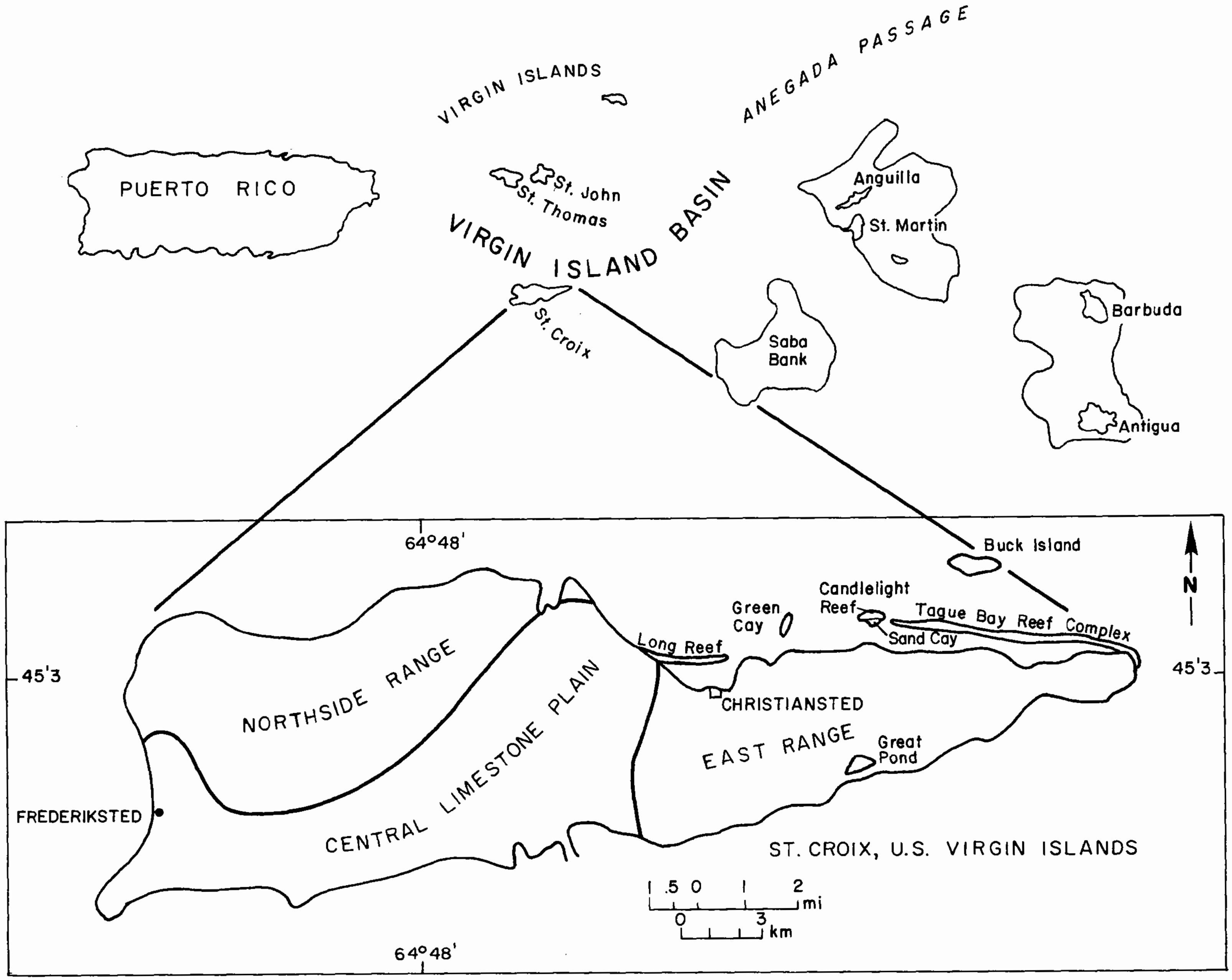

Fig. 1 Index map showing location of St. Croix, Candlelight Reef, and other geographic features.

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ORIGIN AND EVOLUTION OF THE CANDLELIGHT REEF-SAND CAY SYSTEM, ST. CROIX

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by Lee C. Gerhard[1]

INTRODUCTION

The island of St. Croix, largest and most southerly of the U.S. Virgin Islands (Fig. 1) is bordered on its northeastern margin by a well-developed *Acropora palmata* reef that extends from the eastern tip of the island over five miles (8 km) westward. The western terminus of the reef is a large patch reef (Candlelight reef), slightly separated from the main reef by one of only three boat channels crossing the bay-barrier reef.

Prevailing wave trains are from the east and northeast; the reef exhibits higher energy communities in the eastern portions, including coralline algal caps. Poorly developed, very small bays and lagoons are present behind the reef (see also Gerhard and Stoltzman, 1974). The western trailing edge gradually diverges northward from the coast-line and bars deeper and broader lagoons, the most westerly of which is called Coakley bay. Candlelight reef is at the western extremity of Coakley bay.

Candlelight reef has a broad reef flat which is in part covered by a sand pile, locally called Sand Cay, which changes size and shape periodically (Fig. 2).

Bathymetric profiling (Fig. 3) through Coakley Bay indicated an anomolous shallow ridge, a ledge of rock extends from the southeast corner of Coakley Bay shoreline towards Sand Cay, and Sand Cay was found to contain detrital cobbles of mainland rocks (Caledonia Formation, Cretaceous), although separated from mainland by topographic depression.

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The purpose of this study was to try to determine the control for the location of the major northeastern St. Croix bay-barrier reef western termination and to study the atypical nature of Coakley bay and Candlelight reef.

METHODS

Studying the origin and evolution of the reef, cay, strandline, and lagoon of this complex required several sampling methods not commonly employed in terrestrial field studies. Although normal SCUBA and free diving techniques were used throughout the study, two coring methods were instrumental to the study.

Three holes were drilled through Candlelight reef (Fig. 3) by means of a portable gasoline-powered drill. When major sand bodies were encountered, as on the east end of Sand Cay, concrete reinforcing bar was driven into the sediment; ease of driving (hammer blows per foot) changed as a function of depth and material penetrated; however, an abrupt change marked the contact between sand and underlying detrital muds. In the western hole, a soil sampling tube was lowered through the drilled hole and driven completely through the muds. Eight feet of mud was recovered; a chip of underlying limestone substrate was also recovered from the collapsed core barrel. Drilling was done from a drilling platform constructed of tubular aluminum and anchored to the reef. This permitted use of block and tackle for retrieval of drill tubing and reentry of holes.

Cores taken in the lagoon were taken by SCUBA diver teams operating a 100 pound sliding hammer over aluminum irrigation pipe or plastic ewing piston corer linear. A locking handle on the core barrels acted as the anvil for the sliding hammer. This method penetrated sands and gravels without difficulty. Where the core barrel penetrated mud, the mud effectively sealed the core barrel from sample loss. In at least one case (S-5) where the core barrel could not penetrate coarse sediment, a concrete reinforcing bar was driven into dense substrate, recovering mud adhering to the pits and ridges ornamenting the bar.

Mud mineralogy was analyzed by X-ray diffraction. Two radiocarbon dates were run on *Montastrea annularis* from the western drilled hole.

GENERAL SETTING

Candlelight reef forms the seaward margin of a small, complex lagoon named Coakley Bay (Fig. 4). The reef proper is covered with *Acropora palmata,* with smaller amounts of *Porites, Montastrea,* and *Diploria* present. The reef flat is partly algal turf with large numbers of the grazing urchins, *Diadema antillarum* occupying the transition between the reef fauna and the algal turf. *Thalassia testudinum,* turtle grass, is common on the reef flat and on the lagoon side of the reef. *Echinometra* (echinoid) is also abundant in crevices of the reef flat.

During much of the year wave interference produces a westward elongation of the sand bar on top of the reef (Sand Cay). Winter storm waves may change the shape of the cay rapidly, although the position of the island may now be stabilized by a shipwreck. The highest part of the cay, about 0.5 meter above MSL, supports sparse vegetation. Shell middens from both modern and former human populations also are wave-worked into the cay.

The lagoon or bay floor is covered with *Thalassia* except near the strandline where open, rippled sand is present, and back of the cemented sand "beachrock" ridge (Fig. 3) where pavements of coral and mollusc rubble occur. The strandline in the eastern part of the bay is a series of beachrock layers. Bedrock (Caledonia Formation) is exposed on points defining the eastern and western limits of the bay.

The ridge of cemented sand in the southeast, the lobe in the -5 meter contour at core location S-2, and the submarine ridge connecting Candelight reef to the mainland point at the western end of the bay are the most important features of the lagoon (Fig. 3). The "beachrock" ridge appears to deflect the normal longshore current seaward, and water has always been observed to be more turbid along that ridge than elsewhere in the lagoon; the biota of the ridge is largely alcyonarians and deeper water corals, such as *Eusmilia*. This appears to substantiate the continuing high turbidity which produces lower light levels. The corals are poorly calcified as compared to more clear water forms, as well.

Strandline features are a steep sandy beach and beachrock in the eastern part. The sand beach is a bar separating a saltpond from the lagoon. Two passes cut through the bar, a small, now blocked, one at the west end, and a drainage at the east end which is the major channel between the pond and the lagoon. During periods of dry weather, the pond is dry, with blue-green algal crust chips and gypsum crystals on the surface; during high rainfall the pond will hold water to about 0.5 meters deep; excess water exits through the eastern channel. Beachrock starts downcurrent from the point of entrance of the pond drainage into the lagoon.

It appears that the beachrock cementation along the present strandline is at least in part due to the outflow from the pond. Perhaps excess salinity, or driving of hypersaline waters by freshwater runoff may force precipitation of cement (Hanor, 1978; Hanor and Moore, 1974).

The sediment cover of the present lagoon floor does not contain appreciable clastics; no detrital grains larger than sand size are found more than a few meters from exposed Caledonia Formation. Therefore, detrital cobbles on Sand Cay are not now being transported from a bedrock source to the cay.

SEDIMENT FACIES

Lagoon cores contain sediments of several different depositional environments (Appendix A). In all cases, the uppermost beds or zones are low in detrital grains and contain large amounts of skeletal sand, including many *Halimeda* plates, both whole and broken. This reflects the prevailing modern depositional setting of grassbeds with associated codiacean algae and molluscs. Ten to twenty centimeters below the top of each core the amount of detrital grains abruptly increases. A shoreline to lagoon environmental transition can be seen between core S-1, S-2, and S-3 in this zone (Fig. 5). Discoidal beach pebbles in core S-1 are in the same stratigraphic position as a zone of broken mollusc and coarse detrital grain in core S-2, which in turn corresponds with detrital sand mixed with *Halimeda* and mollusc in S-3. Movement of the beach zone upwards from core S-2 to S-1 is indicated by the coarse detrital cobble with *Siderastrea* in the base of core S-2, overlying clastic mud, whereas in core S-1 that position is occupied by clastic mud with some marine mollusc fragments and some *Halimeda*.

Core S-4 also is high in detrital grains in the depth below the existing grassbed. These grains are coarse, pebbles and gravels, but do not exhibit the discoidal shape of pebbles in core S-1.

Two cores were taken in the next bay to the east (S-6, S-7) for comparison. Core S-7, near the shoreline, exhibited no unusual sediments, but core S-6, in a backreef location, cut a cemented layer just above the yellow mud bottom (Fig. 6).

All cores except S-4 penetrated the carbonate sediments and recovered a dense blue or green mud substrate, as did two of three holes drilled on the reef.

Three cores were taken in the vicinity of Green Cay to the west to test for the presence of the dense mud in that area; two recovered mud. One of these was seaward of Green Cay, but behind a lineation apparently marking an outward limit of mud and clastics (Fig. 4).

Three holes drilled around Sand Cay encountered a cap of coral rubble, mixed coral rubble and sand (approximately 3 meters thick in each case) and then thick skeletal sand. Two holes, west and east of the cay, encountered dense mud below the sand; the third in front of the island encountered limestone. In the western core, the mud was cored through to limestone (Fig. 7). This limestone appears to be of Pleistocene age and is an indurated coral-mollusc-*Halimeda* bank. The same material was encountered in core holes further east along the reef, without any mud being present. Thus, at the reef crest, no mud is present and the reef appears to be constructed on an older limestone "lip".

Carbon 14 data on *Montastrea annularis* from the base of the rubble zone in drill hole 1 (west side of Sand Cay) gave results of 1495±65 years and 1750±200 years, which fits well with the sea level curve used by Adey (Adey and Burke, 1976).

MUD SUBSTRATE

Almost all cores in this study, plus two more near Green Cay, recovered blue-green or blue-gray muds, the exceptions being cores drilled on top of the reef, where mud was not present over older limestone, and those that had mechanical penetration problems. Additional probes (S-5) established presence of mud in areas where it was not cored.

X-ray diffraction analysis of these muds indicates quartz to be the major constituent with calcite, aragonite, plagioclase, and halite also present in significant amounts. These analyses are similar to muds sampled at shallow depth in Great Pond, on the opposite side of the island, which is a pond with a single narrow channel for tidal communication. The quartz is largely the result of weathering of the fine-grained turbidites of the Caledonia Formation, and some quartz, plagioclase, and perhaps, where present, hornblende, are from the Southgate diorite which crops out in a belt across the island from Great Pond to Green Cay. The mud has a sloping surface in the Coakley bay area (Fig. 8), rising southward and apparently joining the existing salt pond surface (Fig. 9).

ORIGIN AND EVOLUTION OF CANDLELIGHT REEF AND COAKLEY BAY

Drilling has determined that a Pleistocene or older limestone underlies the length of the northeastern St. Croix bay-barrier reef, at least from Candlelight reef to Tague Bay, and probably through Boiler Bay to the east. Presence of a raised lip on this platform of limestone is indicated by the closely spaced drilling around Candlelight reef, where the reef margin limestone substrate is shoaler than behind the reef. In addition, under the reef, no mud is present between carbonate sands and the limestone, but it is present everywhere else in the lagoon behind Candlelight reef.

Adey and Burke (1976) have related sea level rise with time for St. Croix. Based on their graphs and the radiometric dates from Candlelight reef, a scenario of events from approximately 5500 yr BP to present can be constructed (Fig. 10).

The mineralogic identity of cored muds to those in the present salt pond, the transgressive character of the sediments overlying the muds, and the gradual rise of that surface from reef to shoreline all suggest that all the muds were deposited in restricted circulation saline environments, probably similar to the present barred pond.

Initial transgression over the lip of the *Porites* limestone would have created a bar on top of the limestone (an extension of the former beach) with a restricted pond or lagoon behind. Muds deposited in this pond in part cover the earlier limestone.

The original trend was parallel to the existing reef trend. As transgression progressed, the sand bar was moved landward and reef colonization progressed on the original declivity over the limestone lip. Longshore current from the east was developed.

At Coakley bay, however, a combination of current deflection by rock ridges and fluvial interferences from the Southgate drainage at Green Cay deflected the longshore current northward, and a spit was developed north from western Coakley Bay, along which clastics were transported northward.

The bar by this time was moved shoreward, but was anchored at the site of Candlelight reef by the growing spit. The spit is now the submarine ridge between Candlelight reef and the shoreline.

The next step, at about 3000 yr BP and -2 meters sea stand a pond was enclosed by the remnant bar and spit (Fig. 10D). Drainage from the pond helped form beachrock, which still exists as the submerged line of cemented material in the eastern part of Coakley Bay. A later pond drainage channel may be on the site of the -5 meter bathymetric contour nose at S-2 (Fig. 3). There is no doubt that a well-developed beach existed at S-1 where discoidal beach pebbles are present, transported northward by longshore currents.

Clastics were carried out to the site of Candlelight reef by longshore drift along both spit and bar, creating a pile of debris at their conjunction. As *Acropora palmata* was established, reef colonization became rapid.

The current transgressive episode slowed and the spit-bar combination migrated shoreward to its present position, barring the present salt pond.

SUMMARY

Candlelight reef is the buttressing western terminus of the northeastern St. Croix reef system because of a combination of paleotopography and longshore drift which created a stable pile of detrital material at the position of Candlelight reef. Reef colonization proceeded eastward along the former slope break on the limestone terrace; turbid gyres along the eastern margin of the former Southgate drainage prevented further westward colonization. It is quite possible that the old limestone bench has also been breached west of Candlelight reef, or else turns northwestward (which appears likely on aerial photographs).

The presence of detrital cobbles in Sand Cay and Candlelight reef is easily explained by this model, as well as the submerged ridge and submerged beachrock.

One of the interesting subsidiary results of this study is the demonstration that an unconformity between underlying fine-grained

quartzose rocks and overlying carbonates, with basal conglomerate, need represent only an eustatic sea level rise rather than any fundamental tectonic event. Dynamic environmental translocation of sediment bodies can appear to represent disconformities that do not really exist.

ACKNOWLEDGEMENTS

This study is a compilation of the work done by the writer, his students, and associates over several years. In particular, my 1975 summer Field Sedimentology class of the West Indies Laboratory, especially Kipp Carroll, Douglas George, and Rick Haack, did most of the coring. Dick Holt and Craig Shipp, then of the West Indies Laboratory, Jonathon Fuller, and Timothy Cross have all assisted in the completion of this study. Jon Reiten and David Brekke, of the University of North Dakota, made the X-ray diffraction analysis. Randolph Burke provided the C-14 analyses.

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APPENDIX A. CORE DESCRIPTIONS

S-1. On approximate line with submerged beachrock northwest of Mill Point.

0-17 cm	*Halimeda*--clastic sand with *Thalassia* rhizomes. Contact with lower unit is fine-grained silty sand.
17-75 cm	Gravel of discoidal pebbles of Caledonia Formation and large broken mollusc fragments in a fine sand matrix. Large clasts are aligned parallel to bedding. Bioclasts in part encrusted by *Petaloconchus*. *Cerithium* common. One ungaped *Pitar* at 65 cm.
75-82 cm	Peat, unidentifiable origin, with minor carbonate grains and one large detrital clast.
82-91 cm	Detrital-skeletal conglomerate; thin-shelled molluscs, *Halimeda*, like mangrove biota.
99-112 cm	Blue-green mud with very few carbonate grains.
112-135 cm	Blue-green mud.

S-2 Northeast of end of submerged beachrock.

0-26 cm	*Halimeda* plates in fine-grained skeletal sand. A few mollusk fragments. Whole *Halimeda* plates in lower part of unit; *Thalassia* rhizomes in upper part. Transitioned contact with lower unit.
26-61 cm	Medium-grained *Halimeda*-mollusc sand with detrital pebbles. *Mesophyllum* and gorgonian spicules are present, many *Cerithium*. Sharp contact with lower unit.
61-104 cm	Massive bedded, clastic-mollusc gravel, clastics well-rounded, many small gastropods, a few large pelecypods.
104-126 cm	Nearly the same as upper unit but average grain size of larger clasts is increased.
126-140 cm	Clastic gravel in carbonate sand matrix. Lowest particle is fist-size detrital clast encrusted by *Siderastrea*. "Basal conglomerate."
140-153 cm	(TD) Blue-green mud. Irregular contact like disconformity with overlying unit.

S-3 Northeast of S-2, outside (NE) of the submerged beachrock

0-9 cm	Poorly sorted skeletal sand with few large mollusks. *Halimeda,* gastropods, pelecypods. Gradational contact with lower unit. *Thalassia* rhizomes present.
9-19 cm	*Cerithium,* other large mollusks, *Halimeda,* in a fine-grained skeletal sand matrix. A few detrital medium to coarse sand grains. Contact with underlying unit is sharp.
19-56 cm	*Cerithium* gravel with large numbers of unbroken *Halimeda* plates; minor matrix of fine-grained skeletal sand. Many smaller molluscs appear abraded. Gradational contact with underlying unit.
56-72 cm	Skeletal sand grading downward from *Cerithium-Halimeda* gravel to mollusc sand. Some clastic sand grains.
72-95 cm	Coarse pelecypod-clastic gravel with *Oculina, Cerithium, Nerites,* and crustose coralline algal coated *Porites.* Sand matrix. Contact with underlying unit irregular and sharp.
95-118 cm	(TD) Yellow-green and blue-green mud. Contact with overlying unit has 2-3 cm relief. A minor amount of finely comminuted skeletal detritus. Entire core exhibits very little bedding, may have been bioturbated, no preferential orientation of flat particles.

S-4 Taken on the submerged ridge between the western headland of Coakley Bay and Candlelight reef

0-8 cm	Medium- to fine-grained sand with some relatively unbroken *Halimeda* plates: a few small mollusk shells. *Thalassia* rhizomes, few clastic grains. No bedding. Transitional contact with underlying unit.
8-24 cm	Moderately coarse skeletal sand with fine-grained sand admixture grading downwards to base of unit which has large broken *Codakia* shells. *Halimeda* abundant. Some clastic sand, increases downwards. Abraded *Homotrema.* Transitional contact with underlying unit.
24-32 cm	Coarse sand and gravel, whole *Cerithium,* other gastropods, large clastic grains, and broken *Halimeda* plates infiltrated with fine-grained sand. Clastics are rounded. Transitional contact with underlying unit.

32-69. Coarse clastic gravel, well rounded, as if beach pebbles; discoidal clasts. Abraded *Cerithium* shells, other large mollusc fragments. Contact with underlying unit is abrupt.

69-91 cm (TD) *Halimeda*-mollusc sand with well-rounded clastic granules and pebbles, but a much lesser amount than in overlying unit.

S-5 Probe, just northeast of S-4

Blue-green mud on probe tip at depth of 195 cm.

S-6b Taken in front of Coakley Bay condominiums a few meters lagoonward from reef

0-11 cm Coarse skeletal sand. May be washed.

11-32 cm Medium coarse skeletal sand, nearly 10% clastic sand grains.

32-68 cm *Halimeda*-mollusc-clastic gravel. *Cerithium* abundant. Well burrowed. *Homotrema* abundant.

68-83.5 cm Coarse mollusc valves, clastics, with less *Homotrema*. Cemented nodule of pelecypod fragments, oriented parallel with sediment-water surface, about 1 cm thick.

83.5-87 cm (TD) Yellow-green mud with few carbonate grains.

S-7 Taken just off beach in front of Coakley Bay condominiums

0-13 cm Fine-grained skeletal sand with foraminifera, *Halimeda* plates and *Thalassia* rhizomes. Molluscs common.

13-62 cm Overall coarser than overlying unit, poorly sorted with coral fragments, *Cerithium* and extremely abundant whole *Halimeda* plates. Clastics less than 10%. Many large mollusc valve fragments, including *Codakia*. *Oculina* and *Mesophyllum* both present. Gradational contact with underlying unit.

62-82 cm Grain size greatly increased because of very large mollusk fragments and sub-rounded to sub-angular detrital clasts. *Oculina* at top of unit and *Mesophyllum* is abundant. One large *Natica* is intact with root etchings. Many broken but fresh pelecypod shells. Contact with underlying unit is relatively sharp.

82-89 cm Fine-grained sand containing *Oculina, Mesophyllum,* and detrital sand. Abrupt contact with underlying unit.

89-99 cm (TD) Blue-green mud with few carbonate particles, surface with overlying unit 1-2 cm relief. Shell fragments appear to be thin-walled molluscs.

APPENDIX B. DRILLED HOLE LOGS

SC-1 West of Sand Cay

0-4 feet	Water
4-5 feet	Cap rock of coral rubble
5-10 feet	Sand and coral rubble
10-19 feet	Carbonate sand
19-25 feet	Blue-green mud
25-28 feet	Green mud
TD	*Porites* limestone (Pleistocene?)

SC-2 North of Sand Cay

0-4 feet	Water
4-5 feet	Cap rock of coral rubble
5-9 feet	Sand and coral rubble
9-25 feet	Carbonate sand
TD	Limestone

SC-3 East of Sand Cay

0-3 feet	Water
3-3.5 feet	Cap rock of coral rubble
3.5-9.5 feet	Sand and coral rubble
9.5-24 feet	Carbonate sand
24-24.4 feet TD	Blue-green mud

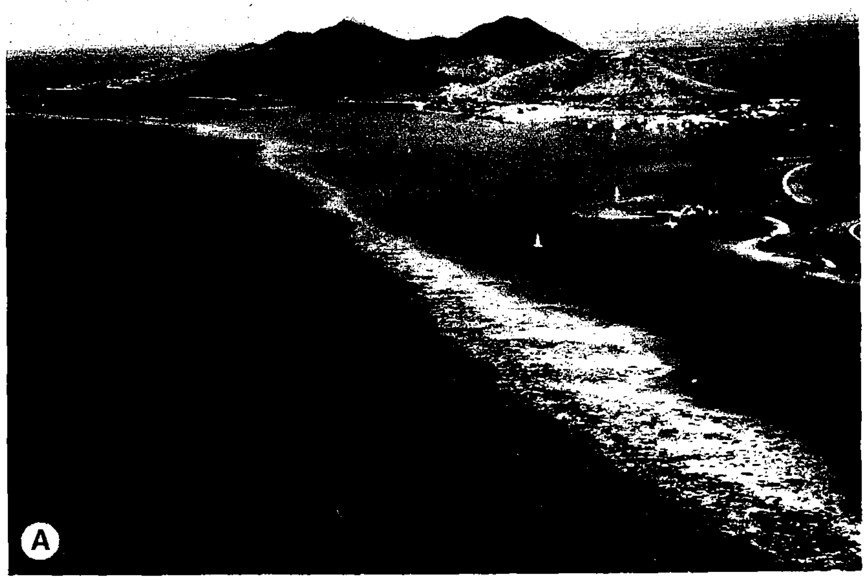
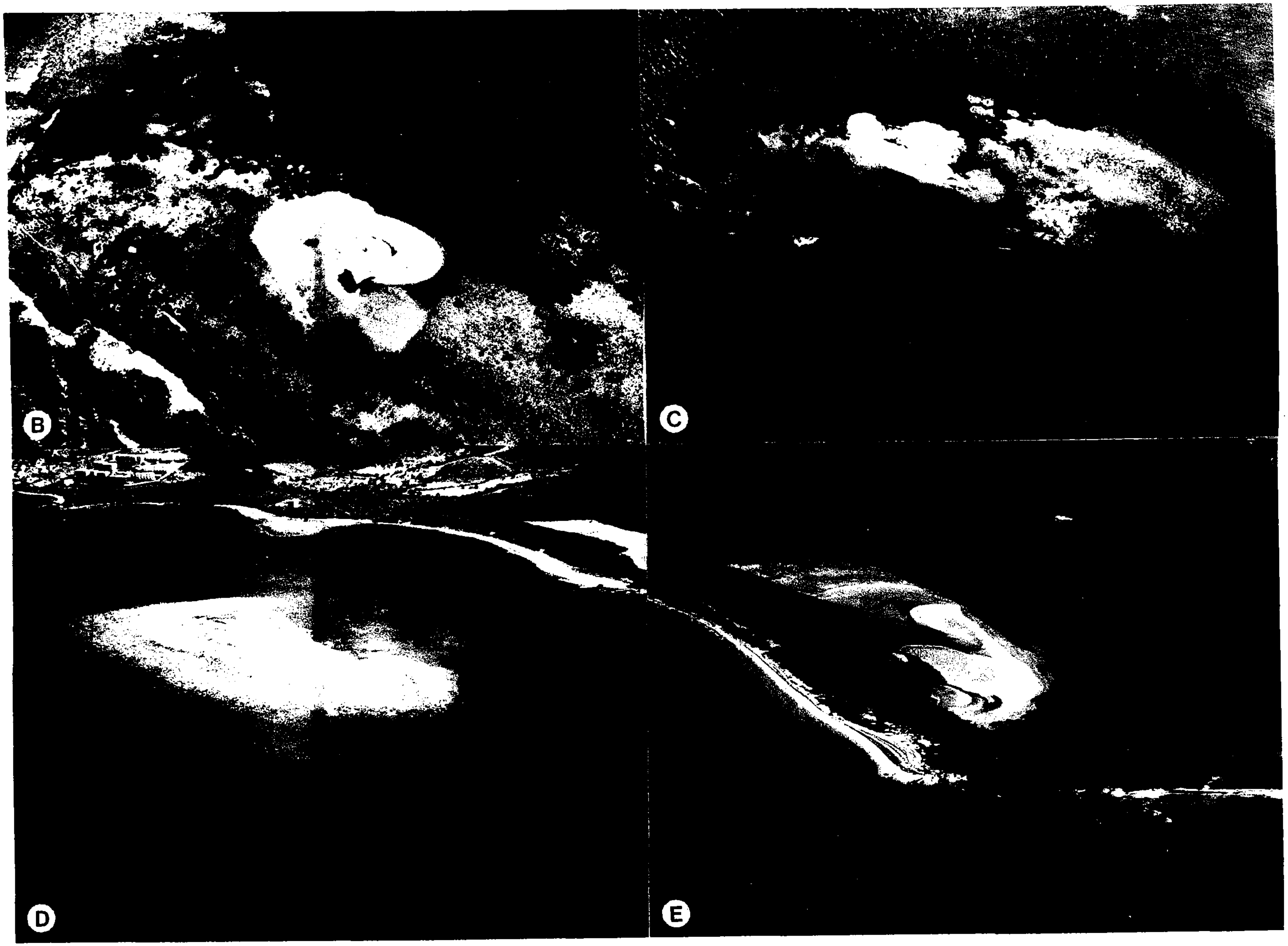


Fig. 2 Aerial photographs of Sand Cay and Tague Bay reef complex. A. Tague Bay reef complex, view looking east. *Acropora palmata* is major coral of reef crest. B. Sand Cay, August, 1973. C. Sand Cay, February, 1974. D. Sand Cay, March, 1977. E. Saltpond behind bar, Coakley Bay, St. Croix. B, C, and D looking south, E looking southeast.


B
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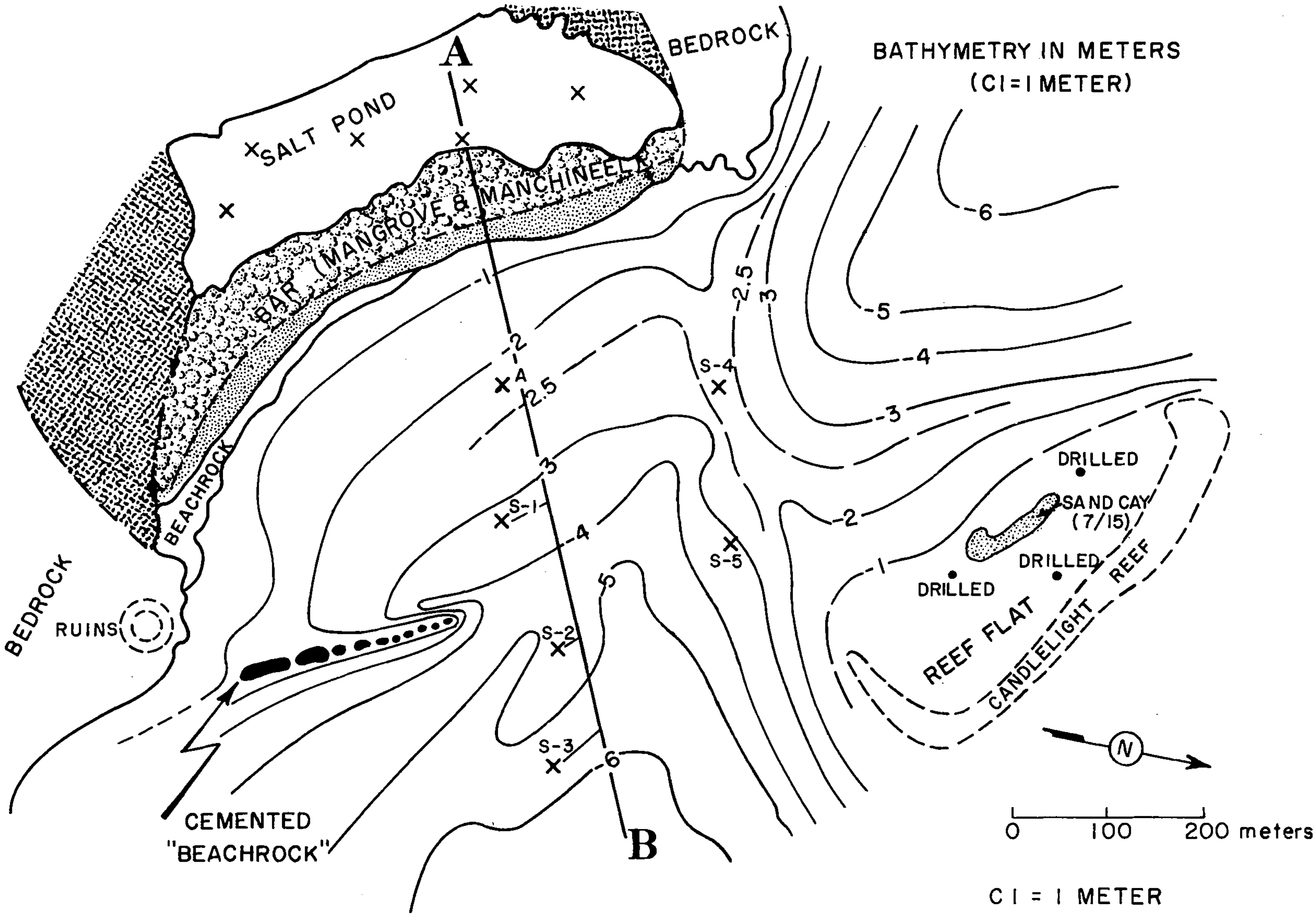


Fig. 3 Bathymetric map of Coakley Bay area, St. Croix, showing core locations (X) and line of section for figure 9.

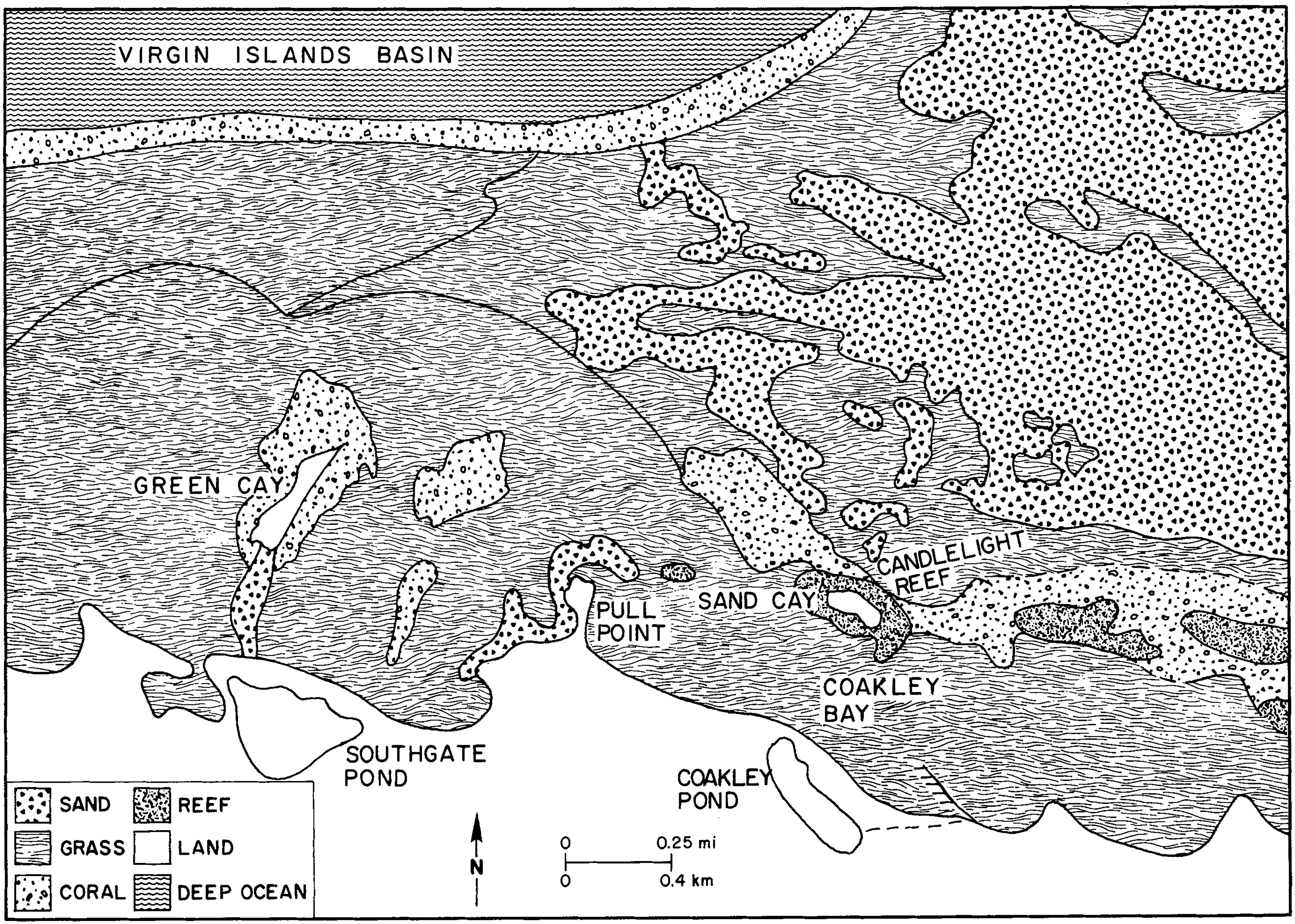


Fig. 4 Substrate types central north St. Croix shelf. Lineation north of Green Cay may indicate limit of muds or edge of Pleistocene limestone terrace; N-S lineation appears to be formed drainage channel.

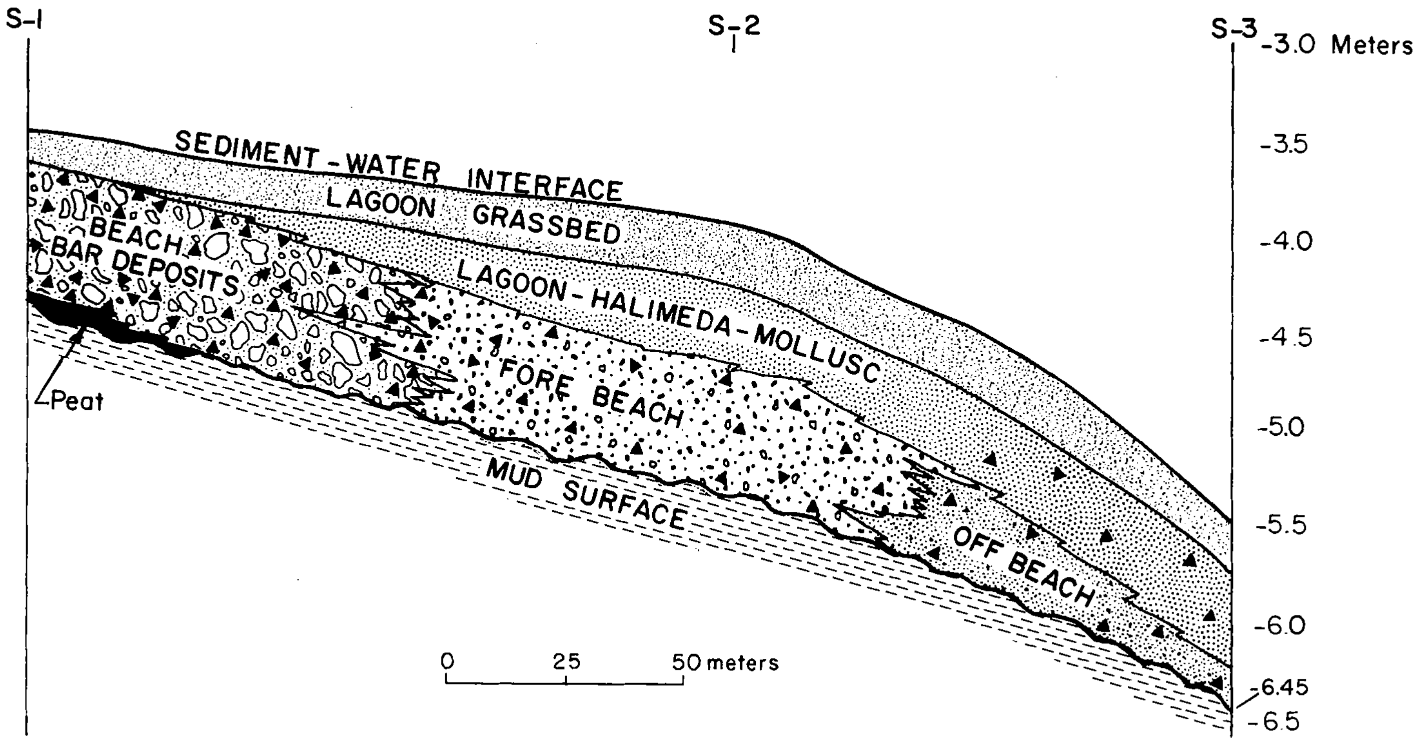
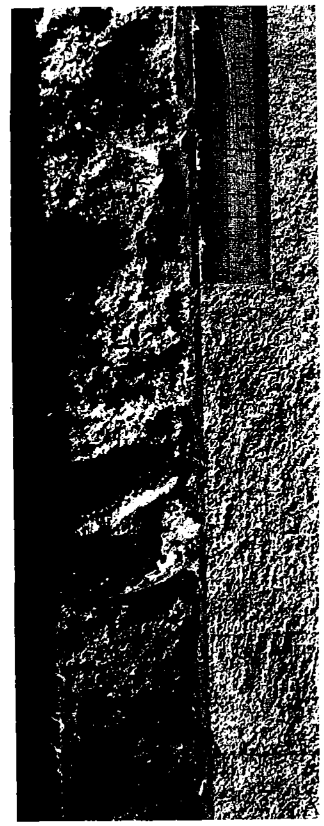


Fig. 5 Correlation of cores S-1, S-2, and S-3 with (a) interpreted environments of deposition. Dark triangles indicate relative abundance of detrital clasts. Photographs are from: (b) S-1 (59-71 cm); (c) S-2 (110-145 cm); (d) S-3 (71-85 cm); (e) S-3 (19-34 cm).

B.

C.



D.

E.

Fig. 6 Photomicrograph of cemented layer recovered in core S-6 showing *Halimeda,* mollusc and foraminifera grains in micritic cement and matrix. Field of view is 10 mm wide.

Fig. 7 Photomicrograph of limestone substrate below sand cay, showing *Halimeda* grain and bored and micritized probable *Porites* grain. *Halimeda* grain is 2 mm diameter.

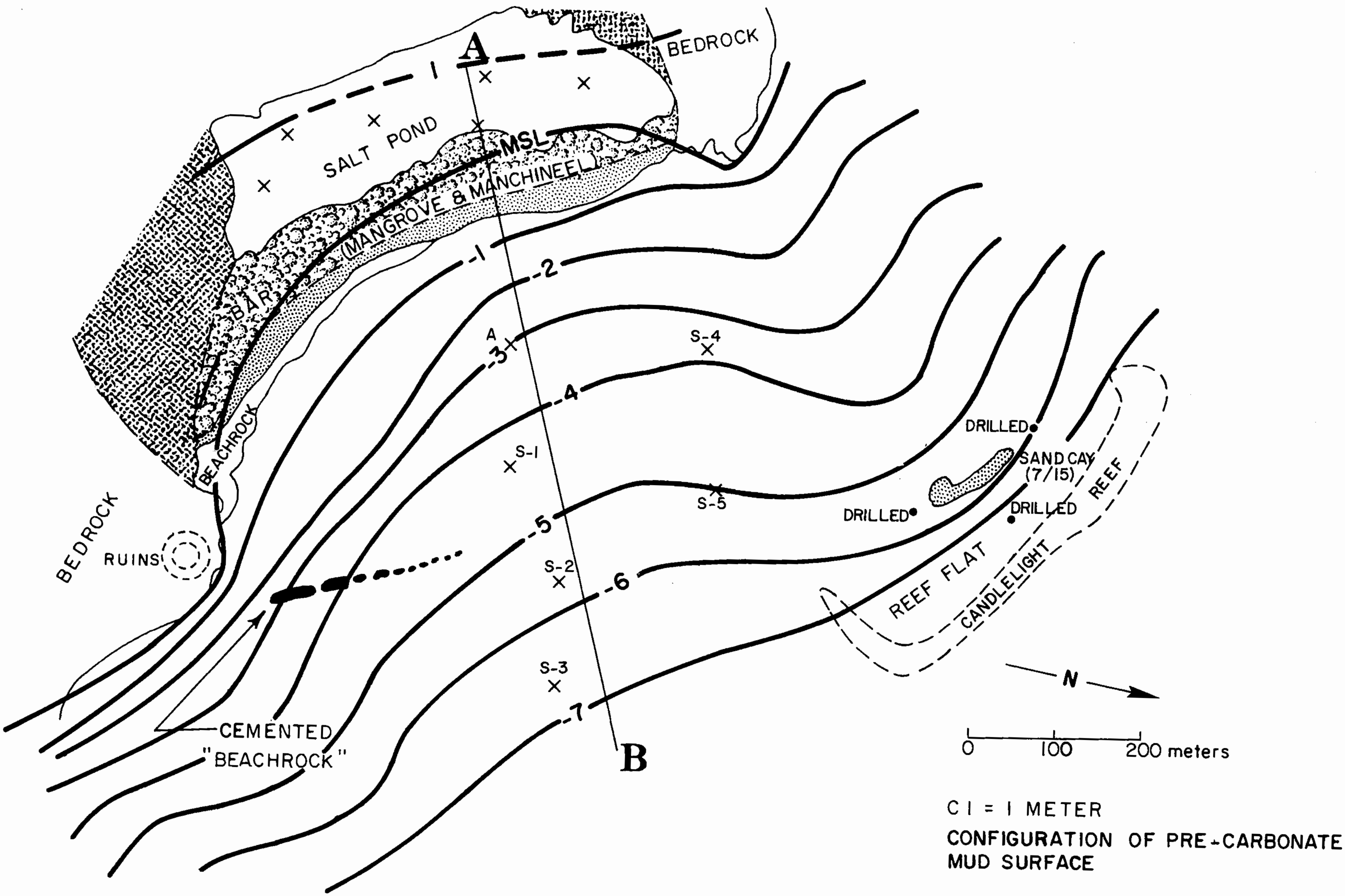


Fig. 8 Topography of mud surface, Coakley Bay, St. Croix.

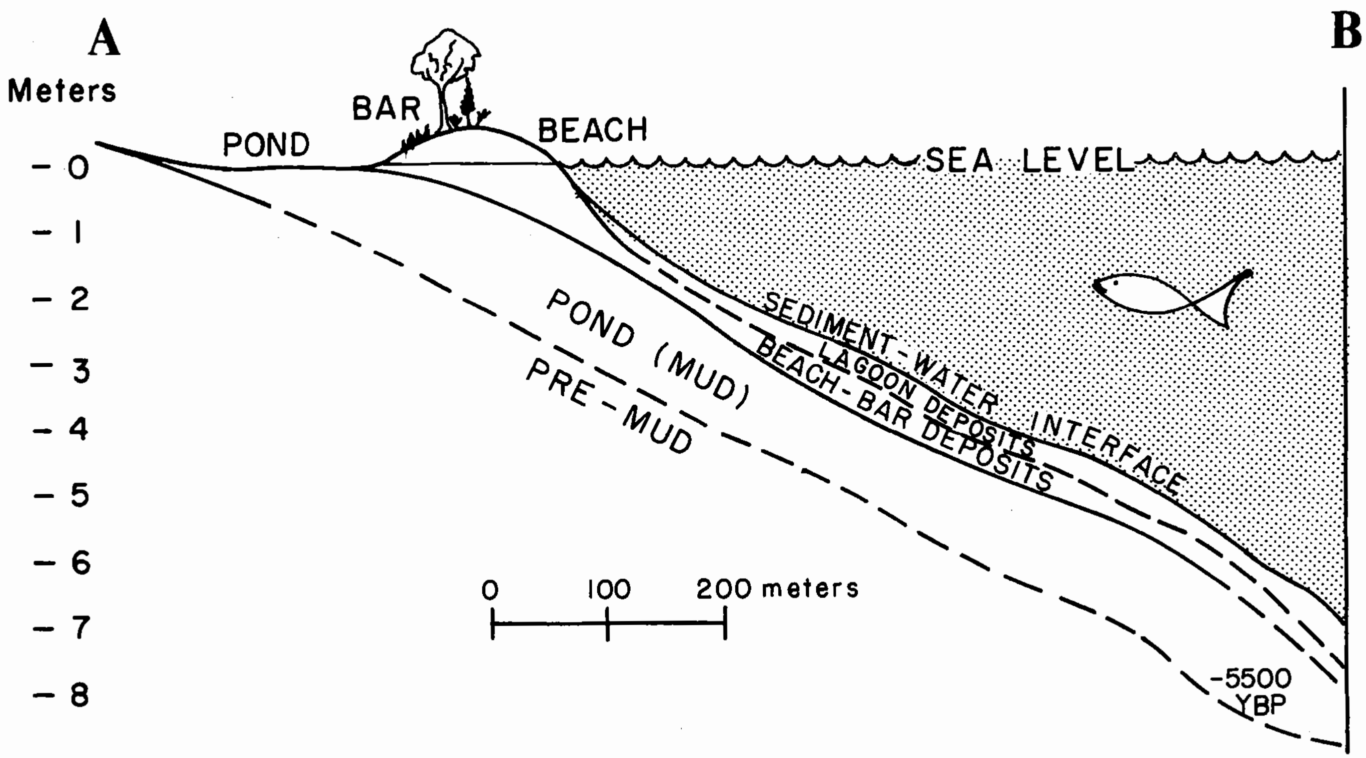
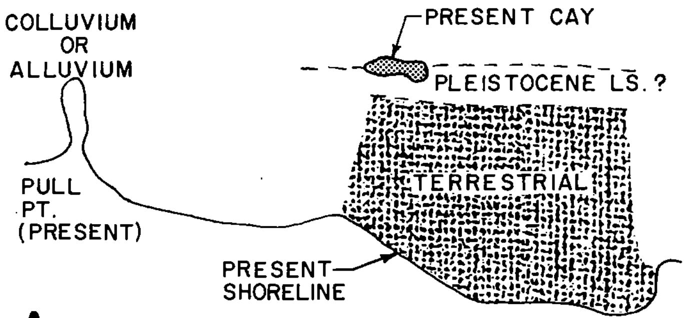


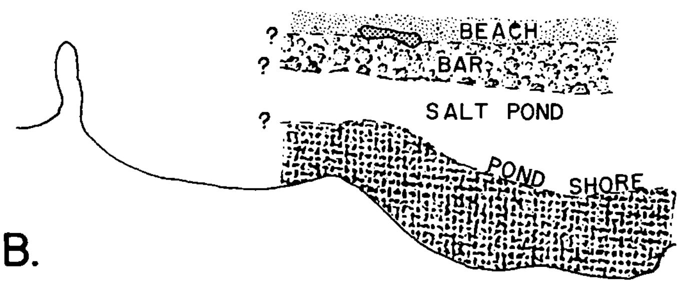
Fig. 9 Schematic cross-section through Coakley Bay showing stratigraphic relationships between modern and earlier sediments.



A.

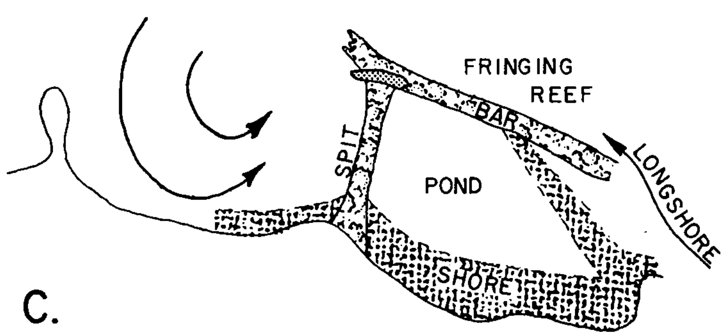
SEA LEVEL - 8 meters, ~5500 YBP.

Fig. 10 Interpreted development stages for Sand Cay, Coakley Bay, and associated features. A. >5500 YBP. B. ∿5000 YBP. C. ∿4200 YBP. D. ∿3000 YBP. E. Present.



B.

SEA LEVEL - 7 meters, 5000 YBP

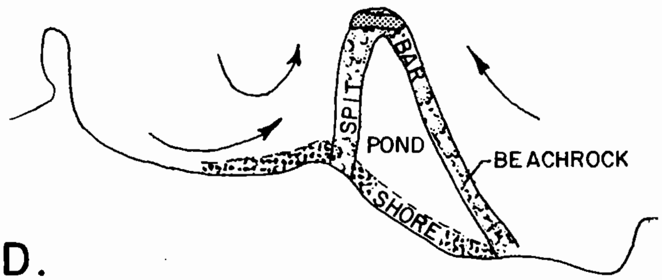


C.

SEA LEVEL - 5 meters, ~4200 YBP

0 .5 miles

0 .5 kilometers



D.

SEA LEVEL -2 meters, 3000 YBP.

E.