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SEDIMENTOLOGY OF SOUTHWESTERN ROADS REGION, U.S. VIRGIN ISLANDS - ORIGIN AND RATE OF SEDIMENT ACCUMULATION

by

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SEDIMENTOLOGY OF SOUTHWESTERN ROADS REGION, U.S. VIRGIN ISLANDS - ORIGIN AND RATE OF SEDIMENT ACCUMULATION

Abstract

Sand deposits on the southern shelf of the U.S. Virgin Islands were investigated to determine their origin and to relate origin to environmental processes and production rates. Analysis of sea-floor samples for composition shows that the sand has been derived mainly from calcareous algae and molluscs *in situ*. Zonation of the dominant sand producers is related to the present environmental setting; water depth has the greatest influence.

Carbon-14 dating of cores as long as 5 m indicates accumulation rates of slightly less than 1 mm/year for the last 5,000 years in areas of thickest sand. Faunal studies show that the climate during the last 5,000 years was similar to that of today. The only changes in environmental conditions appear to have been an increase in water depth and a concurrent change in the patterns of water movement. In areas protected during lower sea level, the subtidal barnacle, *Balanus venustus*, disappeared and the amount of coralline algae in the sediment gradually increased beginning approximately 1,500 years ago. The disappearance of the barnacles probably was caused by the introduction of open-marine conditions into a previously protected lagoonal area. On the other hand, the articulate coralline algae increased in the quiet waters on the lee side of the offshore islands because of the change in habitat created by deepening waters.

Introduction

Sand and gravel constitute the largest production of nonfuel mineral resources in the United States. By the year 2000, the domestic resources of sand and gravel accessible at present-day cost may be exhausted (Yeend, 1973). In the Virgin Islands, the supply of sand and gravel was depleted almost a decade ago; however, because of social and economic problems, the construction industry has been only moderately active, and the depletion has had a minimum effect. In the past few years, the pace of construction has quickened and the need for new sources of sand and gravel has become critical.

In September 1977, a study of the distribution and origin of sand and gravel deposits on the St. Thomas-St. John Shelf was begun by the U.S. Geological Survey and Government of the Virgin Islands. The location and distribution of the sand deposits were reported in the first-year report by Holmes (1978). This report presents the result of the second year of investigation on the origin and rate of sediment accumulation in the Southwestern Roads region, the site of the most significant accumulation.

The Southwestern Roads is the region bounded by the southwestern coast of St. Thomas and the offshore islands of Saba (fig. 1) and Savana. Within this area, two bathymetric ridges trend northwest from the Flat Cay and Saba Island rises. These ridges are separated by a distinct channel between the Flat Cay high and the shoreface of the Saba island.

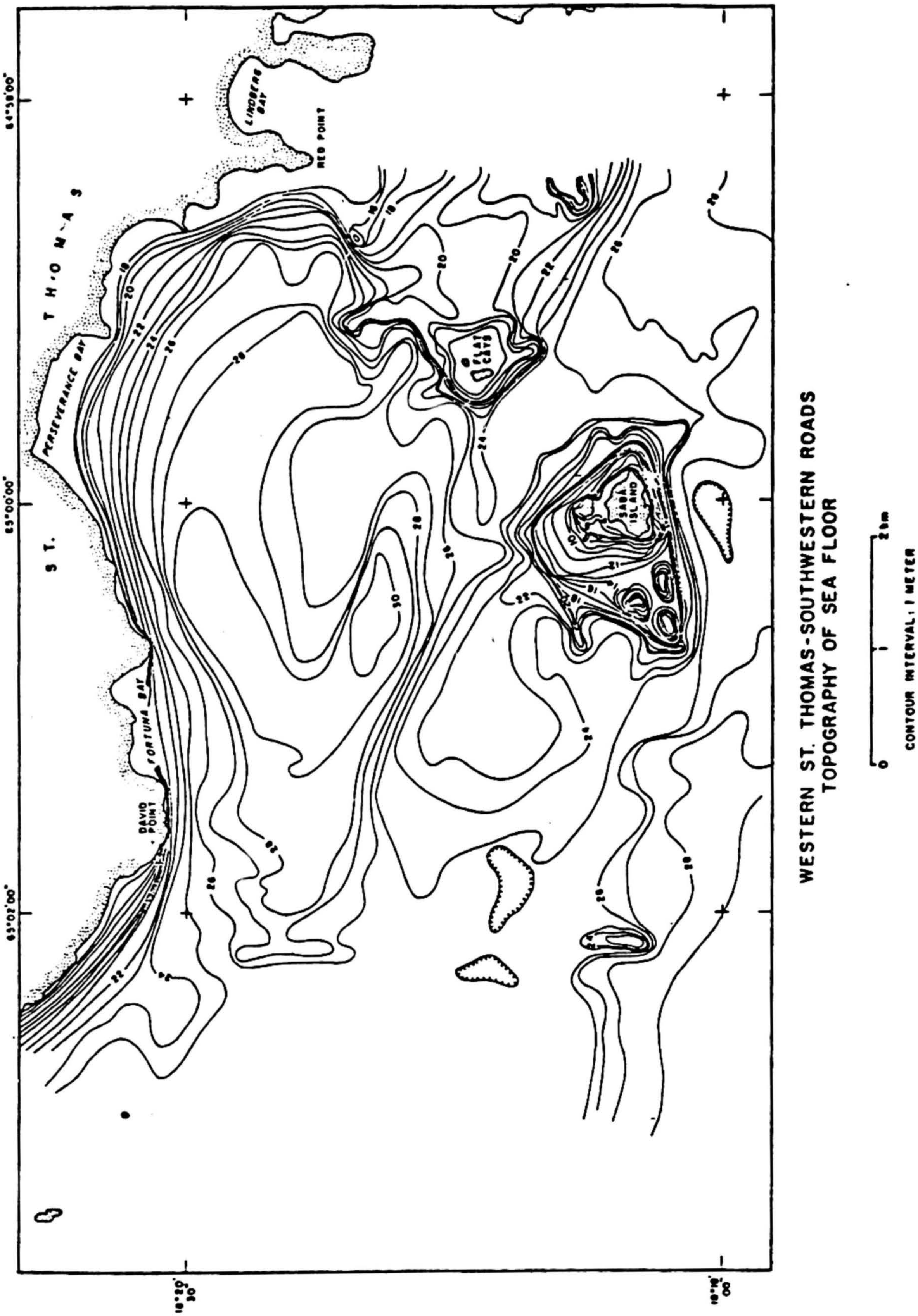

Fig. 1 - Bathymetric map of the Southwestern Roads region - St. Thomas Shelf.

The high-resolution seismic-reflection survey of this area clearly defines these ridges as recent sedimentary deposits. The cross section normal to the shore shows that the deposits are in an irregular basin of bedrock (fig. 2). Internal reflectors were mapped within the deposits closest to land. The apparent offset of one reflector noted near the toe of the shoreface sand body (fig. 2) is inferred to be a fault, indicating relatively recent tectonic activity. The extent of these deposits is shown by the isopach map (fig. 3).

METHODS

Although this study began in 1977, it is based partly on samples collected by the U.S. Geological Survey in 1970. Sampling of the sediment was divided into two phases: a reconnaissance sampling (figs. 4, 5) of the southern shelf of St. Thomas and a detailed sampling (fig. 6) of the Southwestern Roads region to determine production rates of the sand. The first phase, a widespread sampling grid over the entire shelf, provided samples for study of the origin of sand presently being produced. The sampling stations were intended at the intersections of lines spaced 1.7 km apart north to south and 3.3 km apart east to west, but owing to navigation error, these are only approximate distances (fig. 4). Navigation was handled by the ship's officers using visual fixes to determine sample-site location. The expected coarseness of the bottom sediments dictated the use of a Shipek* grab sampler, which is very effective in loose carbonate sand. The first phase of sampling was completed between April 4 and 18, 1970.

*Use of brand names in this report does not imply endorsement by the U.S. Geological Survey.

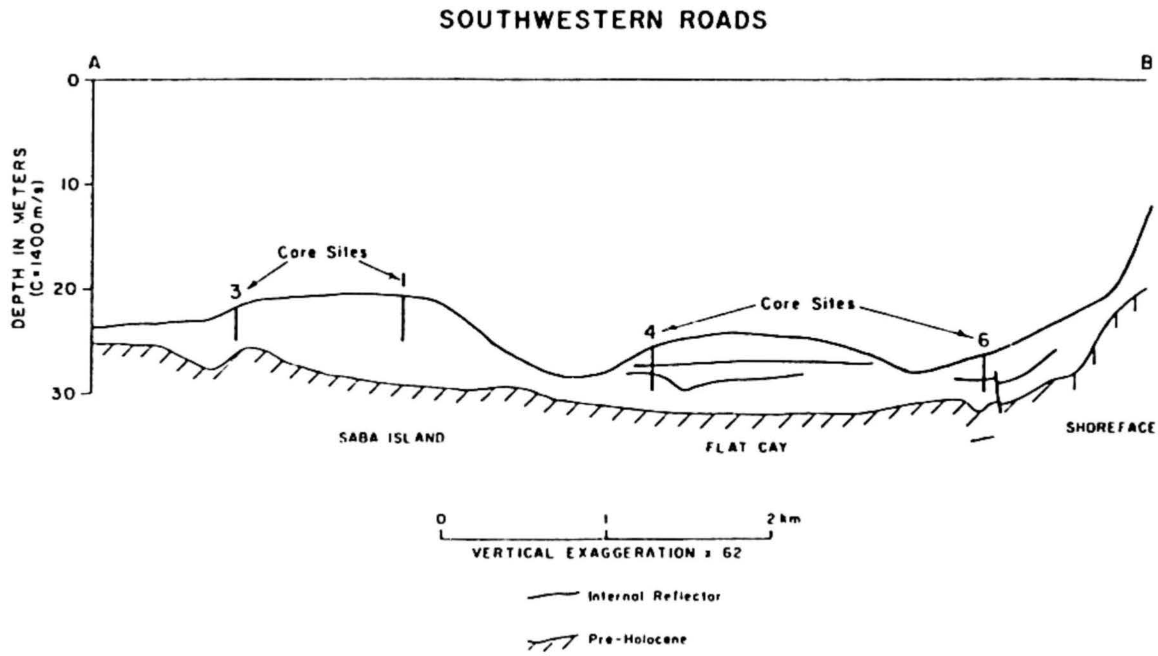

Fig. 2 - Cross section of the sand masses of St. Thomas shelf. Location of section is shown in figure 3. C = velocity of sound in water.

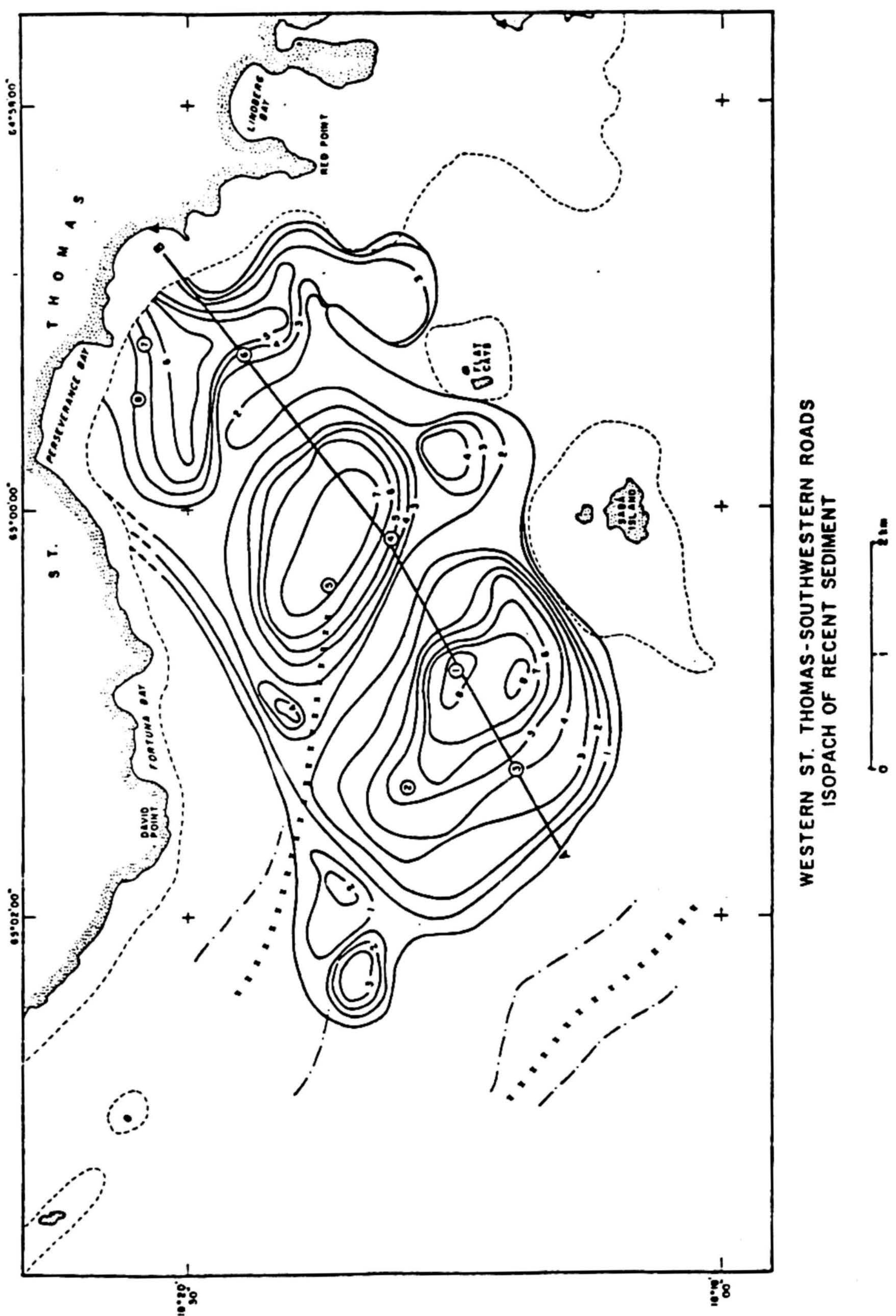

Fig. 3 - Isopach map of sand deposits in the Southwestern Roads region - St. Thomas shelf.

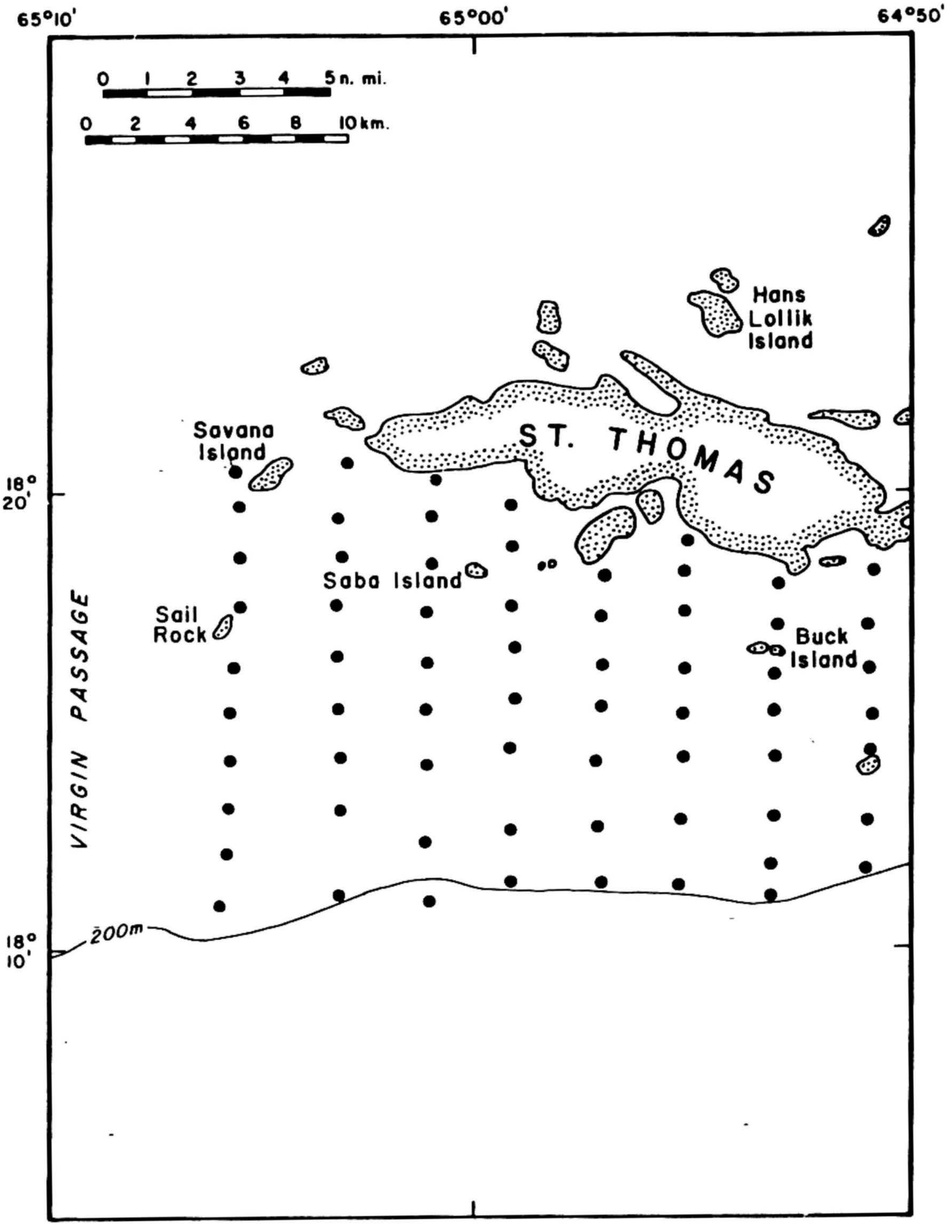

Fig. 4 - Locations of sediment sample sites on the southern St. Thomas shelf, April 1970.

● - Sample site

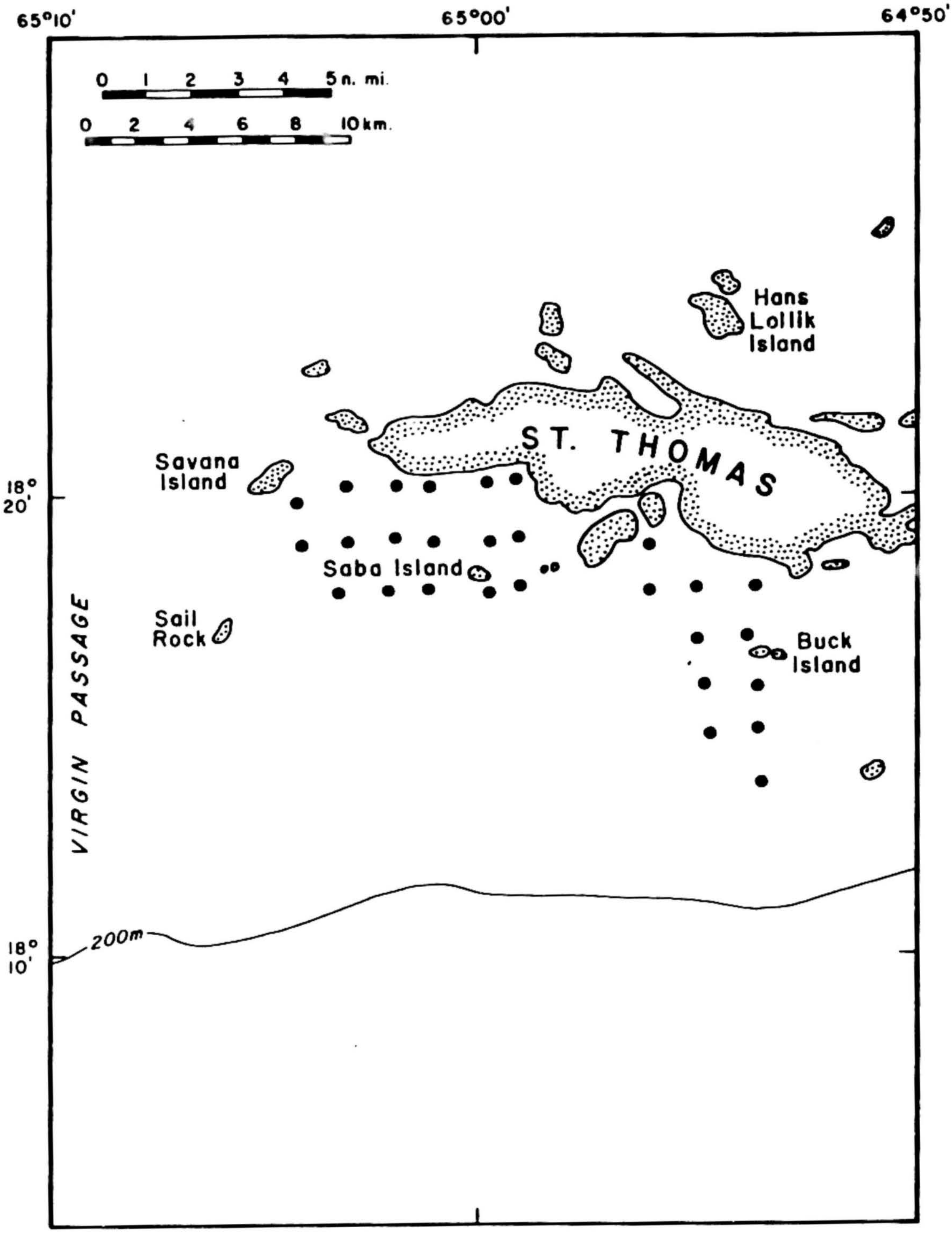

Fig. 5 - Locations of sediment sample sites on the southern St. Thomas shelf, October 1970.

● - Sample site

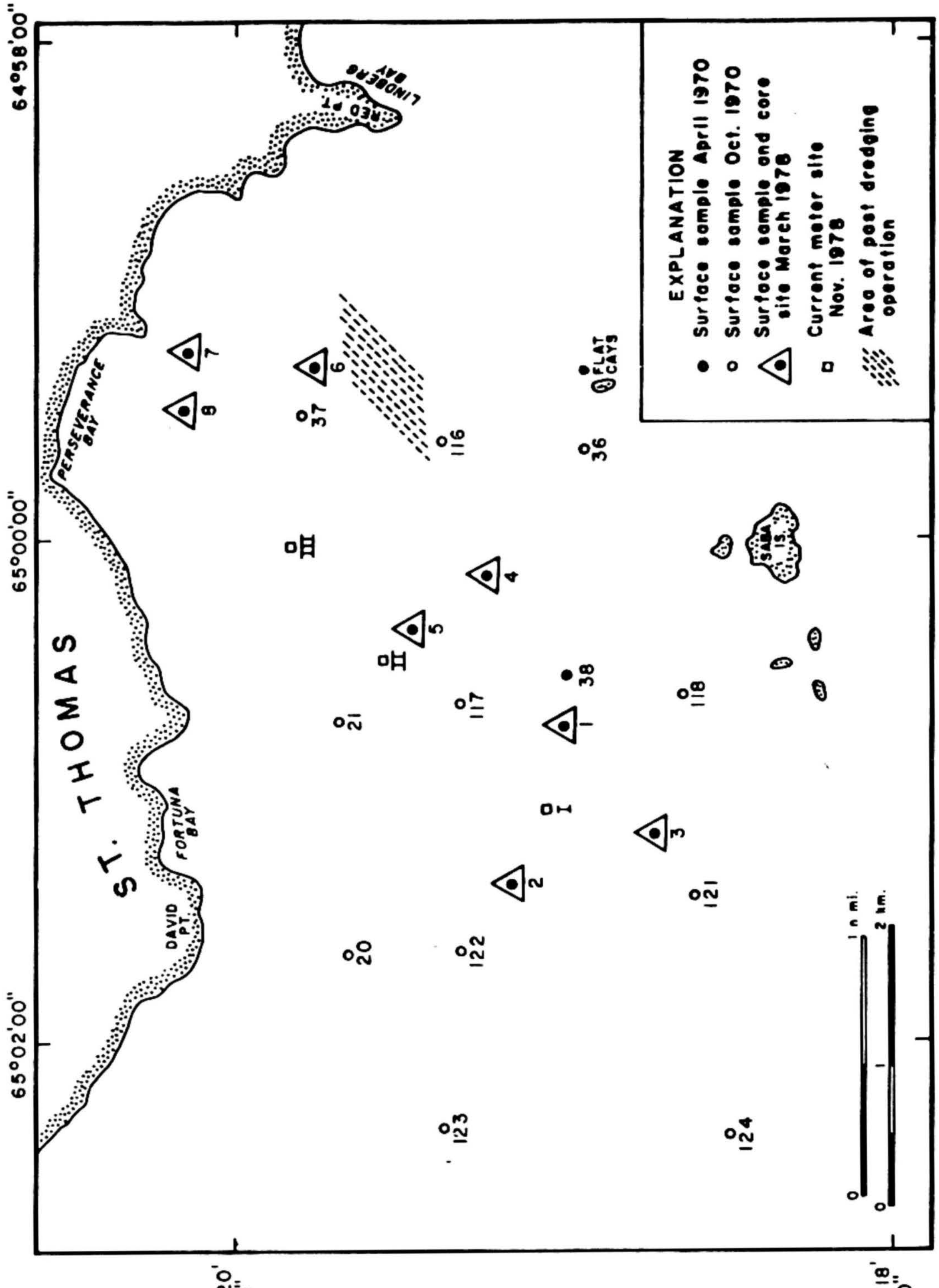

Fig. 6 - Locations of sediment samples collected by SCUBA divers for the detailed studies within the Southwestern Roads region.

The detailed study, to provide samples for determining sand production rates, consisted of intensive surface and subsurface sampling of areas of thick sand deposits (fig. 3). Surface sampling began in October 1970 after a seismic-reflection study to locate thick sand bodies. Sampling techniques used during this phase were similar to those used in phase one, except that sample stations were at intersections of lines approximately 1.7 km apart in both north-to-south and east-to-west directions, and fewer stations were sampled (fig. 5). Further sampling took place in the spring of 1978 after additional seismic work during the fall of 1977 pinpointed areas of thick sand deposits of interest for subsurface sampling. This additional sea-floor sampling (fig. 6) was done by SCUBA divers to provide direct observations and underwater photographs. Because of the heaviness of the Shipek sampler, the divers used a small box core to retrieve a sample equivalent in volume to the Shipek sample. Subsurface sampling (fig. 6) was done by using a Dokken-Circe vibracorer (Dokken et al., 1979). The cores were 6 cm in diameter and had an average length of 5 m. The cores were split in the laboratory, and approximately 50-g subsamples were taken every 25 cm for the first meter and every 50 cm thereafter.

In addition to sampling sediment, we placed Bendix water current meters at three sites (fig. 6). They were set 1 m above the bottom and continually recorded current speed and direction for approximately 1 week. Navigation for the 1978 part of phase two was provided by a miniranger system. The second phase sampling was completed between March 1 and 29, 1979.

The samples were given two washings in tap water and a final washing in distilled water. The samples were then dried under infrared lights and split into three fractions: one for constituent analysis, one for textural analysis, and one for geochemical analysis. The portion used in the constituent analysis was then sieved through a 2-mm sieve to remove the gravel-size fraction. To separate the sand- and mud-size sediments, the <2-mm portion was placed in a 1-liter settling jar. Five hundred milliliters of distilled water was added, and the jar was shaken. After a calculated period of time during which the sand-size grains (0.062 mm-2.0 mm) settled to the bottom, the suspension was siphoned off. This process was repeated until the suspension was visually clear and the suspension upon drying contained no sediments. The sand-size fraction was then passed through a 0.125 mm sieve to separate out the very fine sand fraction. The dried gravel-size, sand-size, and very fine sand-size fractions used for constituent analyses were each weighed to determine their percentage of the whole sample.

The constituent compositions of the gravel and the sand, excluding the very fine fractions, were determined for each sample. A binocular dissecting microscope was used to identify and count a minimum of 300 grains per sample according to the loose-grain point-count technique of Ginsburg (1956) for gravel-size sediment. The greater than 0.125-mm size sand was affixed to a thin section, and the microscopic structures of the grains were analyzed. Again 300 grains were identified and counted per thin section with the aid of a Swift automatic point counter. Identifications of both fractions were made by using Milliman's (1974) keys. The constituent composition counts were categorized (Appendix I) by using Ginsburg's (1956) eight categories except that the Halimeda category was combined with other calcareous green algae and classified as Chlorophyta. Also, the coralline algae group was labeled Rhodophyta. The only difference in counting technique between gravel and sand was that a separate subcategory for barnacles was kept in the gravel fraction. The percentages of barnacle remains were recorded because increases in numbers at certain locations within cores seemed to indicate environmental changes.

The percentage of composition calculated for each of the eight categories counted for both fractions, along with the sample location, were keypunched onto computer cards. A trend-surface program for geologic uses written by Merriam (1968) was used to aid in calculations of zonation trends.

Constituent identifications of the very fine sand and smaller fractions of the sediment were not attempted because of the difficulties and expenses involved. However, a group of 12 samples of the very fine sand fractions was analyzed by scanning electron microscope (SEM) to determine the amount of grain wear and the degree of cementation or recrystalization. We hoped to use the degree of wear or cementation as an index to the amount of transport for the finer size fraction.

In addition to constituent composition, carbon-14 analyses of the cored sediment were made to provide information on past sedimentation rates for use in determining past climatic conditions. Carbon-14 dating was conducted by the Radiocarbon Dating Laboratory of the University of Miami on unprocessed samples taken at 75-cm intervals from cores 3 and 5 (fig. 6).

RESULTS AND DISCUSSION

Analysis of the surface-sediment samples obtained in the first phase of the sampling program reveals that the sediments of the southern shelf are biogenic and that the producers of the material were probably subject to environmental zonation. In both gravel and sand, three categories of biogenic material make up more than 80 percent of the sediment (table 1). The two most productive groups of taxa, Chlorophyta and Mollusca, produced nearly equal amounts of sand and gravel. However, the third-ranking producer of gravel in the samples was Rhodophyta, whereas Foraminifera ranked third in the production of sand. The three major producers of sand and the three major producers of gravel prefer different areas of the shelf.

Table 1. **Average constituent composition of the gravel and sand fractions of samples from the southern shelf of St. Thomas, U.S. Virgin Islands, and the Southwestern Roads region**

	St. Thomas Southern Shelf		Southwestern Roads region	
	Average (percent)	Range (percent)	Average (percent)	Range (percent)
Gravel-size constituents >2 mm				
Chlorophyta	28.2	3.8 - 72.1	21.4	5.7 - 40.0
Mollusca	31.2	4.6 - 60.2	25.7	15.9 - 54.2
Rhodophyta	15.2	.3 - 48.5	21.0	1.1 - 48.5
Foraminifera	3.0	.0 - 13.3	3.9	.2 - 13.3
Coral	1.2	.0 - 5.2	1.9	.0 - 5.2
Misc. skeletal	9.8	2.6 - 36.7	12.4	3.6 - 36.7
Nonskeletal	7.8	.5 - 29.2	7.7	1.8 - 29.2
Unknown	2.8	.0 - 5.0	2.7	.5 - 5.0
Sand-size constituents >1/8 mm & <2 mm				
Chlorophyta	33.6	9.0 - 54.2	31.1	15.3 - 54.2
Mollusca	30.0	16.5 - 52.4	29.7	16.5 - 52.4
Rhodophyta	3.8	.0 - 27.0	4.9	.0 - 8.7
Foraminifera	15.6	3.2 - 29.4	17.1	6.6 - 29.4
Coral	.3	.0 - 2.5	.5	.0 - 2.5
Misc. skeletal	9.9	2.8 - 16.3	10.9	7.6 - 16.3
Nonskeletal	3.4	.6 - 10.6	3.3	.6 - 7.7
Unknown	3.1	1.3 - 4.8	3.5	1.3 - 4.8

The calcareous green algae, Chlorophyta, form the most abundant group. Trend-surface maps indicate two distinct areas of dominance on the southern shelf (fig. 7). Halimeda makes up most of this group, and large Halimeda fragments were identified in several samples. These fragments indicate that a shallow-water species complex, Halimeda incrassata, occupies the nearshore zone and a deeper water complex, Halimeda tuna, occupies the offshore zone. The percentage of Chlorophyta increases shoreward. Chlorophyta makes up 49.0-72.1 percent of the sediment found in the offshore region. Observations by divers and bottom photos in both nearshore and deeper water areas show that Halimeda sand is presently being produced. Although Halimeda grains are quickly infilled with other sediments (Ginsburg, 1956), most of the Halimeda observed was free of infilling and looked very fresh. With the exception of a very few samples near the Virgin Passage (fig. 7), very little wear or recrystallization was noted in the Chlorophyta group.

Molluscs, the second most abundant group, are evenly distributed across the shelf. This group constitutes a substantial percentage (>15 percent) of almost every sample (table 1). The computer trend map (fig. 8) indicates a decreasing percentage of molluscs shoreward across the shelf. This decrease, perhaps, is more related to the increasing abundance of the other groups than to a zonation of the molluscs themselves. Samples analyzed for living material show that live molluscs are still abundant on the southern shelf of St. Thomas.

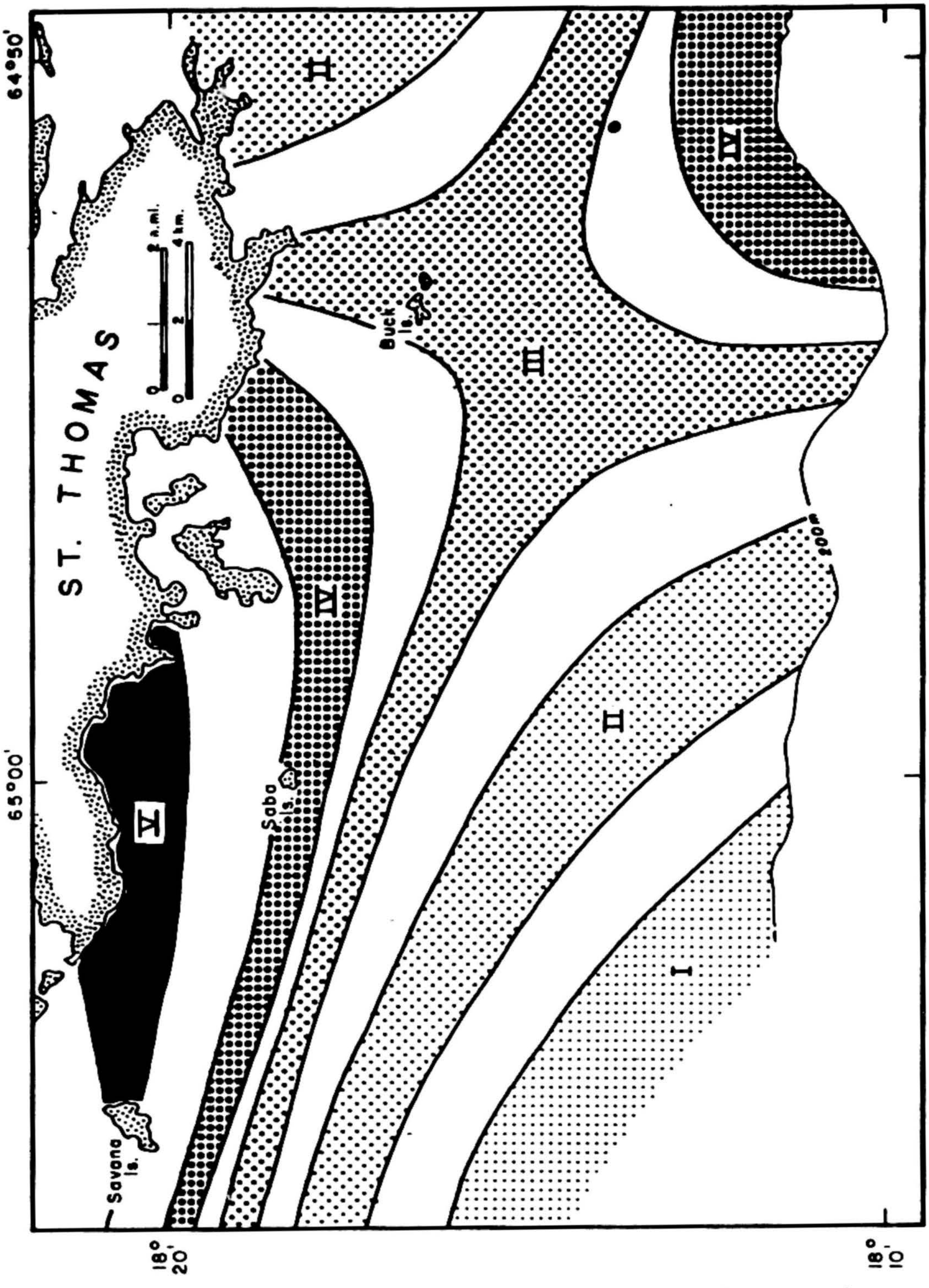

Fig. 7 - Trend-surface map (third order) of Chlorophyta on the southern St. Thomas shelf. Concentration of Chlorophyta increases from I to V.

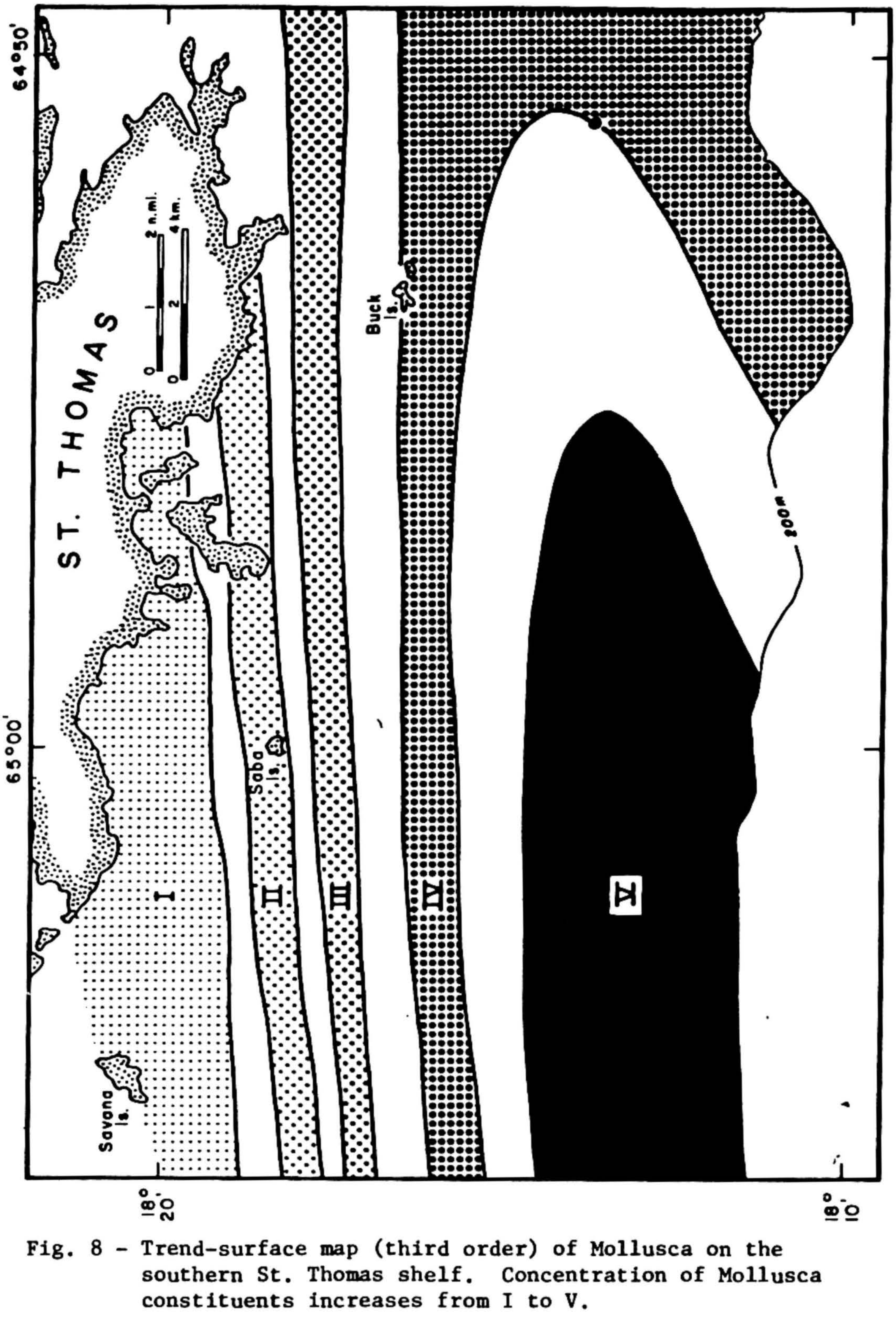

Fig. 8 - Trend-surface map (third order) of Mollusca on the southern St. Thomas shelf. Concentration of Mollusca constituents increases from I to V.

The calcareous red algae, Rhodophyta, are the least abundant class and have the greatest variation in numbers of the three major classes in gravel-size sediment. The computer trend map (fig. 9) shows that this group increases towards shore. Scuba divers observed that the Rhodophyta are greatest in number in a shadowlike pattern leeward of the nearshore islands and that most of the Rhodophyta are living in these areas. Most sediment formed by this group comes from the articulate or branching species. The Rhodophyta also form, partially or totally, calcareous nodules that form a veneer over the sediments in some areas on the shelf. These nodules, although noted when found, were not studied in any detail.

The Foraminfera are abundant only in the sand-size sediment as the natural size of the tests corresponds to the size of sand grains. The trend-surface map (fig. 10) indicates that the Foraminifera prefer the quieter waters of protected inshore areas. The lack of strong tidal currents probably enhances their survival and eventual addition to the sediment. Although the Foraminifera were not classified by type, almost all are benthic. Live Foraminifera were present in all samples studied for living material.

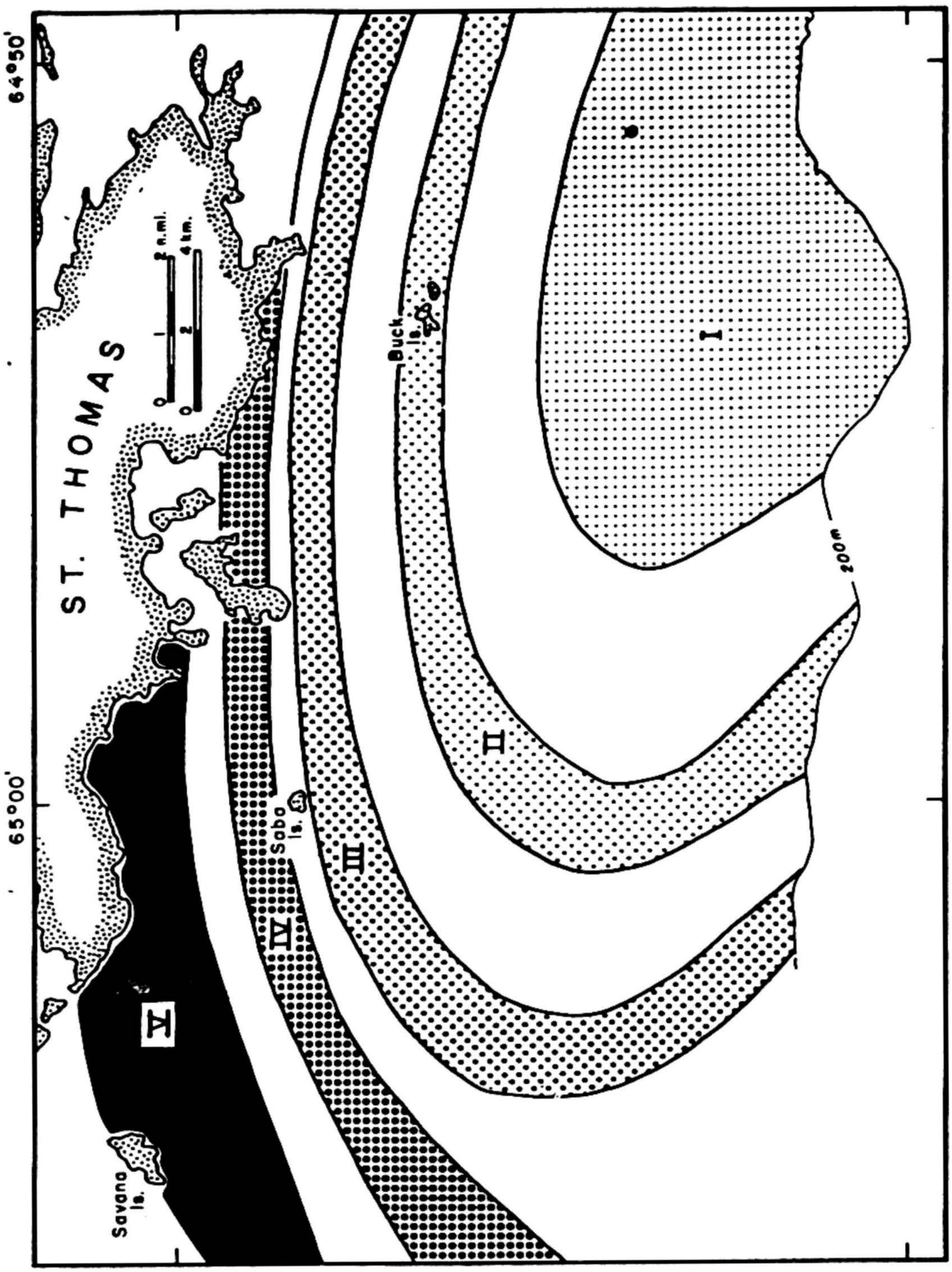

Fig. 9 - Trend-surface map (third order) of Rhodophyta on the southern St. Thomas shelf. Concentration of Rhodophyta constituents increases from I to V.

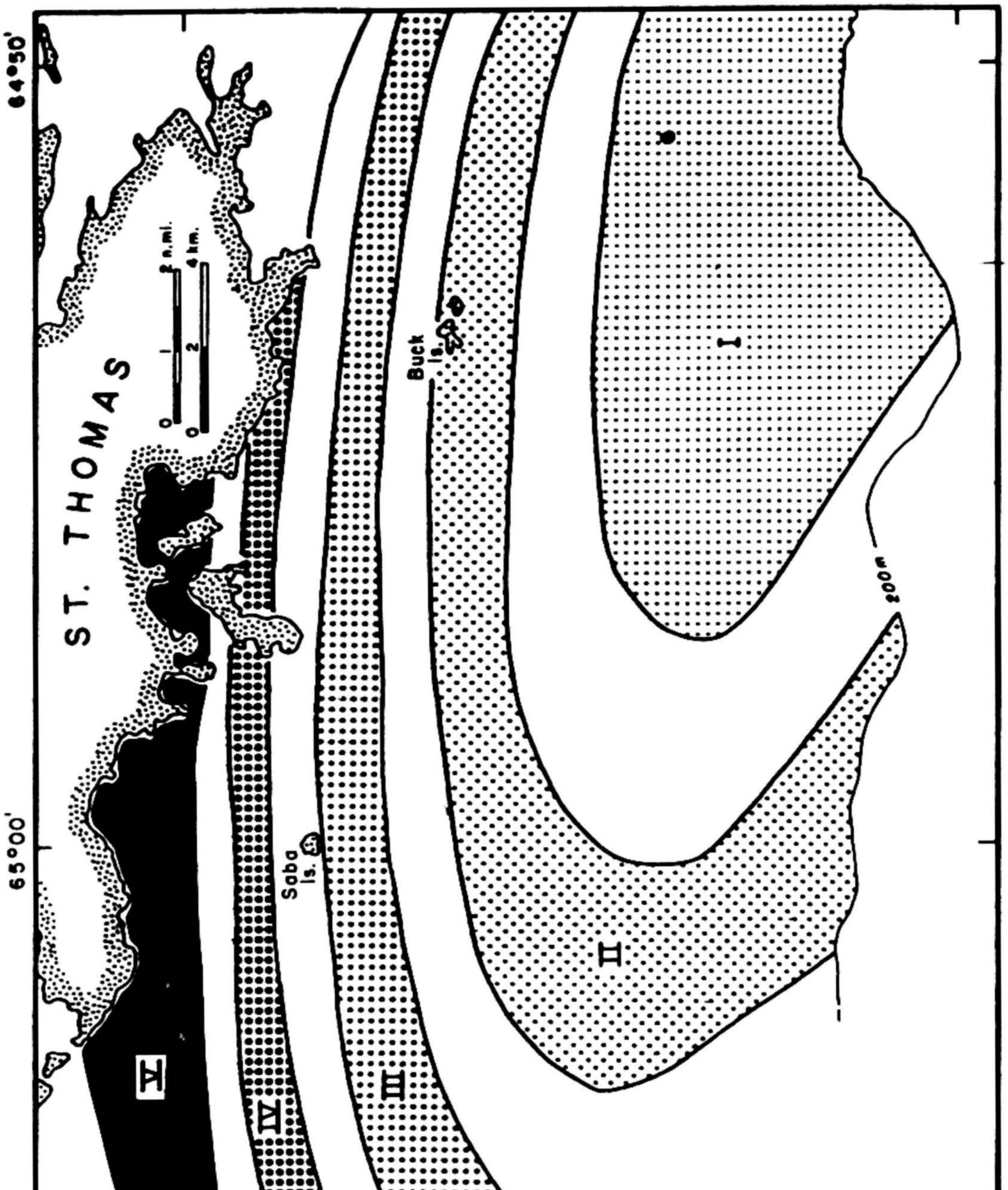

Fig. 10 - Trend-surface map (third order) of Foraminifera on the southern St. Thomas shelf. Concentration of Foraminifera constituents increases from I to V.

The remaining four groups (coral, miscellaneous skeletal, nonskeletal, and unknown) in most places make up less than 20 percent of the sediment (table 1). Almost none of the sediment contains coral. The miscellaneous skeletal category commonly is small and, except in two areas, consists largely of bryozoan and echinoderm fragments. In an area previously dredged (fig. 6), the barnacle percentage has increased dramatically, probably because subsurface sediments were exposed. In the farthest offshore samples, the encrusting Foraminifera become very abundant. The encrusting Foraminifera are placed in the miscellaneous skeletal category because of their difference in habitat from the free-living forms. The nonskeletal category is very small, the remains in this category are usually made up of skeletal fragments cemented together. No grapestones or oolites common in other carbonate areas (Illing, 1954) were found. In all samples, the unknown category is 5 percent or less, indicating that the statistical error is within proper limits (Ginsburg, 1956) for statistically sound data.

Comparison of results of analyses of the subsurface sediments with results obtained from analyses of the sea-floor sediments indicates that sedimentation is a long-lasting ongoing process and provides additional information for interpretation of the sediment budget. The major sand producers have been the same, with the exception of the Rhodophyta group, which dramatically decreases mostly in the first meter of sediment to become a very minor constituent (fig. 11). The Chlorophyta group percentages vary only slightly throughout all cores, except for a marked decrease at -200 cm in core 5 and an increase at -250 cm in core 3. Minor sediment infilling is noted in *Halimeda* grains in the lower parts of the cores, but no recrystallization appears to have taken place. The mollusc group is at an almost constant level of abundance throughout all cores. In all cores, the percentage of Foraminifera gradually increases mostly in the first meter of sediment; this group replaces the Rhodophyta group as third in importance as an earlier sediment producer. Below the first meter of sediment, the numbers of Foraminifera level off and remain stable in all but cores 2 and 3, where the number of Foraminifera decreases abruptly in the lower parts of the cores. A significant increase in the barnacles, which are counted as a subgroup of the skeletal category, also corresponds to the Rhodophyta decrease. The barnacles were identified by Dr. William Newman of Scripps Institution of Oceanography as being of one species, *Balanus venustus*, a subtidal species whose members live on loose-sediment bottoms.

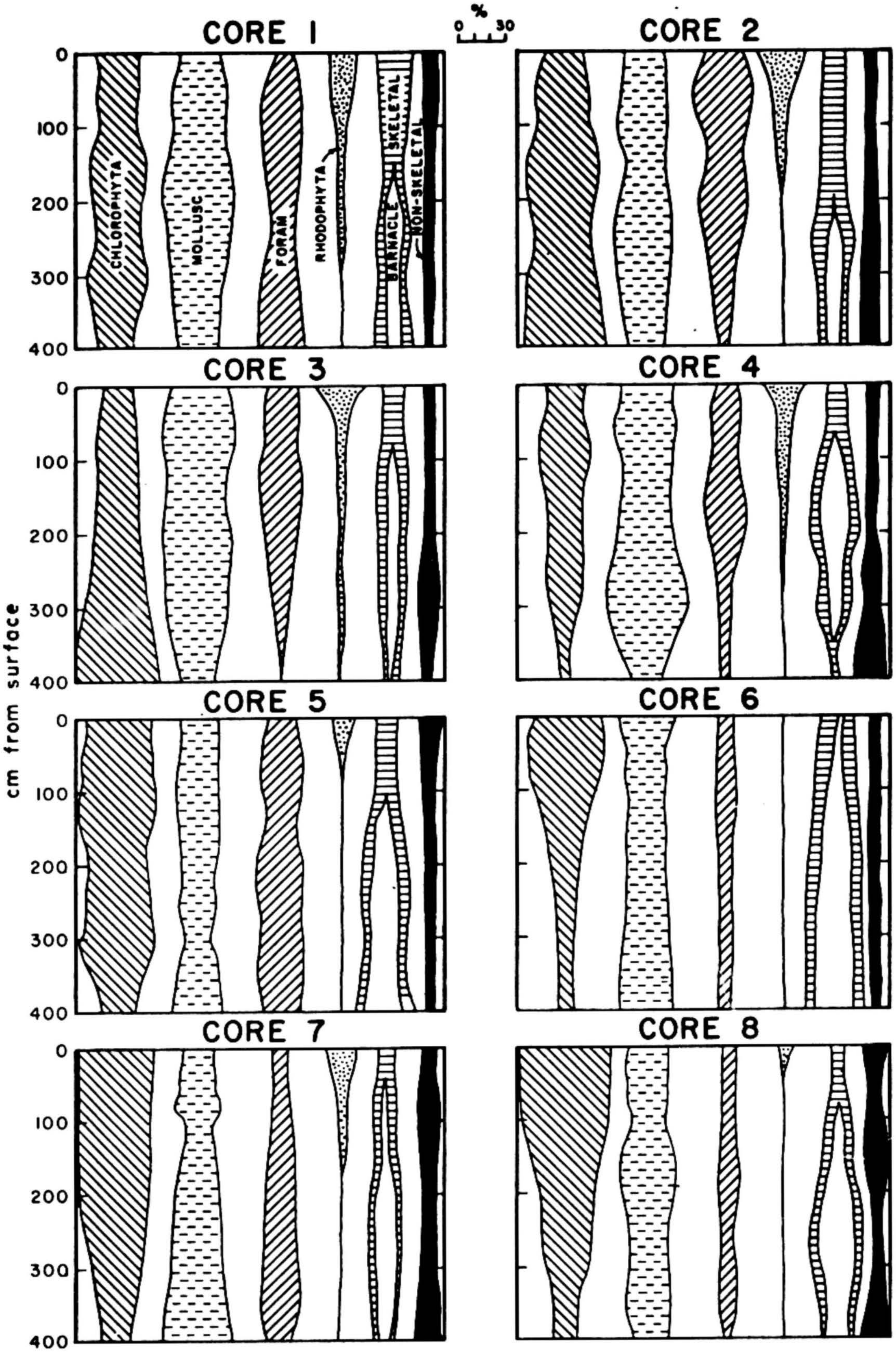

Fig. 11 - Constituent percentage of cores taken from the Southwestern Roads region.

The textures of the sea-floor and subsea-floor sediment are distinctive. The surface sediment is bimodal and contains a gravel fraction and a fine sand (0.3-0.15 mm) fraction. Below the surface of the sea floor, however, the nodules are extremely rare, and fine sand is dominant. The mud fraction (<0.062 mm) ranges from 10 to 20 percent and also has a tendency to increase as depth increases. One remarkable feature of the sediment is the very low (1-3 percent) content of insoluble material.

No diagenesis was noted in samples analyzed for constituent percentages, and grain wear was indicated only in samples from near the Virgin Passage area (fig. 4). Samples of the very fine sand of core 5 were studied by SEM photographs and revealed no evidence of submarine cementation or recrystallization of carbonate grains. These photographs support the observed absence of diagenesis in the carbonate sands of cores taken in the Southwestern Roads region.

Carbon-14 dates in cores 3 and 5 from the Southwestern Roads region indicate fairly steady accumulation of sediment during the last 5,000 years at a rate of slightly less than 1 mm per year ($\sim .2 g/cm^2/yr$) (fig. 12). This rate agrees with production rates determined by Adey (1975) for the St. Croix shelf. Comparison of the cores shows that the production rate is very similar in both cores. The lower part of core 3 is older, probably because the core is farther offshore (fig. 6) and in the deeper water. As sea level rose from its last low stand, this area would have been submerged first; thus, carbonate production would have begun earlier.

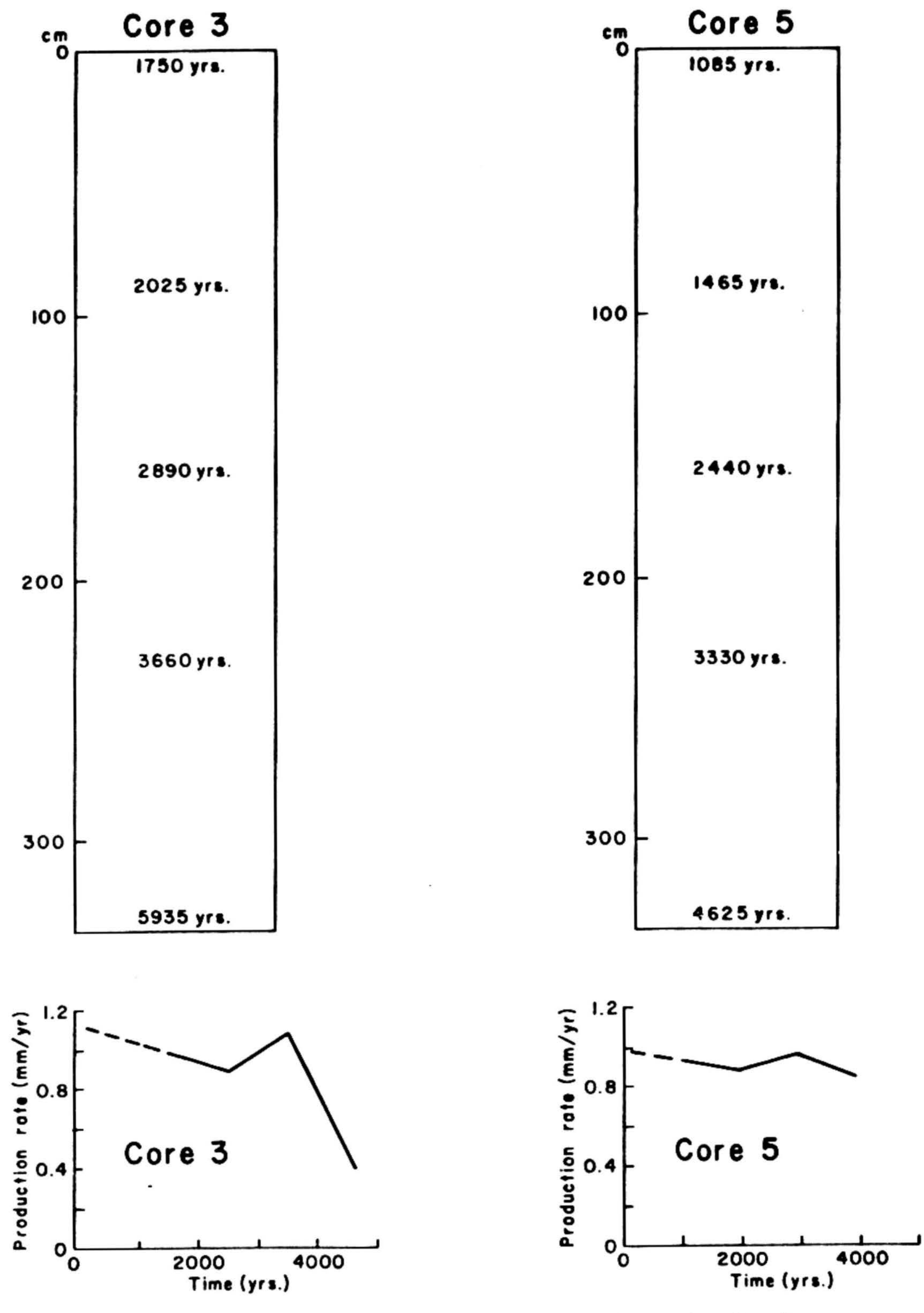

Fig. 12 - Carbon-14 dates of cores taken from the Southwestern Roads region.

Dates of sediment at the sea-floor level in both cores are older than would be expected. These older dates could be a function of the incorporation of older carbon into the carbonate presently being produced or of the mixing action of bioturbation, which would combine older sediments with those presently being produced. Older carbon is incorporated within living systems at a fairly constant rate in each geographical region. The effect of bioturbation can be roughly calculated if we know the rate of sedimentation and depth of turbation. According to Clifton and Hunter (1973), large amounts of carbonate sand can be moved vertically. They observed biomixing to depths of 20 cm. If biomixing at the sites of cores 3 and 5 did extend this deep, then the dates indicated at the tops of the cores may be reasonable. Although correcting the dates to zero time is difficult, the consistency of dates below the area of mixing indicates that production rates typical of slow continuous sand deposition in the Southwestern Roads region are probably correct.

Measurements of direction for water flow in the Southwestern Roads region demonstrate a semidiurnal cyclic ebb and flood pattern of water movement (fig. 13) that has predominance in two almost opposite directions. Direction of water flow changed fairly rapidly and very little current was noted during the change. The direction of greatest flow (flood tide) varies from northerly to westerly (fig. 14) and is probably the result of bottom topography. At all sites, a reverse current (ebb tide) flows in almost the opposite direction of strongest flow. This reverse current is nearly 180° opposite the dominant current except at site III, where it averages 180° opposite the dominant current. During the spring, when the current readings were recorded, the tradewinds blow steadily from the east (Towle, 1976). These winds are probably responsible for the dominance of the flood-tide current which flows almost downwind. The reverse current is therefore weakened and slightly diverted (Ekman spiral) by flowing into the wind. However, because site III is nearer land and is in more protected waters, the effect of the wind on water movement is probably reduced, and the two directions of current flow are more nearly opposite. Bottom topography influences both current direction and speed. The current meter at site II, which was in a low area between the two large sand bodies (fig. 14), recorded water speed of more than 1 knot on several occasions. Currents were weaker at sites I and III, which are in more protected waters on topographic highs. Divers noted coarse carbonate sand at all three sites, but no indications of sediment transport such as ripple marks or scour were seen. Although the data are limited, the observed water movements follow the tidal rhythm; a very regular pattern establishes the dominance of tidal control, and wind and bottom topography are secondary influences on water currents of the insular shelf of St. Thomas. The maximum current on the sea floor was 1 knot. The measured water-surface current was 1.5 knots.

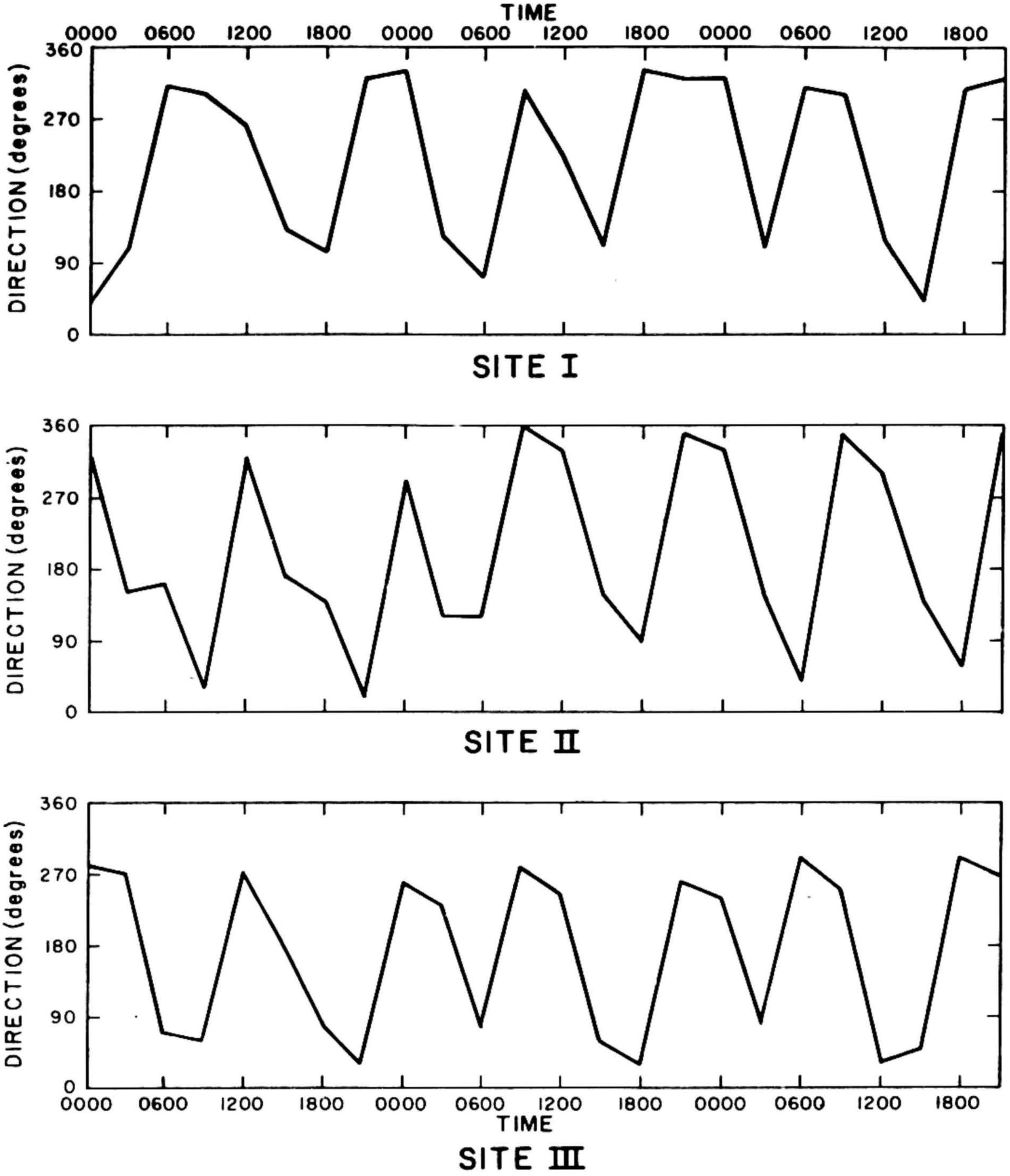

Fig. 13 - Water-current-direction graphs of the Southwestern Roads region
The three current-meter sites are shown in figures 6 and 14.

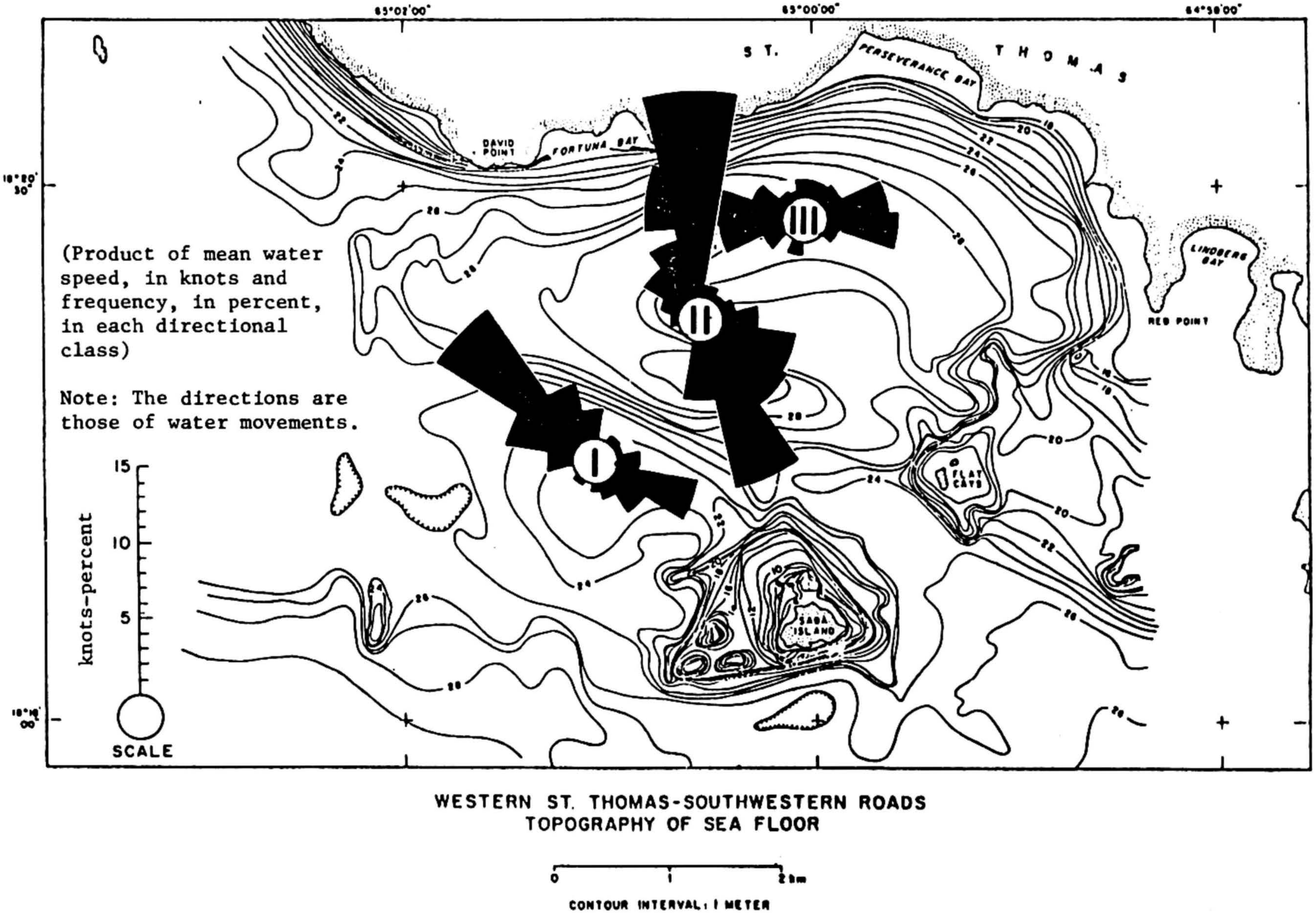

Fig. 14 - Water-current measurements of Southwestern Roads region.
I, II, III = current-meter sites.

CONCLUSIONS

Data from both the surface and subsurface samples indicate that most of the sediment is produced in situ. The absence of grain wear and sediment transport indicators such as ripple and scour marks indicate little movement of sand-size sediment. However, water currents probably transport silt- and clay-size sediment and may be largely responsible for variances in water clarity. The type and amount of biological production from area to area seem somewhat influenced by water movement, which may supply nutrients or may suspend fine sediments, therefore reducing sunlight penetration. Additional support of in situ production comes from observations of living constituents in the study areas. These observations show that percentages of living sediment-producing organisms are similar to percentages of the dead organisms in the sediment of that area. Studies by Chave et al. (1972) indicate that sediment production is well within the capabilities of the fauna and flora found in the study area. Environment controls the type and amount of biogenic sediments produced. The changes in sediment zonations in the study are inferred to be the result of environmental control of biogenic production.

Comparison of zonations with the bathymetry (fig. 15) of the area indicates a strong correlation between water depth and the biota. Water-temperature and amount of sunlight are considered by most authors to be the most important environmental factors affecting biogenic carbonate production. Water temperature measurements (Towle, 1976) taken on the St. Thomas southern platform average 26.5°C and vary less than 2°C throughout the year. Such a narrow range probably excludes temperature as a major influence on carbonate production here. Sunlight, therefore, seems to be the dominant influence, and its penetration is directly related to water depth. Because a direct relationship exists between sunlight and photosynthesis, the marine plants and fauna containing symbiotic algae would be most sensitive to sunlight change. The marine animals without symbiotic relationships, although indirectly dependent upon sunlight, would be affected less by change. This dependence on sunlight accounts for the decrease in the Chlorophyta and Rhodophyta groups as available sunlight decreases with increasing water depth. Thus, offshore the Chlorophyta group gives way to the mollusc group as greater water depth begins to limit photosynthesis. An exception to this is shown in figure 7 where the deeper water species complex of Halimeda tuna is found in large numbers. However, in general, nearshore or shallow waters would be most productive, except for very shallow areas where wind-generated current flow creates turbidity and thus lowers sunlight penetration.

Fig. 15 - Bathymetry of the Southern shelf of St. Thomas (Holmes, 1978).

The area studied in the Southwestern Roads region is productive of carbonate sediment because here, the shallowness (20-30 m) and low turbidity allow sunlight penetration and, hence, species production. Shallower waters nearshore tend to have more turbidity because of greater susceptibility to wind-driven currents (direct observations by SCUBA). The Southwestern Roads area also is partially protected from strong currents by offshore islands, and the water is probably less turbid than open shelf waters. The productivity of this area probably accounts for the thickness of the sand deposits here.

The similarity of the surficial and subsurface sediments indicates that sediment production has been a continuous process during the time span represented by the cores. The appearance of the barnacle fragments at the approximately 1.5-m level (fig. 11) in cores and the decrease in Rhodophyta between the sea floor and the 1.5-m level may indicate subsidence of the region, causing an increase in water depth over the shelf. Tectonic subsidence is suggested by geophysical records in that area (Holmes, 1978). Subsidence, creating an increase in water depth would cause a change in the environment in the Southwestern Roads area (fig. 16) from a protected lagoon to the open-shelf conditions of today. Tidal currents would be able to sweep the area with much greater effect. Habitat and food supply might have changed. This change in environment from a relatively shallow protected area to an open-marine environment could account for the disappearance of Balanus venustus from the area approximately 1,500 years ago (W. A. Newman, oral communication, 1979). The increase in water depth has probably provided a habitat suitable for the Rhodophyta, which seem to prefer the deeper calm waters in areas protected from the full force of tidal currents. This increase in water depth would account for the increase in Rhodophyta in the uppermost 1 m of sediment and on the lee side of offshore islands. Although water depth appears to have increased during the past few thousand years, this change seems to have had little effect on the other sediment producers or on the rate of sediment production.

Indications are that the sediment budget of the southern shelf has remained fairly stable during the past 5,000 years and is controlled by in situ biogenic production of carbonate sediment.

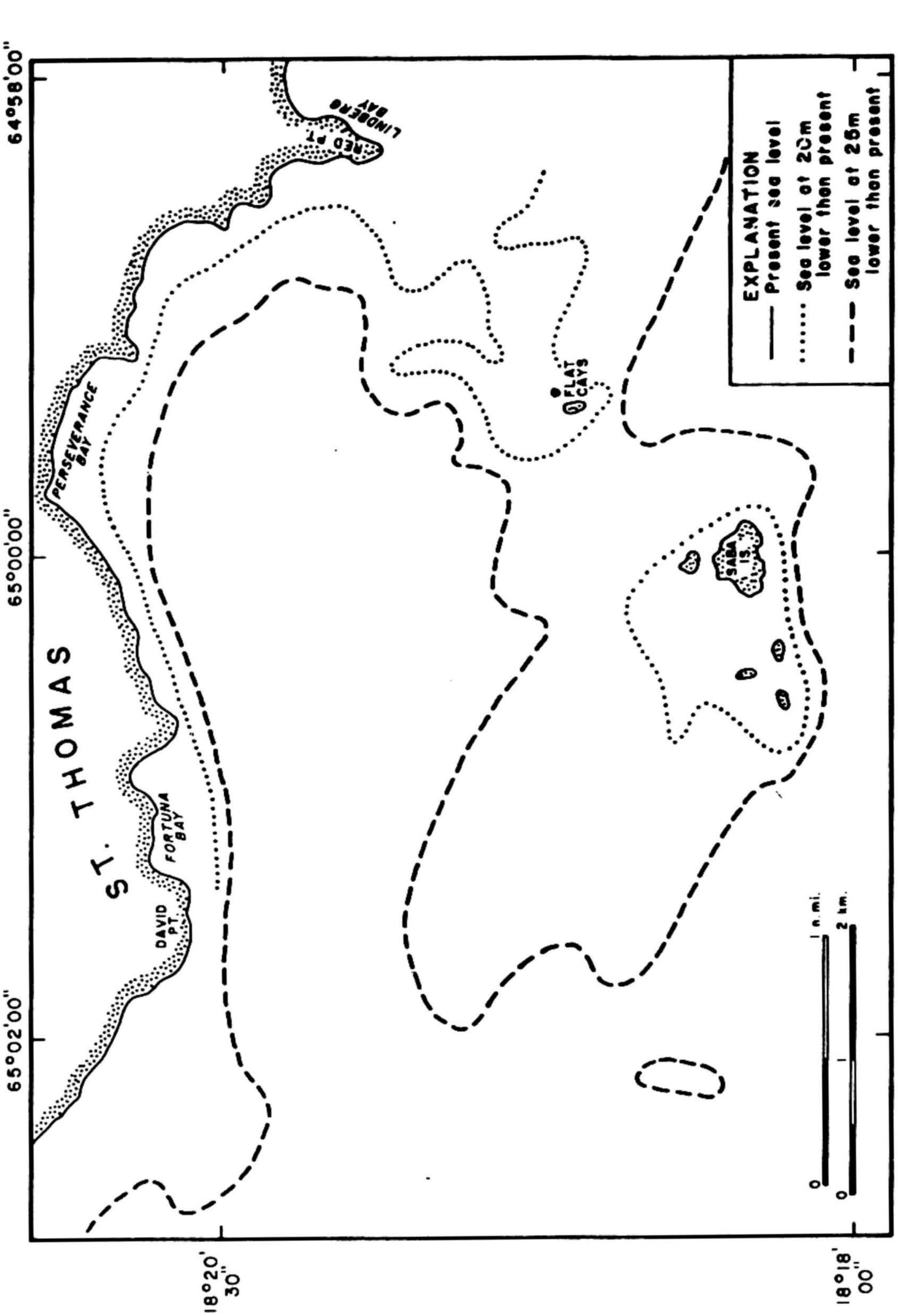

Fig. 16 - Shoreline of Southwestern Roads region at lower relative sea levels.

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APPENDIX I

EIGHT CATEGORIES OF CARBONATE SEDIMENT

We grouped the constituents of our sediment samples into eight categories defined by Ginsburg (1956).

Chlorophyta

The calcareous green algae are represented in Virgin Island sands by the family Codiaceae. This family is recognized by the tubelike structures of the plant segments. *Halimeda* is by far the greatest carbonate producer of this group in the sands studied. *Halimeda* is easily recognized by the porous flat plates. Although the porous structure is commonly infilled by carbonate recrystallization, the relic structure can usually be recognized. Grains were assigned to this category whenever an indication of this tubelike structure was observed.

Mollusca

Mollusca include bivalves and gastropods. Grains were placed in this group if shape, transparency, or crystal arrangement were diagnostic of molluscan structure. In loose grain counts, suspected mollusc fragments showing excessive wear or alteration by other organisms could be determined by gently removing outside layers with a weak HCl solution. Identifications in thin sections were made according to microstructure under polarized light.

Rhodophyta

The calcareous red algae are represented by the family Corallinaceae and are often referred to as coralline algae. Grains belonging to this category are easily identified by the distinct rectangular cell structure. The Corallinaceae have two different forms of growth. The free-standing or branching forms are called articulated, and the encrusting forms are called crustose. When the latter form was found to make up more than 50 percent of the grain of sand, the sand was placed in this category.

Foraminifera

The Foraminifera category contains only the free-living forms, which are easily distinguished by the shape and chambered structure. Very small fragments in thin sections were determined by the wavy extinction pattern under polarized light.

Coral

Although coral was seldom found in the sands studied, grains were placed in this category if shape, transparency, or microstructure indicated Scleractinian coral origin. Under reflected light, the septa are the distinguishing characteristics for coral identification. In thin section, the radiating extinction of the fibrous or bundle microstructure of the coral fragment make recognition simple.

Miscellaneous Skeletal

The miscellaneous skeletal category consists of all skeletal fragments not covered by the above categories; it includes fragments of echinoderms, bryozoans, crustaceans, (including barnacles) spicules, worm tubes, and encrusting Foraminifera. The echinoderms form a large percentage of this group and were recognized by the cell structure and by unit-extinction under polarized light. Bryozoans were identified by their large cell structure. The grayness and shape of crustacean fragments were their distinguishing features. Both sponge and alcyonarian spicules were recognized by shape (Milliman, 1974). Worm tubes were identified by shape and the parallel structure in thin section. Encrusting Foraminifera were recognized by large cell structure having pores and encrusting nature. Grains were placed in this group if more than 50 percent of them consisted of encrusting Foraminifera.

Non-skeletal Grains

Non-skeletal grains are all grains that could be determined not to originate from skeletal production. Rock fragments were seldom found but could be recognized by shape and, in thin section, by crystal structure. Also placed in this group were aggregates of small fragments. Although these grains often consisted of skeletal debris and were probably formed as a result of biological activity, they were assigned to this category because they had no direct skeletal relationship. Very few fecal pellets, ooids, and lumps, as described by Illing (1954) were found, but, when found, they were placed in this category. This category made up only a small percentage in all but a very few samples.

Unknown

The unknown includes any grain whose origin could not be determined. The count of grains in a sample was considered valid if this group consisted of 5 percent or less of the sample.