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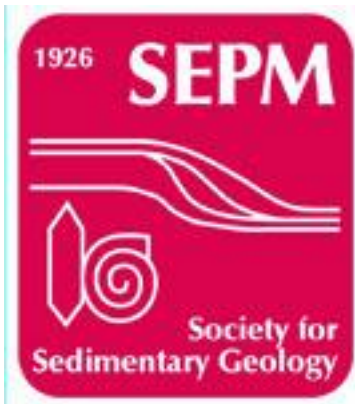
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## ICHTHOLOGY OF PLEISTOCENE CARBONATES ON SAN SALVADOR, BAHAMAS

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**ABSTRACT**—Trace fossils, well preserved and in full relief, are present in Pleistocene calcarenites of subtidal, beach, and dune facies on San Salvador, Bahamas. Most prominent are irregular boxworks of *Ophiomorpha* sp. that occur in current-bedded, medium to coarse skeletal calcarenites in association with fossil coral reefs in the subtidal facies. *Ophiomorpha* sp. also occurs in beds deposited in a tidal delta environment. Found with *Ophiomorpha* sp., often in abundance, are vertical burrow tubes assigned to *Skolithos linearis*. Trace fossils are absent from beds of the lower beach facies, but upper beach facies beds (backshore zone) contain distinctive Y-shaped crab burrows, attributed to the burrowing activity of the ghost crab *Ocyropode quadrata*. Rhizocretions formed of calcrete and initiated by plant root systems are present in all facies and are particularly well developed in eolianites of the dune facies. In some cases rhizocretions easily can be confused with trace fossils of invertebrate origin, particularly *Ophiomorpha* sp. Criteria for distinguishing *Ophiomorpha* sp. from rhizocretions include: 1) *Ophiomorpha* sp. burrows have a uniform lining and consistent diameter; rhizocretions are irregular with respect to lining and diameter. 2) The interior surface of an *Ophiomorpha* sp. burrow is smooth and the exterior surface distinctly mammillated; rhizocretions have highly variable interior and exterior surfaces. 3) *Ophiomorpha* sp. complexes have much more consistent patterns of shaft/tunnel arrangement than those exhibited by rhizocretion systems. Modern carbonate environments of San Salvador exhibit much trace-making activity and contain analogs for the Pleistocene trace fossils. The implications of these analogs for further interpretation of the trace fossils and their associated paleoenvironments are examined with respect to each trace fossil.

### INTRODUCTION

SEDIMENTOLOGISTS have studied modern shallow-water carbonate environments of the Florida Keys and Bahamas intensively over the past two decades, but the literature on biogenic sedimentary structures in these carbonates is surprisingly sparse and little or no mention is made of trace fossils in Pleistocene carbonates of the region. Shinn's 1968 paper on "Burrowing in Recent Lime Sediments of Florida and the Bahamas" remains as the principal reference to biogenic structures in modern carbonates, well supplemented by the work of Garrett (1977) on bioturbation effects. Furthermore, while tracemaking organisms are numerous in carbonate environments, it is widely held that trace fossils are better preserved and best studied in clastic settings (Basan, 1978). This owes principally to the idea that trace fossils are generally difficult to recognize in carbonate rocks because of diagenetic modification after trace formation. However, this certainly is not always the case as the present example clearly demonstrates. Trace fossils are often common and well preserved in the Pleisto-

cene carbonate rocks of San Salvador, Bahamas.

The primary purposes of this paper are: 1) to describe the principal trace fossils that occur in carbonates on San Salvador; and 2) to demonstrate how these trace fossils can be used in concert with texture, physical sedimentary structures, and stratigraphic position to define and characterize the various carbonate lithofacies in this and similar settings. Since these Pleistocene lithofacies are all thought to be less than 200,000 years old (Carew, 1983), it seems certain that modern tracemaker organism analogs for the trace fossils are active today in the depositional environments of the island. Where possible, these tracemaker organisms will be identified and discussed along with the trace fossils.

### THE GEOLOGIC SETTING

San Salvador is one of the easternmost Bahamian islands, lying beyond the main part of the Bahamas platform, about 600 km ESE of Miami, Florida (Figure 1). The island is small ( $9.5 \times 17$  km) and is bordered by a narrow shelf with an abrupt shelf-edge break

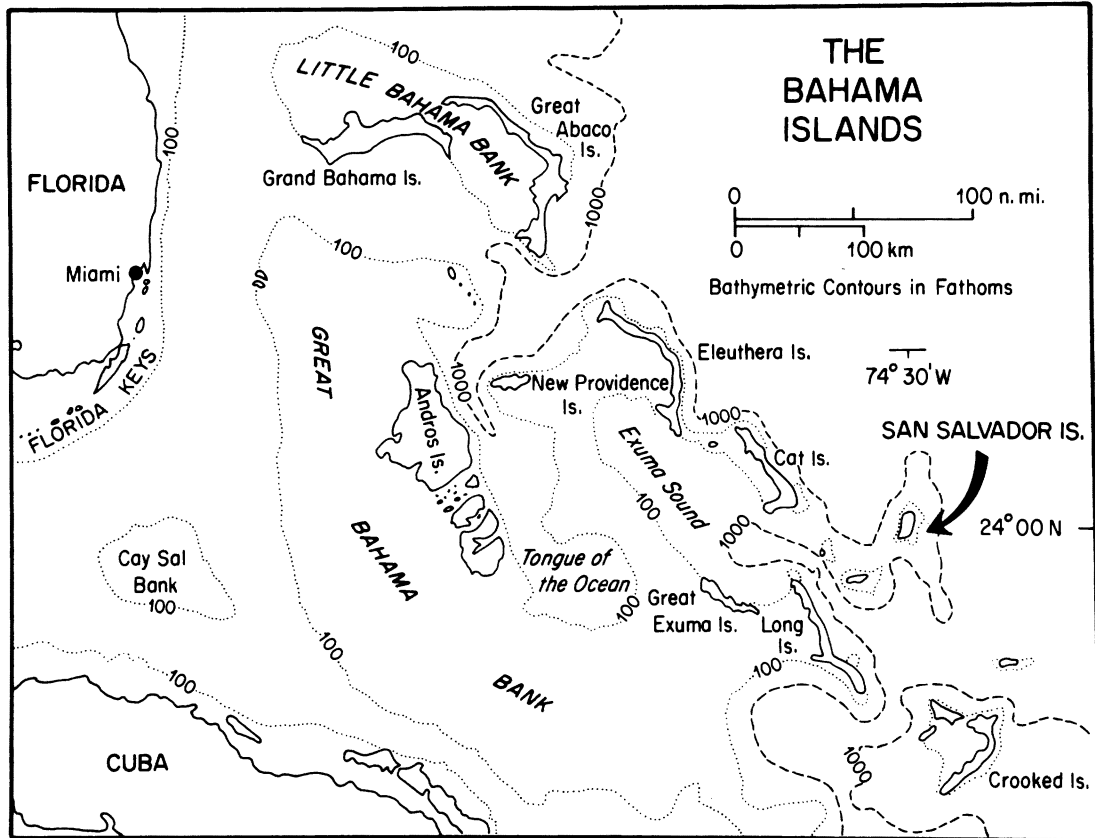


FIGURE 1—Index map to the Bahamas and San Salvador Island. Cockburn Town fossil reef exposure is on San Salvador's west coast, and the Pigeon Creek estuary is at the southeast corner of the island.

leading to a very steep continental slope. The topography of the island is dominated by arcuate hills interpreted as representing successive stages of carbonate eolian ridge accretion (Adams, 1981); shallow lakes occupy the low inter-dune areas. The island's shoreline is characterized by cliffed headlands of eroded eolianite; fine- to medium-grained carbonate sands form beaches between headlands, and Holocene beachrock is common.

Natural rock outcrops are largely confined to the coastal areas of the island. A dense vegetation cover restricts access to the island's interior, a karst surface with calcrete or caliche crusts, red soils, and solution phenomena that further obscure characteristics of the underlying rock. Road cuts and several quarries along the island's coastal highway provide good exposures for study, supplementing information from the coastal out-

crops. All localities referred to in this report are indexed and described in a field guide to San Salvador compiled by Gerace (1981) and in Curran (1983).

No formal stratigraphic column for the Quaternary rocks of San Salvador has been established, but Titus (1981) has proposed that these rocks can be subdivided into two formations, each consisting of a fining-upward sequence of subtidal, beach, and dune facies. Titus (1983) interprets each sequence as representing sedimentation during an interglacial-glacial onset event, with the sequences separated by a major unconformity. Regardless of formational assignment, rocks of a given facies are similar across the island; the general characteristics of each facies are described below.

*Subtidal facies.*—Medium- to very coarse-grained, cross-stratified calcarenites. Com-

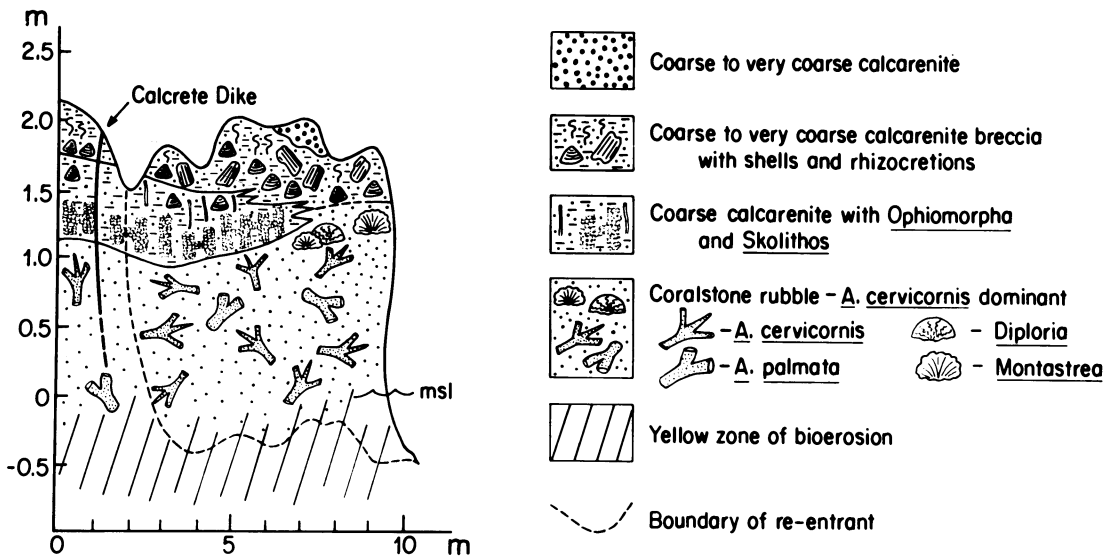


FIGURE 2—Stratigraphic column located at a small coastal re-entrant at the Cockburn Town fossil reef exposure. *Ophiomorpha* and *Skolithos*-bearing calcarenite beds overlie and interfinger with beds of coralstone rubble.

mon fossil components include mollusk shells and shell fragments, foraminifera, fragments of calcareous algae, and coral clasts. Small, well-preserved coral patch reefs occur in the subtidal facies at several locations on the island, and an extensive fringing reef complex is preserved along the island's west coast, just north of Cockburn Town, the largest village on the island. Subfacies of this reef complex have been described briefly by Moshier et al. (1979). This is the location of the best exposure of *Ophiomorpha*-bearing beds, and a stratigraphic column for this locality is presented in Figure 2.

**Beach facies.**—Overlying exposures of the subtidal facies are medium- to fine-grained, gently seaward dipping, thin-bedded calcarenites. Fossil fragments are normally small and polished. At some exposures these beds grade upward into beds of the dune facies.

**Dune facies.**—Fine- to very fine-grained

calcarenites with small- to large-scale cross stratification. Shells of the land snail *Cerion* occur in these beds, and rhizcretions often are abundant. Rocks of this facies cap most of the island.

#### SYSTEMATIC ICHNOLOGY

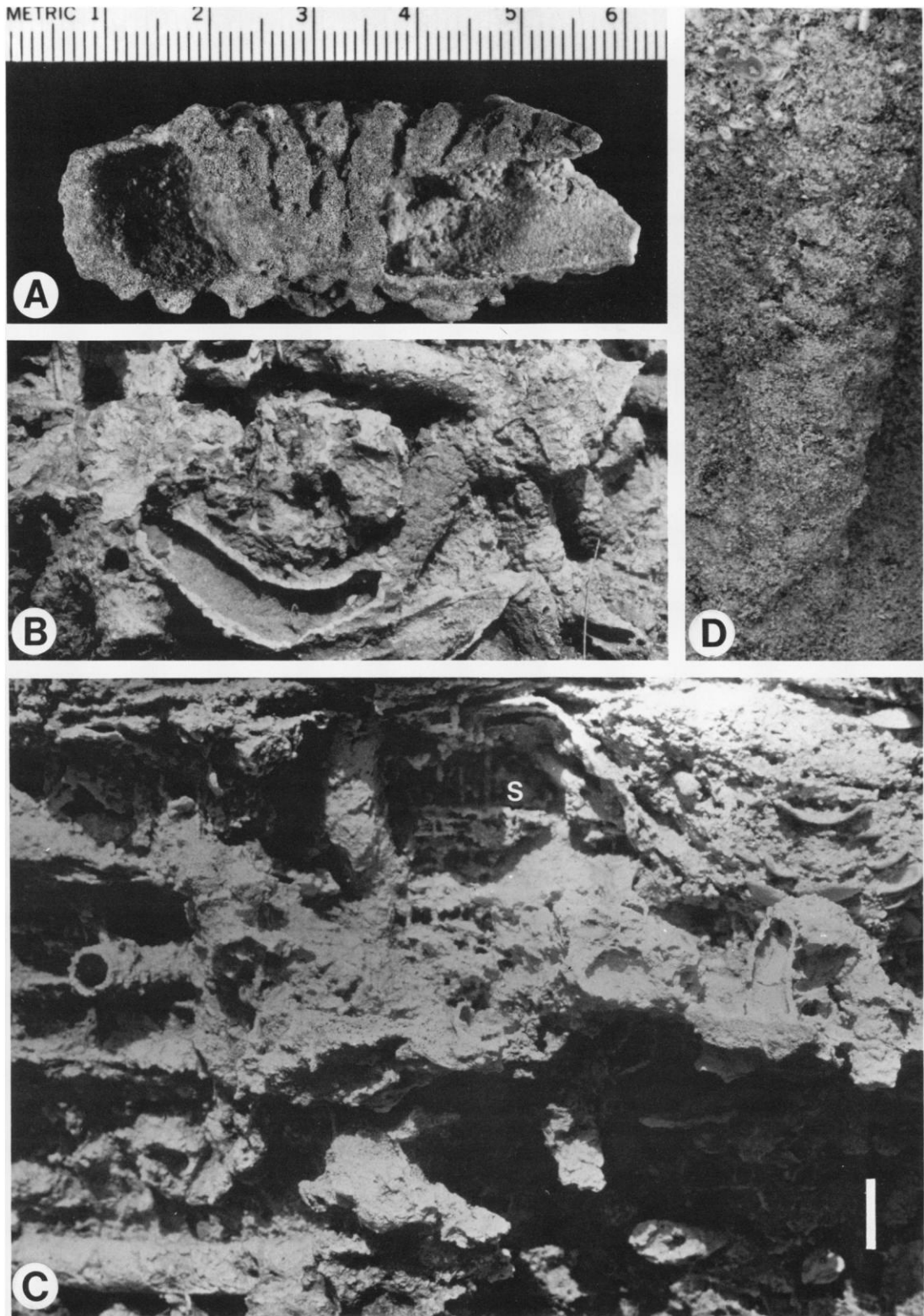
Ichnogenus OPHIOMORPHA Lundgren, 1891

OPHIOMORPHA sp.

Figure 3A–D

**Description.**—Branched burrow systems preserved in full relief and consisting of shafts and horizontal to gently inclined or curved tunnels. Burrow tubes have thick walls (2–3 mm) formed of micritic material with smooth interior surfaces and distinctly mammillated to irregularly rugose exterior surfaces. Tubes have outside diameters of 1–2.5 cm, and individual shaft or tunnel segments can be measured for lengths of up to 25 cm. Burrows normally filled with sediment like that of the

FIGURE 3—A, close-up of *Ophiomorpha* sp. tube showing mammillated to rugose exterior surface. B, *Ophiomorpha* sp. in outcrop; broken tube wall shows smooth interior surface. Tube diameter = 2 cm. C, vertical exposure reveals numerous *Ophiomorpha* sp. shafts and tunnels and tubes of *Skolithos linearis* (=S); bar scale is 4 cm long. A–C from Cockburn Town fossil reef locality. D, *Ophiomorpha* sp. shaft in coarse, poorly lithified, tabular cross-stratified calcarenites at the Pigeon Creek quarry. Shaft is 2 cm in diameter.



surrounding matrix, but unfilled tube segments are not uncommon.

*Occurrence.*—*Ophiomorpha* sp. is found only in the subtidal facies on San Salvador. The most abundant occurrence is in medium- to coarse-grained, skeletal calcarenites that overlie and interfinger with coralstone facies of the fossil reef complex exposed along the coast about 100 m north of the Cockburn Town dock (Figures 2, 3A–C). Here *Ophiomorpha* sp. occurs in an irregular boxwork configuration of interconnecting shafts and tunnels, similar to that described by Frey, Howard and Pryor (1978, fig. 2E). These *Ophiomorpha*-bearing beds have been dated by amino acid racemization techniques as being between 120,000 to 140,000 years old (Carew, 1983).

Specimens of *Ophiomorpha* sp. (Figure 3D) also are present in tabular cross-stratified, *Halimeda*-rich, coarse-grained calcarenites of subtidal facies exposed in the principal wall of a small quarry just north of the Pigeon Creek estuary, located near the southeast corner of the island. These beds are interpreted as having been deposited in a Pleistocene tidal delta setting similar to the modern tidal delta seaward of the mouth of Pigeon Creek (Thalman and Teeter, 1983). Here, *Ophiomorpha* sp. is present in the form of well-developed but somewhat isolated shafts; connecting tunnels are less common and conspicuous than at the Cockburn Town reef exposure.

*Discussion.*—*Ophiomorpha* sp. specimens on San Salvador exhibit an obviously pelleted to rugose exterior wall surface (Figure 3A, D), but the pattern of pellet arrangement is not nearly as regular and distinct as that found in specimens of the ichnospecies *O. nodosa* (single-pellet wall) or *O. borneensis* (double-pellet wall; see Frey, Howard and Pryor, 1978, fig. 1) preserved in siliciclastic sediments. For this reason, I have not assigned the San Salvador specimens to an ichnospecies. The *Ophiomorpha* sp. specimens may represent a new ichnospecies by virtue of their often irregularly rugose outer wall structure, or it may be that the rugosity of the wall is a diagenetic effect. Further study of the range and causes of morphologic variation in *Ophiomorpha* sp. specimens in carbonate settings is needed before this taxonomic question can be answered.

Occurring commonly with *Ophiomorpha* sp. are branching rhizocretion structures formed of calcrite and presumably initiated by the action of plant roots (Figure 4B). Rhizocretions can be easily mistaken for trace fossils of invertebrate origin, particularly *Ophiomorpha* sp., and care must be taken in differentiating the two types of structures.

Criteria for distinguishing *Ophiomorpha* sp. from rhizocretions include: 1) *Ophiomorpha* sp. has a uniform and distinct lining of regular thickness, and individual segments of the burrow system have consistent diameter; rhizocretions do not have a uniform lining and are irregular in diameter. 2) The interior surface of *Ophiomorpha* sp. is smooth and the exterior surface distinctly mammillated to rugose; rhizocretions have highly variable interior and exterior surfaces, with many rhizocretions being solid or with a small-diameter, tubular interior. 3) Although somewhat irregular, *Ophiomorpha* sp. complexes have more consistent patterns of shaft/tunnel arrangement and branching than those exhibited by rhizocretion systems.

A further identification problem can occur when *Ophiomorpha* sp. is in close association with coral-bearing beds such as at the Cockburn Town reef exposure on San Salvador. Here, fossilized branches of the coral *Acropora cervicornis* also easily can be confused with *Ophiomorpha* sp. because the diameter of the coral branches is similar, the exterior surface of the coral becomes bumpy as the cups of the polyps wear, and the Y-shaped branching of the coral resembles superficially the branching of *Ophiomorpha* sp. However, comparison of *A. cervicornis* and *Ophiomorpha* sp. in cross section will reveal that *A. cervicornis* specimens are composed of solid calcium carbonate with crystals radiating from the center; if weathering has occurred, a small-diameter tubule may be present. *Ophiomorpha* sp. tubes normally are filled with calcarenite matrix, and the presence of the micritic wall is obvious in cross section. Furthermore, close examination will show that the pelleted exterior surface of *Ophiomorpha* sp. is quite different from the polyp-bearing surface of *A. cervicornis*.

*Modern tracemaker analog.*—One of the best documented modern tracemaker-trace fossil relationships is the ghost shrimp *Callinassa major* as the maker of *Ophiomorpha*

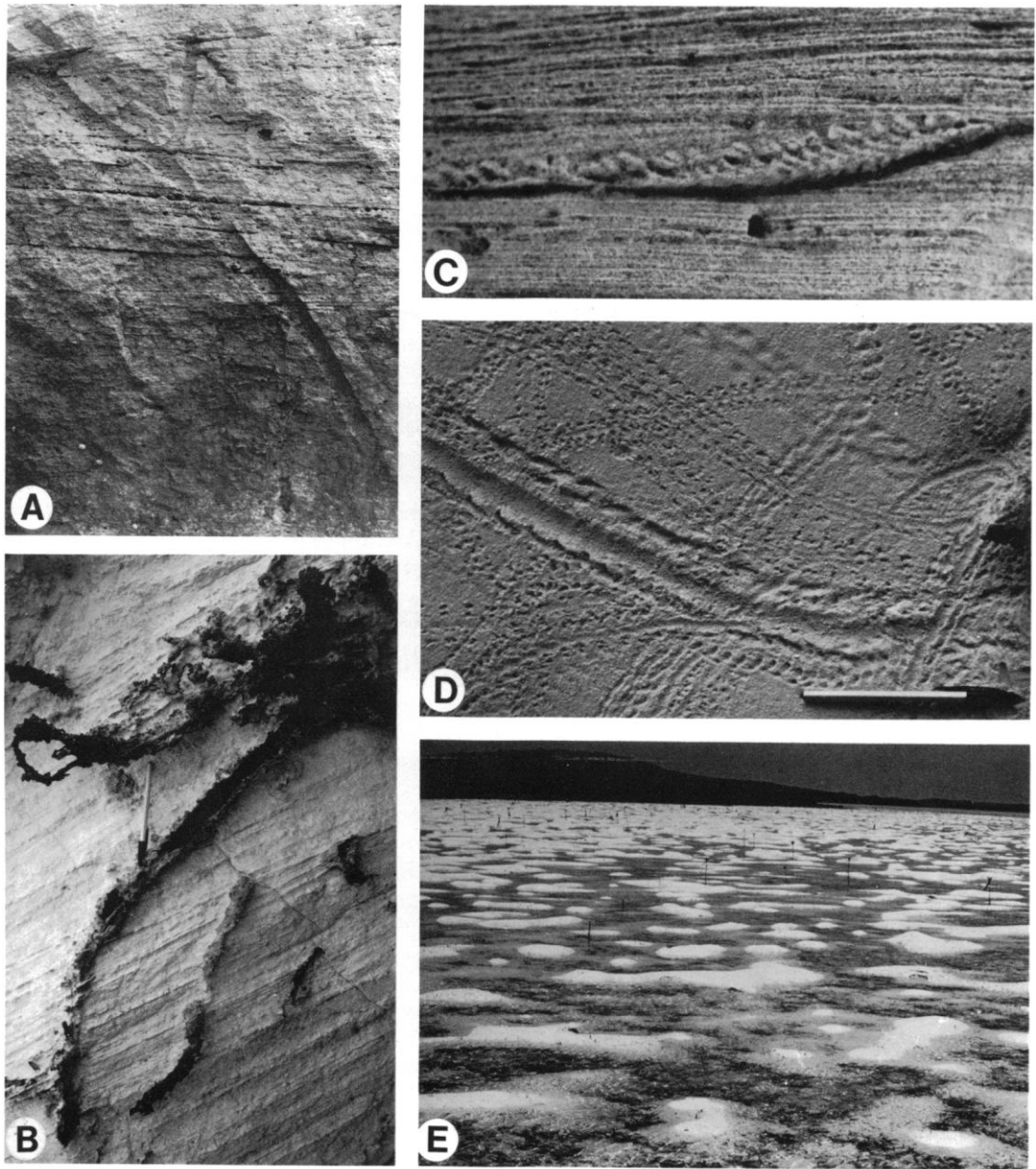


FIGURE 4—*A*, Y-shaped crab burrow in upper beach facies calcarenites. Burrow shaft is 1.2 m long. *B*, rhizocretions in eolianite beds. Note superficial resemblance of rhizocretion branching pattern to *Ophiomorpha* sp. shaft and tunnel systems; pen is 15 cm long. *C*, crab trackway (?) in upper beach facies calcarenites. Structure is 15 cm long. *D*, trackways of modern crabs on carbonate sands of a backshore zone; pen is 15 cm long. *E*, sediment “volcanoes” formed by callianassid shrimp exposed at spring low tide, mid-reach of Pigeon Creek estuary. Mounds are about one meter in diameter.



*nodosa* burrow systems (Weimer and Hoyt, 1964); but, as Frey, Howard and Pryor (1978) pointed out, caution is required even with this example because *C. major* is only one of several known species of thalassinidean shrimp capable of constructing pelleted burrow walls. In the San Salvador example, the *Ophiomorpha* sp. systems preserved in Pleistocene subtidal calcarenites presumably were formed by fossorial callianassid shrimp. The author has observed numerous *Callianassa* sp. burrow openings while diving over shallow subtidal, rippled carbonate sand surfaces adjacent to patch and fringing reefs at numerous locations surrounding the island. Such openings normally do not have sediment mounds at their apices. The micritic walls of the burrows sometimes can be seen projecting up from ripple troughs where they have been exposed by shallow erosion. Plastic casts of these burrows have not been made (excavation of such casts in subtidal settings is difficult), but the modern burrow systems probably are very similar to the *Ophiomorpha* sp. systems preserved at the Cockburn Town fossil reef locality.

Shinn (1968) described modern *Callianassa* sp. burrow systems from intertidal carbonate mud flats and *Thalassia* grass beds of the Florida Keys and western Bahamas. This callianassid shrimp (species unidentified by Shinn) forms a large sediment "volcano" at the surface and has a highly distinctive burrow system of radiating tunnels connected to incurrent and excurrent shafts (Shinn, 1968, text-fig. 10). Similar sediment "volcanoes" can be found in *Thalassia* beds of the San Salvador area, and an extensive shallow subtidal to intertidal surface of such "volcanoes" is located along the mid-reach of the north arm of Pigeon Creek estuary (Figure 4E). Presumably burrow complexes formed by the *Callianassa* sp. of Shinn lie beneath the sediment surface, but plastic casts will need to be taken to confirm this. To date, *Ophiomorpha* sp. systems with a radiating tunnel system as illustrated by Shinn have not been found in the rock record on San Salvador or elsewhere.

The limiting factor at present in defining a firm tracemaker-trace fossil relationship for the *Ophiomorpha* sp. burrows on San Salvador is our incomplete knowledge of trop-

ical *Callianassa* species. There are many modern species of *Callianassa* occupying diverse marine habitats and ecologic niches. Biffar (1971) reported ten species of *Callianassa* from the South Florida area, nine of which range through various areas of the Bahamas and the Caribbean. However, little is known about the burrowing habits of these species. The *Callianassa* species occupying subtidal, current-rippled sand areas adjacent to reefs around San Salvador (and which presumably formed the *Ophiomorpha* sp. systems at the Cockburn Town reef exposure) probably is different from the species of *Callianassa* occupying the *Thalassia* grass beds and intertidal flats of the Pigeon Creek estuary. Systematic collection and identification of *Callianassa* specimens from the intertidal and shallow subtidal environments of San Salvador are needed to confirm these relationships.

Ichnogenus SKOLITHOS Haldeman, 1840

SKOLITHOS LINEARIS Haldeman, 1840

Figure 3C

*Description.*—A straight, unbranched shaft typically oriented perpendicular to bedding and essentially parallel to adjacent shafts. Burrow tubes have an outside diameter of less than 1 cm and lengths of up to 15 cm; tubes are formed of fine- to medium-sized carbonate sand grains that presumably originally adhered to the outer surface of a lined dwelling burrow.

*Occurrence.*—*Skolithos linearis* occurs in association with *Ophiomorpha* sp. and is found only in the subtidal facies on San Salvador. The most abundant occurrence is in the medium- to coarse-grained, skeletal calcarenites of the fossil reef complex at Cockburn Town (Figure 2).

*Discussion.*—Specimens of *Skolithos linearis* also potentially can be confused with rhizocretion structures. *S. linearis* specimens are straight shafts, unbranched, grain-lined, and of constant diameter, whereas rhizocretions have variable orientation, branch frequently, are unlined, and usually have variable diameters.

*Modern tracemaker analogs.*—As in siliclastic settings, many different modern polychaetes are likely tracemaker analogs for *Skolithos linearis* burrows (Curran and Frey,

1977). The author has collected *Skolithos*-like, grain-lined polychaete tubes from shallow subtidal, current-rippled carbonate sands surrounding patch reefs on the San Salvador shelf and in the vicinity of the Pigeon Creek tidal delta. Such tubes easily could be fossilized to form *Skolithos linearis* specimens. A survey of the infaunal polychaetes of the modern environments of San Salvador now is needed to identify more specific analogs for *Skolithos linearis*.

#### Y-SHAPED CRAB BURROWS

##### Figure 4A

*Description.*—Unbranched to Y-shaped, unlined burrows. Shafts are steeply inclined to bedding, typically 2.5 to 4.5 cm in diameter, and up to 1.2 m or more in length. Where branched, the angle of bifurcation is 65° to 80°; normally, one branch is slightly smaller in diameter than the other. Openings of branches at the ancient substrate surface are somewhat enlarged. Ends of burrows are not preserved; therefore, measured shaft lengths are less than the original lengths.

*Occurrence.*—Well-preserved Y-shaped crab burrow specimens occur rarely in medium- to fine-grained, planar cross-bedded calcarenites of upper beach to possibly lower dune facies on sea cliffs along the northeast (Atlantic-facing) coast of San Salvador. Fine-grained calcarenites of the dune facies immediately overlie beds bearing the Y-shaped crab burrows.

*Discussion.*—These Y-shaped crab burrows are formally named and described in the context of crab tracemaking activity elsewhere in this issue (Frey, Curran and Pemberton, 1984).

Segments of Y-shaped crab burrow shafts may be rather common at the locality cited above. Holes of the appropriate diameter can be located easily in the friable calcarenites of the sea cliff exposures. However, these beds also contain rhizocretions. The hard calcrete cores of large-diameter rhizocretion shafts can break out of the rock, leaving unlined, relatively straight shafts that are difficult to distinguish from crab burrow segments. The Y-shaped branching pattern thus is the key to positive identification of the burrow, but the juncture in many cases is not preserved. A conservative approach to the identification

of crab burrow specimens is taken here. However, with further study and increased familiarity with various preservations of the form, it may prove to be a common trace fossil.

*Modern tracemaker analog.*—Burrows of the ghost crab *Ocyroide quadrata* are common on the upper foreshore and backshore zones of the narrow carbonate sand beaches of San Salvador. These burrows are unlined; most have diameters of 1–3 cm; many have two entrances that join in a Y-shaped pattern. The fossil Y-shaped burrows are comparable with the modern burrows of *Ocyroide quadrata* and undoubtedly were formed by that animal. Further discussion of this tracemaker analog is given by Frey, Curran and Pemberton (1984).

#### ? CRAB TRACKWAY

##### Figure 4C

*Description.*—An apparent trackway structure 15 cm in length consisting of a series of small, closely spaced, downward-deflected lobes, some of which are elongated and have an imbricate pattern in cross section.

*Occurrence.*—A single specimen is preserved in planar cross-stratified, medium- to coarse-grained calcarenites of the upper part of the beach facies in an exposure on the southeast coast of San Salvador.

*Discussion.*—Biogenic structures such as crab trackways have low potential for fossilization. Tips of crab dactyli can deform laminae beneath the sediment surface (see Schäfer, 1972, fig. 140; Frey, 1973, fig. 5), producing “undertracks” that have greater potential for preservation than tracks at the surface. At present this is the only known specimen of this type from San Salvador, and a physical origin for the structure cannot be ruled out.

*Modern tracemaker analog.*—The trackways of the ghost crab *Ocyroide quadrata* are common in the backshore zone of beaches on San Salvador, and this crab is a likely tracemaker analog for the suspected fossil trackway. Figure 4D illustrates a variety of crab trackways in the upper part of the backshore zone on a beach on the south coast of the island. The closely spaced, deeper penetrating dactyli impressions could well form

an "undertrack" similar to the fossil example.

#### RHIZOCRETIONS Figure 4B

*Description.*—Rhizocretions are tubular concretion-like masses of calcrete, often branching, that form around the living or decaying roots of plants. Exterior surfaces are highly variable, from very rough to smooth; tubes are of irregular diameter and can be relatively open with inside diameters of 2–4 cm or completely filled by mineralization; branching patterns are highly variable.

*Occurrence.*—Rhizocretions are present in all of the calcarenite facies on San Salvador; however, these structures are most abundant in the eolianites of the dune facies (Figure 4B).

*Discussion.*—Although not all workers agree, rhizocretions are considered valid trace fossils by Sarjeant (1975) because the structures result from the activity of plants and only partially reflect the morphology of the plant. The mode of formation of rhizocretions and their potential for use in paleoenvironmental interpretation have been reviewed by Klappa (1980). On San Salvador it seems quite probable that analogs for the various well-preserved rhizocretion forms could be established through study of the root systems of the more common modern coastal plants. Such research has not yet been initiated.

#### PALAEOENVIRONMENTAL SIGNIFICANCE OF THE TRACE FOSSILS

Although trace fossils occur sporadically in the Pleistocene carbonate facies on San Salvador, their presence can be useful in the identification of facies and in the reconstruction of paleodepositional environments. Rocks of the subtidal, non-reefal facies are characterized by the occurrence of the *Ophiomorpha* sp.–*Skolithos linearis* assemblage. Burrows of *Callianassa*, the presumed modern analog for *Ophiomorpha* sp., do not occur in the lower foreshore zone of beaches on San Salvador, as is the case with *Callianassa major* burrows on siliciclastic beaches of the southeastern United States (Frey and Mayou, 1971; Dörjes and Hertweck, 1975). Likewise, polychaete burrows, the analogs for

*Skolithos linearis*, are not found on the narrow San Salvador beaches.

*Callianassa* burrows do not occur in water depths of less than one meter in the sandy bottom areas adjacent to coral patch reefs off San Salvador beaches. By analogy, the occurrence of *Ophiomorpha* sp. in the Pleistocene subtidal carbonates on San Salvador should indicate minimum water depths of greater than one meter, with a maximum depth being the shelf-slope break. This latter depth is today somewhat variable around San Salvador but is normally between 10–15 m; the slope is very steep and rocky and generally not suitable for *Callianassa* burrowing.

Lowermost rocks of the beach facies appear to be devoid of trace fossils. However, rocks of the upper part of the beach facies (upper foreshore and backshore zones) can be characterized by the presence of Y-shaped crab burrows. The analog for these fossil burrows, the burrows of the ghost crab *Ocypode quadrata*, is common today on the beaches of San Salvador in the narrow upper foreshore and backshore zones. Fossil trackways, even if more specimens are found than the one example now known, probably always will be very rare because of their low potential for preservation. However, occurrence of such specimens would be indicative of the backshore zone and areas transitional to dunes.

As described earlier, rhizocretions are ubiquitous to the various calcarenite facies, but they are most abundant and well formed in the eolianites of the dune facies. With further study, modern plant analogs for the rhizocretion systems might be established, yielding significant new paleoenvironmental information.

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