahamian islands. The transition occurs from sands associated with coral reefs on the open shelf to windward or leeward coast beaches to coastal dunes (Fig. 11). Specific conclusions concerning the ichnocoenoses and their significance are as follows:

1. Calcarenites deposited in open shelf, shallow subtidal environments, commonly associated with coral reefs and reefal debris, are characterized by an *Ophiomorpha-Skolithos linearis* ichnocoenosis of the *Skolithos* ichnofacies. *Ophiomorpha* shafts and tunnels can be found even within very coarse coral reef debris (coral rubblestones). The modern callianassid tracemakers of *Ophiomorpha* normally are not found burrowed in the beach foreshore and usually are in waters deeper than one meter, seaward of the surf zone. By analogy, the occurrence of *Ophiomorpha* in Pleistocene subtidal calcarenites of the Bahamas probably indicates minimum water depths of one meter, with a maximum depth being the shelf-slope break (normally 10 to 15 m in the Bahamas).

2. Rocks of the upper foreshore-backshore zone are characterized by an ichnocoenosis dominated by *Pylonichnus upsilon* and assigned to the *Pylonichnus* ichnofacies. The burrow-tracemaker relationship between *P. upsilon* and the ghost crab *Ocypode quadrata* is well established. Because *O. quadrata* is known to confine its burrows principally to the upper foreshore-backshore zone on modern Bahamian beaches, the occurrence of *P. upsilon* in Holocene and Pleistocene calcarenites of the Bahamas and geologically similar areas is a strong indicator of backshore deposits. As such, this trace fossil has the potential to be highly useful in the determination of past sea-level positions.

3. The dunal ichnocoenosis, also assigned to the *Pylonichnus* ichnofacies, is distinctive and is the most diverse of the three ichnocoenoses. *Skolithos linearis* can be common in proto-dunes and dunal deposits of the Bahamas.

This occurrence represents an environmental range extension for this now near ubiquitous trace fossil. *S. linearis* is not diagnostic of an eolian environment per se, but its presence in ancient carbonates should not be used to exclude the possibility of eolian deposition.

The large cluster burrow trace fossils found in eolianites of the Bahamas are unique and quite unlike any other described trace fossil. They are interpreted as having been formed by the hatchlings of a species of digger wasp, as the matured hatchlings migrated to the surface. These trace fossils are confined to the dune environment, and they may well prove to be diagnostic of eolian sedimentation. The small, irregular burrows found in Holocene eolianites on San Salvador probably are not sufficiently distinct morphologically to be regarded as unique to the dunal environment. However, these trace fossils are restricted to sandflow and rainfall strata of the protected, lee-side of dunes, and their presence may aid in reconstructing ancient dune patterns.

4. Root molds and plant trace fossils that occur along proto-dune and dunal bedding planes can have distinctive forms that may be related to modern plant analogs. With further study, these root mold forms and plant trace fossils may prove useful in defining subzones within calcarenites formed in the proto-dune to dune environment.

5. Ichnocoenoses in Bahamian calcarenites can be useful in delineating past environments of deposition and conditions therein and in determining past sea-level positions. Similar ichnocoenoses with corresponding utility undoubtedly are present in the calcarenites of other islands of the Bahamas beyond our areas of study, and they likewise probably occur in other, geologically similar, tropical carbonate settings around the world.

ACKNOWLEDGMENTS

We thank the directors and staff of the Bahamian Field Station for full logistical support of our field work on San Salvador Island. Jimmy Nixon, representative for the Bahamas National Trust, assisted us on Great Inagua Island. Helpful criticism and reviews of our original manuscript were provided by Robert W. Frey (University of Georgia) and two anonymous reviewers. Kathy Bartus performed word processing for the manuscript with skill and patience, and Denise Descoteau did the figure drafting. The Petroleum Research Fund (American Chemical Society) partially supported this research through separate grants to Curran and to White.

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ACCEPTED MAY 20, 1991

