SEDIMENTOLOGIC HISTORY OF THE LOXAHATCHEE RIVER ESTUARY, FLORIDA

By Harold Wanless and Victor Rossinsky, Jr., University of Miami;
and Benjamin F. McPherson, U.S. Geological Survey

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4120

Contract Number: 14-08-0001-G-759
Name of Contractor: University of Miami
Principal Investigator: Harold Wanless
Contract Officer's Representative: Benjamin F. McPherson
Short Title of Work: Loxahatchee River, Florida
Effective Date of Contract: February 15, 1981
Contract Expiration Date: February 15, 1981
Amount of Contract: $33,351
Date Report Is Submitted: March 1984

Prepared in cooperation with the

FLORIDA DEPARTMENT OF ENVIRONMENTAL REGULATION, SOUTH FLORIDA WATER MANAGEMENT DISTRICT, PALM BEACH COUNTY, MARTIN COUNTY, JUPITER INLET DISTRICT, LOXAHATCHEE RIVER ENVIRONMENTAL CONTROL DISTRICT, TOWN OF JUPITER, VILLAGE OF TEQUESTA, JUPITER INLET COLONY, and the U.S. ARMY CORPS OF ENGINEERS

Tallahassee, Florida

1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 3015
227 North Bronough Street
Tallahassee, Florida 32301

Copies of the report can be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, Colorado 80225
(Telephone: (303) 236-7476)

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

For use of readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in)
centimeter (cm)	0.39	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square meter (m^2)	10.76	square foot (ft^2)
cubic meter (m^3)	35.3	cubic foot (ft^3)
cubic meter per second (m^3/s)	35.3	cubic foot per second (ft^3/s)
metric ton (t)	1.102	ton (t)
gram per square meter (g/m^2)	8.922	pound per acre (lb/acre)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8°C + 32$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level, is referred to as sea level in this report.

SEDIMENTOLOGIC HISTORY OF THE LOXAHATCHEE RIVER ESTUARY, FLORIDA

By Harold Wanless and Victor Rossinsky, Jr., University of Miami;
and Benjamin F. McPherson, U.S. Geological Survey

ABSTRACT

Short-term and long-term history of sedimentation in the Loxahatchee River estuary was evaluated based on field sampling and observations, as well as on laboratory analyses of core borings taken through the Holocene sedimentary sequences within the estuary basin. In the main body of the estuary away from sandbars, the sedimentary sequences were dominated by bioturbated mud, or mottled muddy sand, to depths of about 30 centimeters below the sediment surface and by interlayered sand and mud with high-organic content below the bioturbated zone. The biological reworking of the near-surface sediment is interpreted as the result of increased marine influences, possibly associated with "permanently" opening and maintaining Jupiter Inlet since the late 1940's and with altered freshwater runoff.

Sedimentation rates based on radiocarbon dates have decreased from 0.69 millimeter per year about 7,000 years ago to about 0.25 millimeter per year 1,000 years ago. Although this trend is associated with a decrease in the rate at which sea level has been rising, sedimentation rates nevertheless have not kept up with rises in sea level. Although not recognizable in the sedimentary sequence, periods of erosion and nondeposition might explain the apparent anomalously low-sedimentation rates.

Other evidence indicates that sediment is being provided to the estuary at much higher rates than it is actually accumulating, and this suggests that dynamic physical processes of circulation and flushing are inhibiting rapid sediment accumulation. The sources of the sediment that accumulate in the estuary include: (1) fine-grained suspended material brought into the estuary through Jupiter Inlet; (2) biological material produced in the estuary; (3) fine-grained suspended material, including sand and detritus, carried down the river or other tributaries; (4) medium to coarse sand transported as bedload; and (5) fine, medium, and coarse sand suspended during highly turbulent storm periods.

The thin sand laminae in the organic-rich mud of the mid-estuary sediment sequences were deposited primarily from a suspended load. Somewhat thicker sand layers in the mud probably represent catastrophic conditions of highly turbulent transport. The tidal sandbar, about 3 kilometers from Jupiter Inlet, is being built by sand transported from the ocean primarily in suspension. The river delta bar at the upstream reach of the Northwest Fork embayment is built primarily by bedload transport of sand down the river during periods of large freshwater discharges although about 25 percent of the sand in this bar was probably transported as suspended load from upstream.

INTRODUCTION

The Loxahahatchee River estuary empties into the Atlantic Ocean at Jupiter Inlet (fig. 1). The estuarine system consists of three forks--Southwest Fork, North Fork, and Northwest Fork. The Northwest Fork has the longest reach. The three forks converge 3.2 km from the ocean. Between the confluence of the three forks and Jupiter Inlet, the estuary is intersected by the Intracoastal Waterway. From Jupiter Inlet, estuarine conditions extend 8 river km up the Southwest Fork, 9.7 km up the North Fork, and 16 km up the Northwest Fork. Four major river tributaries discharge to the Northwest Fork. Canal-18 (C-18), built in 1957-58, is the major tributary to the Southwest Fork. The North Fork has several small unnamed tributaries.

The Loxahatchee River estuary has an average depth of 1.2 m below sea level. Sandbars and oyster bars in the central embayment of the estuary are occasionally exposed at low tide as is much of the forested flood plain in the Northwest Fork. Some of the deeper parts of the estuary are a result of dredging. In the Northwest Fork, a natural river channel with maximum depths of 3 to 6 m below sea level extends upstream to approximately river km 14.5. Farther upstream, maximum depths are generally less than 3 m.

Unlike more northerly estuaries, upland drainage into the Loxahatchee provides only quartz sand, organic detritus, and some opaline silica tests of diatoms. Clay minerals are not present in the swampy drainage basin, and only a very small amount of clays are provided from the ocean. Clay minerals make up less than 5 percent of the mud in the estuary. The amounts of fine sediment provided and their character of accumulation can, thus, be expected to be very different from estuaries receiving significant clay mineral input.

Historical evidence (B. W. DuBois, written commun., 1976) indicates that the estuary periodically closed and opened to the sea as a result of natural causes. Originally, flow from the Loxahatchee River along with that from Lake Worth Creek and Jupiter Sound helped keep the inlet open. Near the turn of the century, some flow was diverted by construction of the Intracoastal Waterway and the Lake Worth Inlet and by modification of the St. Lucie Inlet (Vines, 1970). Subsequently, Jupiter Inlet remained closed much of the time until 1947, except when periodically dredged. After 1947, it was maintained open by dredging (U.S. Army Corps of Engineers, 1966). A detailed description of dredging in the inlet and in the estuary was outlined by McPherson and others (1982).

In the early 1900's, the inlet was opened by man on several occasions. In 1921, the Jupiter Inlet District (JID) was established, and in 1922 the District dredged about 76,000 m^3 of sediment from the inlet and constructed jetties. The JID dredged the inlet again in 1931 and 1936 and every few years after 1947 (Caleb Christian, written commun., 1980).

Dredge and fill operations have also been carried out in the estuary embayment and forks. In the early 1900's, filling at the present site of the railroad bridge narrowed the estuary from about 370 to 310 m at that place. In the mid-1930's to about 1942, areas east and west of the bridge (and from under the bridge) were removed. The material was high in shell content and

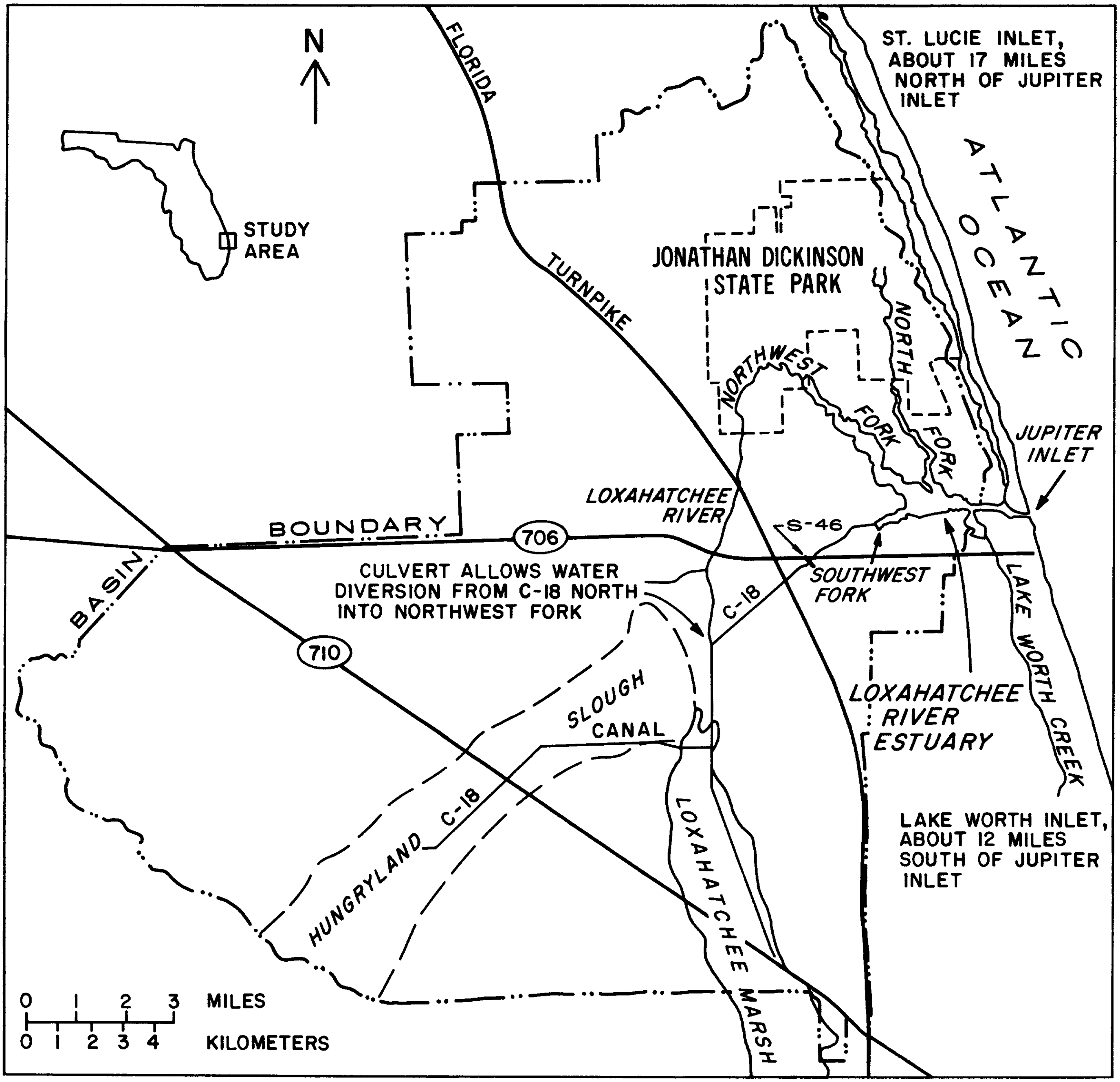

Figure 1.--Location of Loxahatchee River basin and estuary, southeastern Florida.

was used for roads and construction at Camp Murphy, which is now Jonathan Dickinson State Park (JDSP). In 1976-77, an additional estimated 23,000 m^3 were removed from the estuary at the bridge and from an area extending about 180 m to the west. Some dredging was done in the Southwest Fork near C-18 in the late 1960's or early 1970's. In 1980, three channels were dug in the embayment, and an estimated 23,000 m^3 of sediment were removed.

After 1900, man also began to influence the estuary by dredging and by altering drainage in the basin. Generally, ground-water levels were lowered, thereby altering the quantity, direction, and pattern of freshwater inflow (McPherson and Sabanskas, 1980). Historically, the major surface flow to the estuary was into the Northwest Fork from the Loxahatchee Marsh and the Hungryland Slough (fig. 1), both of which drained north (Parker and others, 1955). A small agricultural canal was dug before 1928 to divert a small amount of water from the Loxahatchee Marsh to the Southwest Fork. In 1957-58, Canal C-18 was constructed along the natural drainageway to divert flow from the Northwest Fork to the Southwest Fork of the estuary. A culvert was installed in 1974 to allow water to be rediverted from C-18 to the Northwest Fork.

In recent years, the environmental condition of the Loxahatchee River and estuary has become a major concern to many citizens and agencies. A great deal of controversy has arisen over the environmental well-being of the river and estuary, as well as certain management proposals and decisions related to these water bodies (Cary Publications, Inc., 1978). One major concern has been the sediment transported to the estuary. Large amounts of sediment settling in an estuary might smother bottom life, alter circulation patterns, and accumulate in shoals that impede boat traffic.

The objective of this study was to describe the short-term and long-term history of sedimentation in the Loxahatchee River estuary and to describe the sources, distribution, and transport patterns of sediment in the estuary. The report is based on field sampling and observations, as well as laboratory analyses of core borings taken within the estuary basin.

METHODS

Laboratory Analysis of Core Borings

Initially, 20 vibracore borings were taken to document the long-term history of sedimentation in the Loxahatchee River estuary. The locations of these borings are shown in figure 2. The majority of the cores were from the Northwest Fork because it is the major tributary of the estuary, and the flow is not restricted by water-control gates as is the flow in the Southwest Fork. Vibracore samples ranged from 121 to 586 cm long (table 1). Cores 1 to 6 are rather short because the sandy sediment contained oyster beds that inhibited deep penetration.

Cores were cut into 1-meter sections, split open, and photographed. Cores considered as representative and having adequate penetration were then subsampled. Selected cores were x-rayed. Samples are labeled as follows: The first number refers to the vibracore site; the second number following a dash indicates the sediment depth in centimeters of that sample below the sediment surface. The samples were analyzed in the laboratory for microfaunal and macrofaunal assemblages, grain-size distribution, constituent composition, and radiocarbon age.

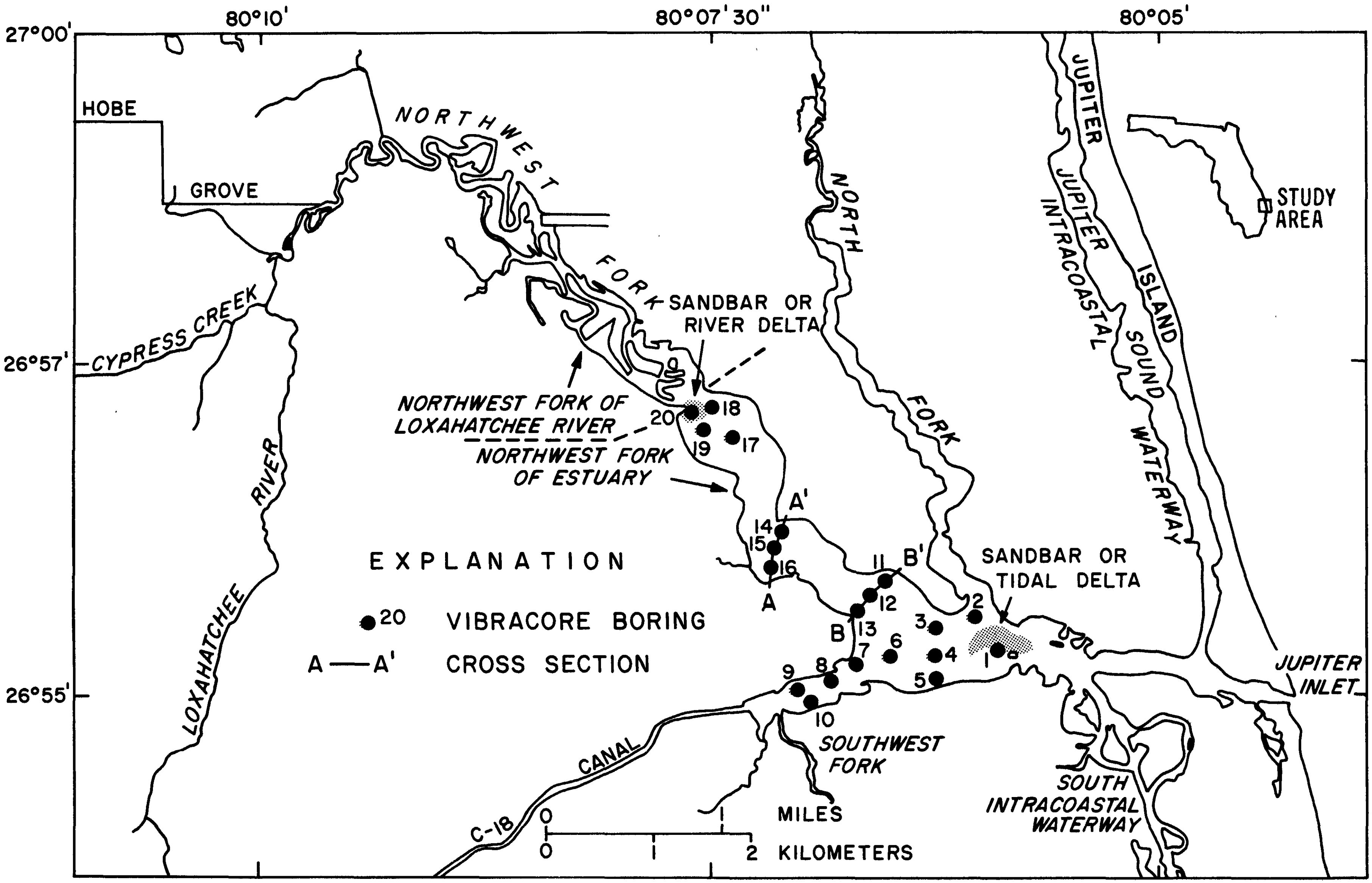

Figure 2.--Location of vibracore sites in the Loxahatchee River estuary.

Table 1.--Vibracore lengths

Core No.	Total length loss and recovery (cm)	Percent-loss and compaction	Percent-recovery	Length of sediment sequence (cm)
1	182	16	84	152
2	205	20	80	165
3	270	17	83	225
4	167	15	85	142
5	148	14	86	128
6	196	38	62	121
7	620	15	85	530
8	640	13	87	560
9	233	26	74	173
10	426	19	81	346
11	607	33	67	407
12	642	17	83	532
13	581	9	91	531
14	455	22	78	355
15	706	17	83	586
16	563	14	86	483
17	623	19	81	503
18	440	20	80	350
19	?	?	?	452
20	637	19	81	517

Subsequently, a series of 24 short cores and 18 surface samples were taken in the field. These were for a detailed evaluation of the most recent history of sedimentation in the estuary and for a study of the character of the surface sediment. Locations for these samples are shown in figure 3.

Sediment Grain-Size Analyses

Forty-six samples were analyzed for grain size by settling in a visual accumulation tube (Inter-Agency Committee on Water Resources, 1957). This method was preferred over sieve analyses because it is a reflection of the hydrodynamic behavior of the particles wherein shape and specific gravity of the grains are considered. These particle parameters become very important where the sediment consists of both shell fragments (flat and commonly less dense) and quartz grains (round). Hydrodynamically equivalent quartz and shell particles would have very different physical sizes as recorded by sieving. Sieving would, thus, yield erroneous results for the purposes of studies of sediment dynamics.

Diving Observations

Characteristics of the bottom surface of the estuary were documented by diving. Several diving transects were made across the Northwest Fork to observe the sites of most short core borings and surface-sediment samplings.

Radiocarbon Analyses

Carbon-14 age dating was obtained from samples of molluscan skeletal remains in the cores, as well as from peat. Eleven samples were analyzed at the University of Miami under the direction of Jerry Stipp. The samples are referred to by two sets of characters (numbers, letters, or both) separated by a dash. The first character, or character set, refers to the core location (fig. 4). The second character set following the dash is always a number and indicates the sediment depth (in centimeters) at which the sample was taken (table 2). The ages, kinds of materials used for the dating, as well as the sediment types and depths where they occurred are given in table 2.

Calculations are based on the Libby half-life of 5,568 years and referenced to the NBS oxalic acid radiocarbon modern standard. The apparent C-14 age compared to this standard has then been corrected for reservoir depletion by subtracting 410 years. The uncertainty quoted is one-standard deviation based only on the random decay of the background, modern, and unknown sample count rates (Jerry Stipp, University of Miami, oral commun).

The majority of the samples analyzed consists of shell material, including the mollusks *Crasostrea virginica*, *Mercenaria mercenaria*, and *Chione cancellata*. Sample 17-479 is a wood sample and 18H-60 is freshwater peat.

The sediment sequence in the Loxahatchee River estuary provides very limited material for C-14 dating. This is especially true for the interlayered sand and mud and the homogenized mud deposits within the estuary. Most shell samples were of necessity derived from the clean or mottled quartz sands beneath the mud or towards the bank of the estuary.

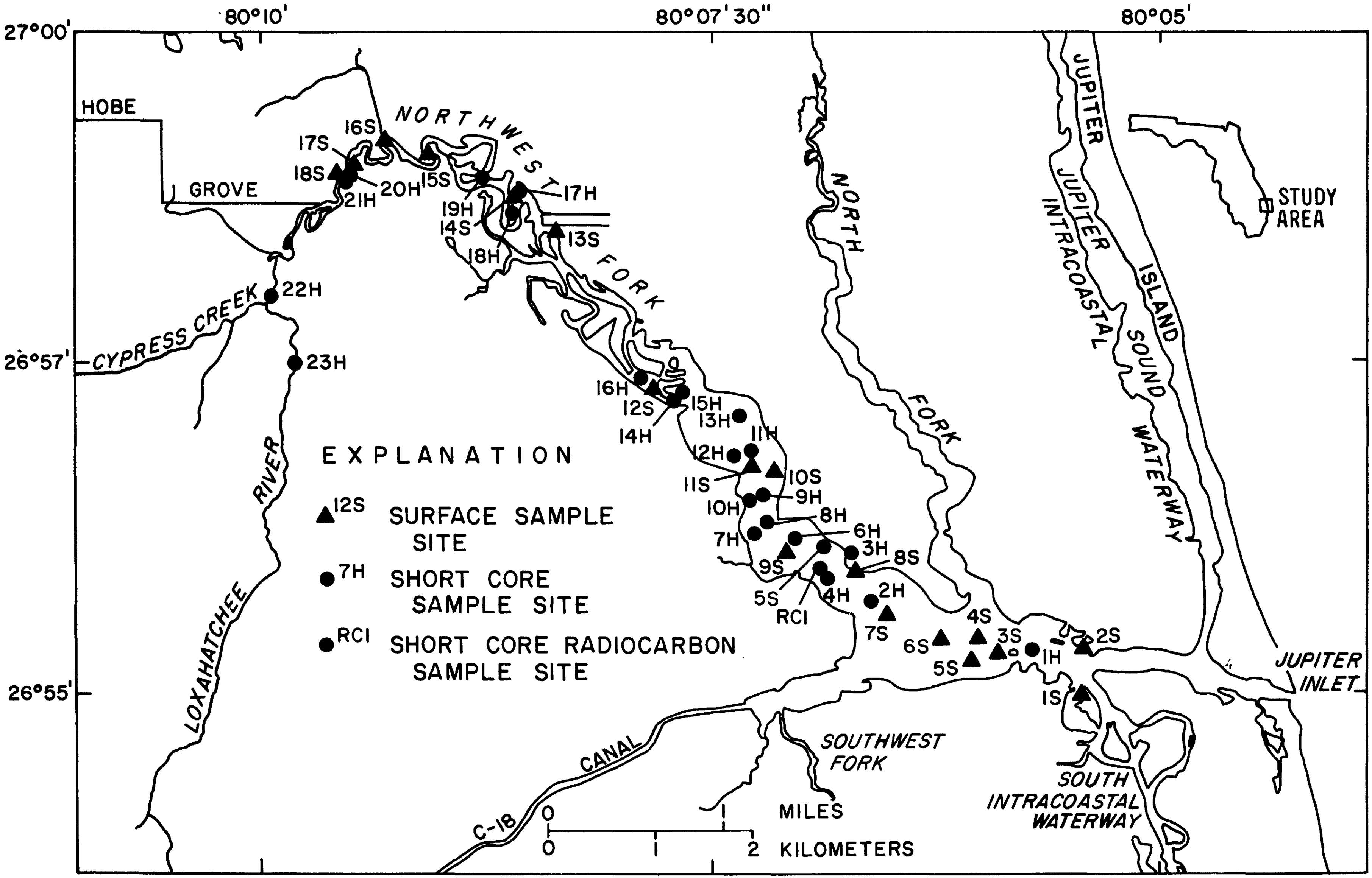

Figure 3.--Location of surface sample and short core sites in the Loxahatchee River estuary.

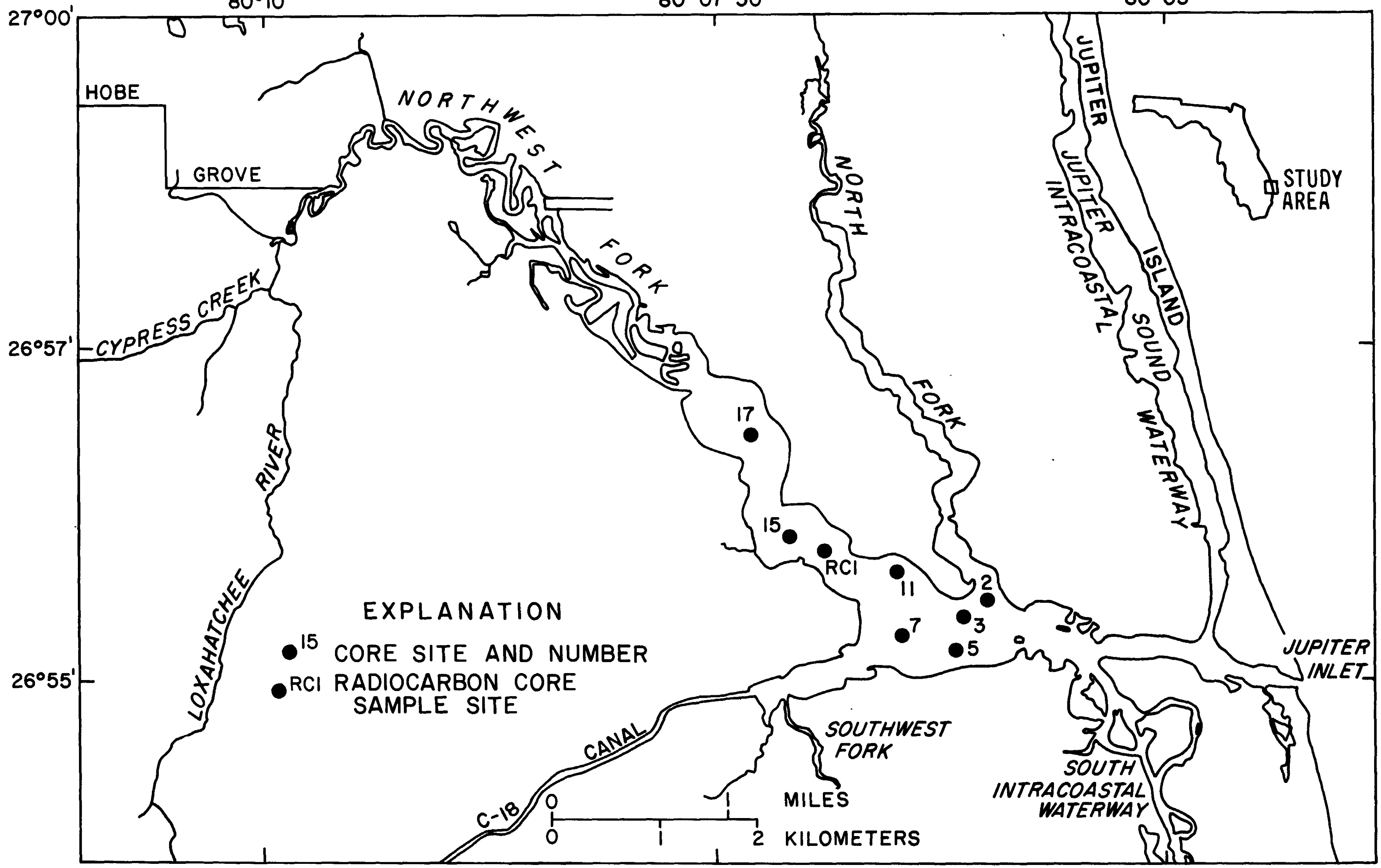

Figure 4.--Locations where material for radiocarbon analyses was obtained, Loxahatchee River estuary.

Table 2.--Radiocarbon age of samples collected in the Loxahatchee River estuary

Sample No.	C-14 age	Material	Sediment depth (cm)	Sediment association
2-77	2600±70	Oyster shell	77	Oyster bed in clean quartz sand
3-49	2680±175	Oyster shell	49	Oyster bed; clean quartz sand above; mottled sand below.
3-100	3630±80	Oyster fragments	100	Shell layer (concentration) in mottled quartz sand
3-110	4610±335	Large oyster fragments	110	Same as 3-100
5-20	1220±50	Shell material	20	Shell layer; mottled quartz sand above; oyster bed below.
7-112	3100±50	*Mercenaria*	112	Mottled quartz sand
11-30	1810±50	Shells and shell fragments.	30	Homogenized mud above; mottled quartz sand below
15-432	7800±70	Unworn grainstone	432	Interlayered sand and mud above; mottled quartz sand below.
17-479	6900±80	Wood	479	Mottled quartz sand with peat above; peat below
RC1-25	990±80	Sieved shell fragments	25	Homogenized mud and interlayered sand and mud
18H-60	1140±50	Peat	60	Clean quartz sand above peat layer.

To obtain at least one date from the homogenized mud near the top of the estuarine mud sequence, several short cores were taken at site RC1. These were extruded on site, and a 10-cm section was taken at a sediment depth of 20 to 30 cm for radiocarbon analysis. These were collected and sieved until enough mollusk fragments, dominantly *Macoma*, were obtained.

Pore-Water Analyses

Four sites in the Northwest Fork (fig. 5) were selected for studying the chemistry of the pore water. A hand core was collected at each site, and salinities of filtered pore water were determined optically by refractometers.

The pH values were recorded by inserting a probe directly into the mud immediately after the core was cut into sections. This was done in the field to prevent exchange with atmospheric CO_2.

Alkalinity was determined by extracting pore water from the mud, filtering through a 0.4-micron Millipore filter[1/], and titrating with 0.01 N or 0.1 N hydrochloric acid to an equivalence point of pH = 4.3. Alkalinity was then determined using:

$$V_o\ [Alk] = V_2\ [C_{Acid}]$$

where V_o is initial volume (milliliters);

[Alk] is alkalinity (milliequivalents per liter);

V_2 is final volume (milliliter);

$[C_{Acid}]$ is acid concentration (milliequivalent per liter).

Filtering is imperative to prevent minute calcium carbonate ($CaCO_3$) particles from being dissolved during titration, and thus, increasing the alkalinity.

Salinity, Temperature, and Current Velocity Measurements

Conductivity, salinity, temperature, and current velocity were measured at 14 stations shown in figure 6. (The number given each station indicates the sampling sequence of data collection during a tidal cycle; see table 4). These parameters were measured at different depths to determine the mixing of saltwater with freshwater. Conductivity, salinity, and temperature were measured with a multiparameter water-quality instrument. Current velocities were determined by the electromagnetic method.

1/ Use of the trade name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

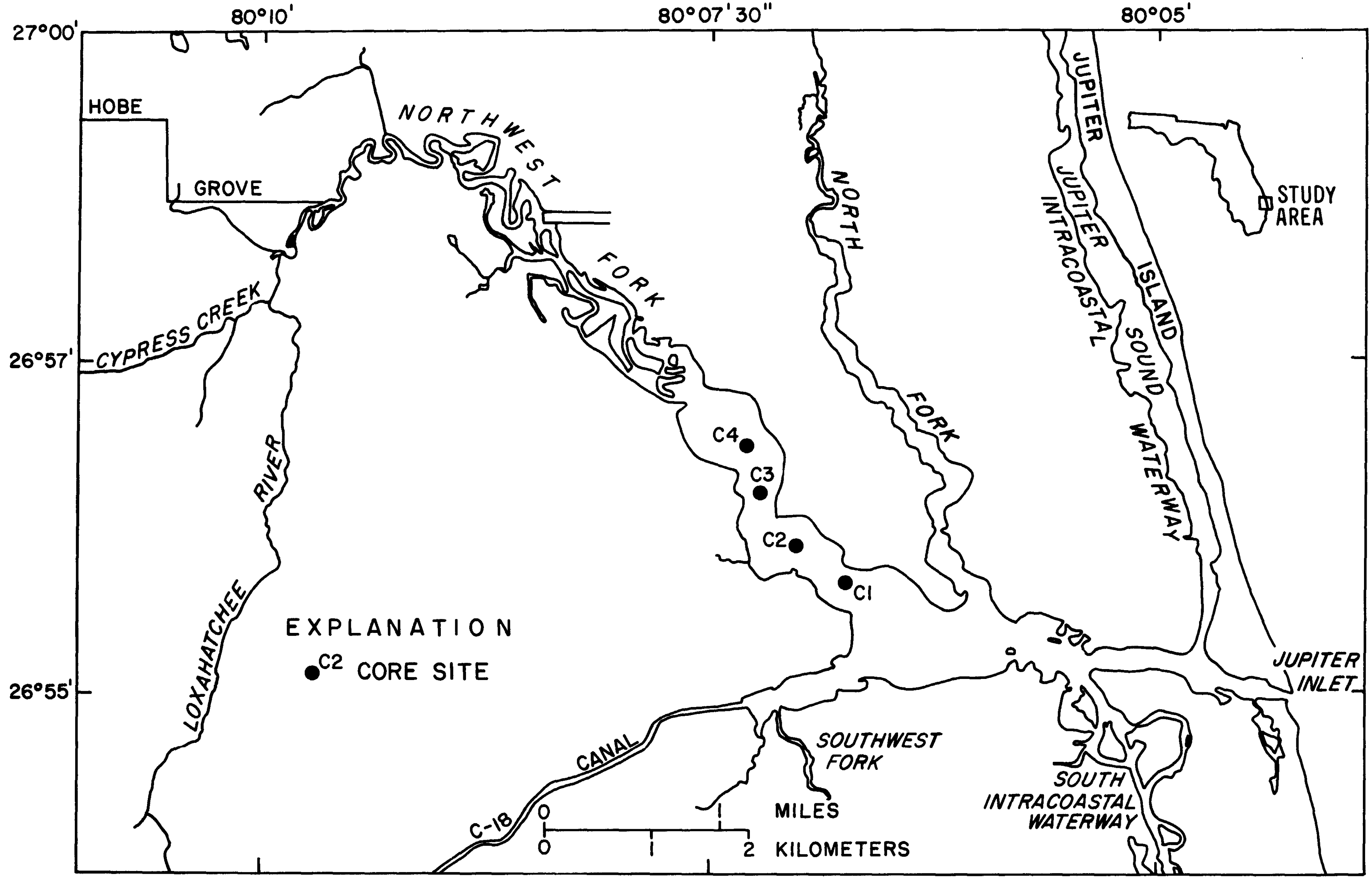

Figure 5.--Sites of hand cores used for pore-water studies in the Loxahatchee River estuary.

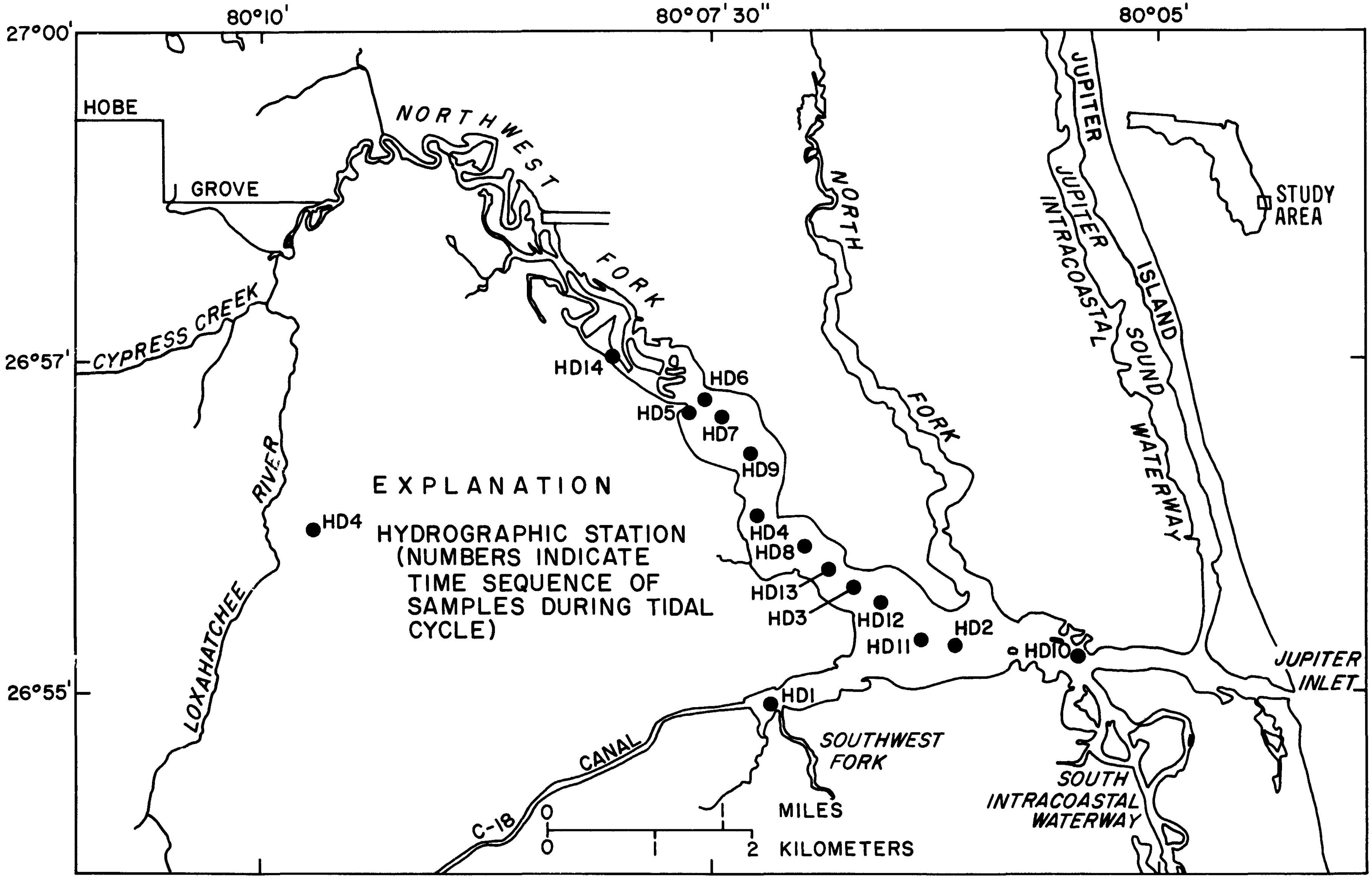

Figure 6.--Location of hydrographic stations.

SEDIMENT TYPES

Sediment recovered in hand-driven cores and vibracores can be divided into nine basic types. Six of these appear to be Holocene; three appear to be Pleistocene.

The most abundant sediment type is an organic-rich mud containing discrete and very sharply defined lenses and laminae of sand (interlayered sand and mud). In some cases, sand units are as much as several centimeters thick, but generally they are less than 2 to 3 mm. Sand is generally very fine (less than 125 microns); however, many of the laminae contain a minor amount of coarse sand. The sand laminae and lenses are generally horizontal although inclined laminae are noted. In some sections, burrows infilled with quartz sand are also present. These vary from vertical to horizontal and are also very sharply defined. In some cases, it is difficult to differentiate between horizontal burrow tubes and sand lenses of physical sedimentation origin. The mud is composed predominantly of fine organic particles but also contains minor amounts of quartz sand and shell fragments.

Homogenized organic-rich mud (bioturbated mud) containing a small amount of sand is a common sediment type in the estuary near the present sediment surface. This sediment type appears to be produced by intense biologic reworking of the interlayered sand and mud as described previously. It also appears at deeper depths in several cores.

Pure fine quartz sand containing numerous oyster shell layers (fine quartz sand), as well as scattered oyster shells, is the main sediment type of the shallow sandbar just seaward of the convergence of the three arms of the estuary. Occasional layers of oyster shells provide the only visible layering in these cores.

Quartz sand that lacks any evidence of physical or biogenic structures (clean quartz sand) is found commonly in the lower part of cores through the sandbar at the upper reaches of the Northwest Fork and also at the northeastern edge of that fork. Clean quartz sand also occurs below a layer of shell hash which is traceable in the Northwest Fork.

A medium-grained quartz sand containing a low percentage of mud (mottled, muddy quartz sand) is characteristic of the upper part of the sediments in the bar at the head of the Northwest Fork and is also present towards the top of several other cores along the margins of the estuary and in the Southwest Fork. At deeper depths, this type is less abundant.

Medium- to coarse-grained quartz sand with peat layers and laminae (quartz sand with peat) is a common sediment type upstream from the main estuary. Detrital peats are generally extremely thin, but in a few samples range up to several centimeters thick. This sediment type also occurs in the Southwest Fork near the surface and at deeper depths in a few cores from the Northwest Fork.

A layer consisting of shell fragments containing coarse quartz sand (unworn molluscan grainstone) occurs in several vibracores at a sediment depth ranging between 310 and 420 cm. The thickness of these traceable shell layers is between 11 and 25 cm.

A whitish grainstone of well-polished shell fragments (worn molluscan grainstone) occurs in core 11 at a sediment depth of 361 to 374 cm. This is completely different in character from the unworn mollusks in the lower part of other core sequences in the Northwest Fork. This worn molluscan grainstone overlies an erosional contact and is very early Holocene or Pleistocene in age. These shells either represent a reworking of material from the Pleistocene Anastasia Formation or represent a thin layer of the Anastasia Formation.

A medium- to coarse-grained sand layer (greenish-brown quartz sand) lies beneath the worn molluscan grainstone described in core 11. Though there are color variations from greenish-brown to reddish, these do not form distinctive layers or mottling patterns characteristic of biogenic structures. The color indicates that this is an oxidized unit and is interpreted to be Pleistocene in age.

SEDIMENT SEQUENCES AND HISTORY

Cores through the main body of the estuary, but remote from sandbars, are dominated by interlayered sand and mud. The upper 20 to 40 cm of these cores are generally bioturbated mud or mottled muddy sand. The sandbar at the lower reaches of the estuary (about 3 km in from Jupiter Inlet) is dominated by fine quartz sand with oysters. The deeper parts of this sandbar were not penetrated by vibracoring. The sandbar at the upper reaches of the Northwest Fork (about 7 km in from Jupiter Inlet) contains clean medium-coarse quartz sand in the lower part and mottled muddy sand in the upper part.

Two cross sections, A-A' and B-B' (fig. 2), show the varying sedimentary character across the Northwest Fork (figs. 7 and 8). The southwest bank and central part of the fork are dominated by interlayered sand and mud and mottled muddy sand. The northeast bank has mottled muddy sand overlying clean medium-coarse quartz sand.

The interlayered sand and mud in the main body of the estuary is rich in organic material. X-ray diffraction was performed on the silt and clay fraction at different sediment depths in cores 12 and 15 to determine the mineralogic trends in the mud. Quartz is by far the most abundant mineral. Calcite is minor at intermediate sediment depth, 2.5 to 4 m, but is more abundant above and below this zone. Other minerals are pyrite, rutile, kyanite, chlorite, illite, and possibly kaolinite and smectite.

The mud-dominated sequence of the main part of the Northwest Fork grades rapidly to a nearly pure quartz sand in the vicinity of the sandbars at the head and mouth of this fork. A similar rapid transition occurs toward the northeastern bank. This transition from mud-dominated to sand-dominated sediment in estuarine environments has been described previously by Howard and others (1975).

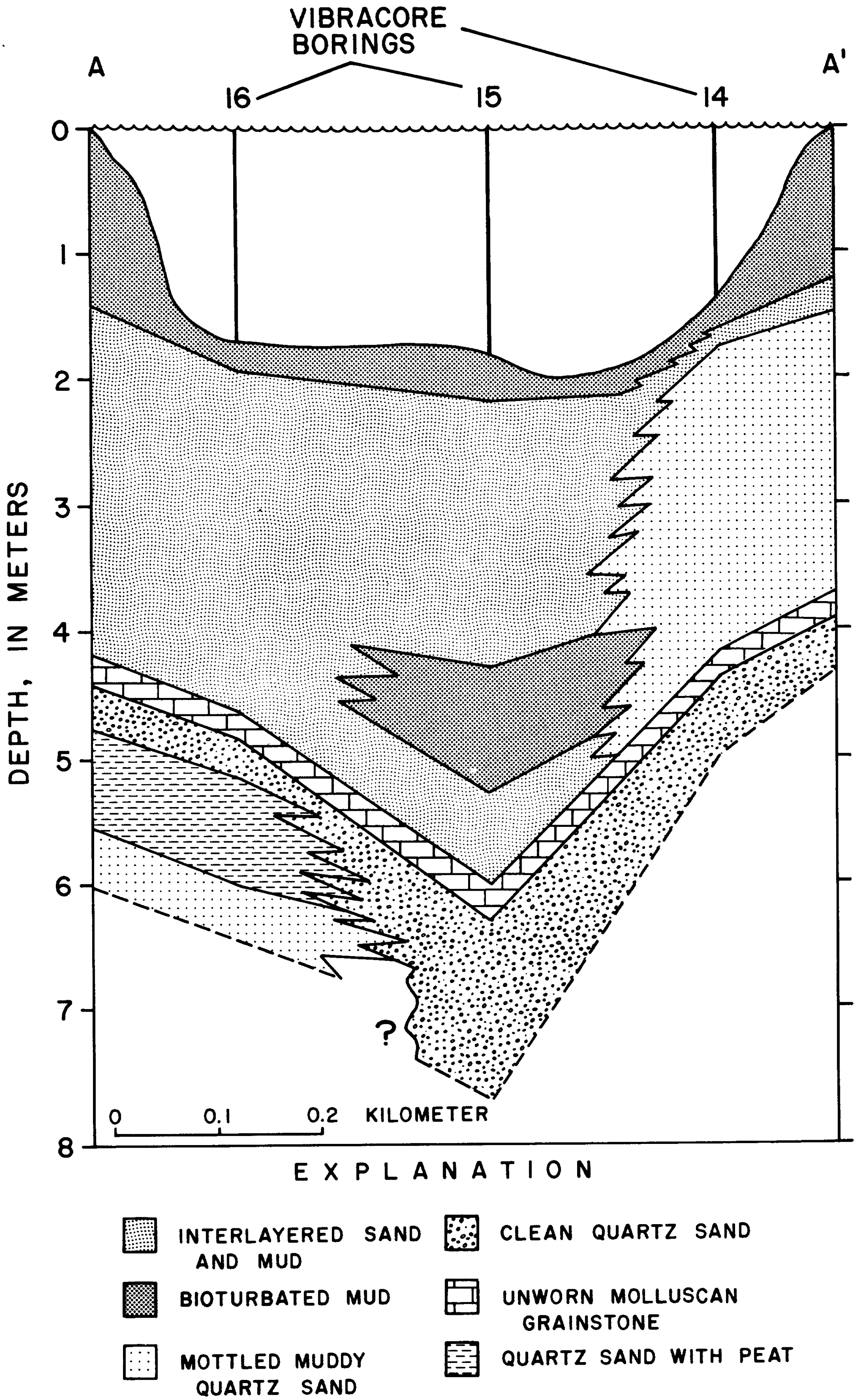

Figure 7.--Cross section along A-A'.

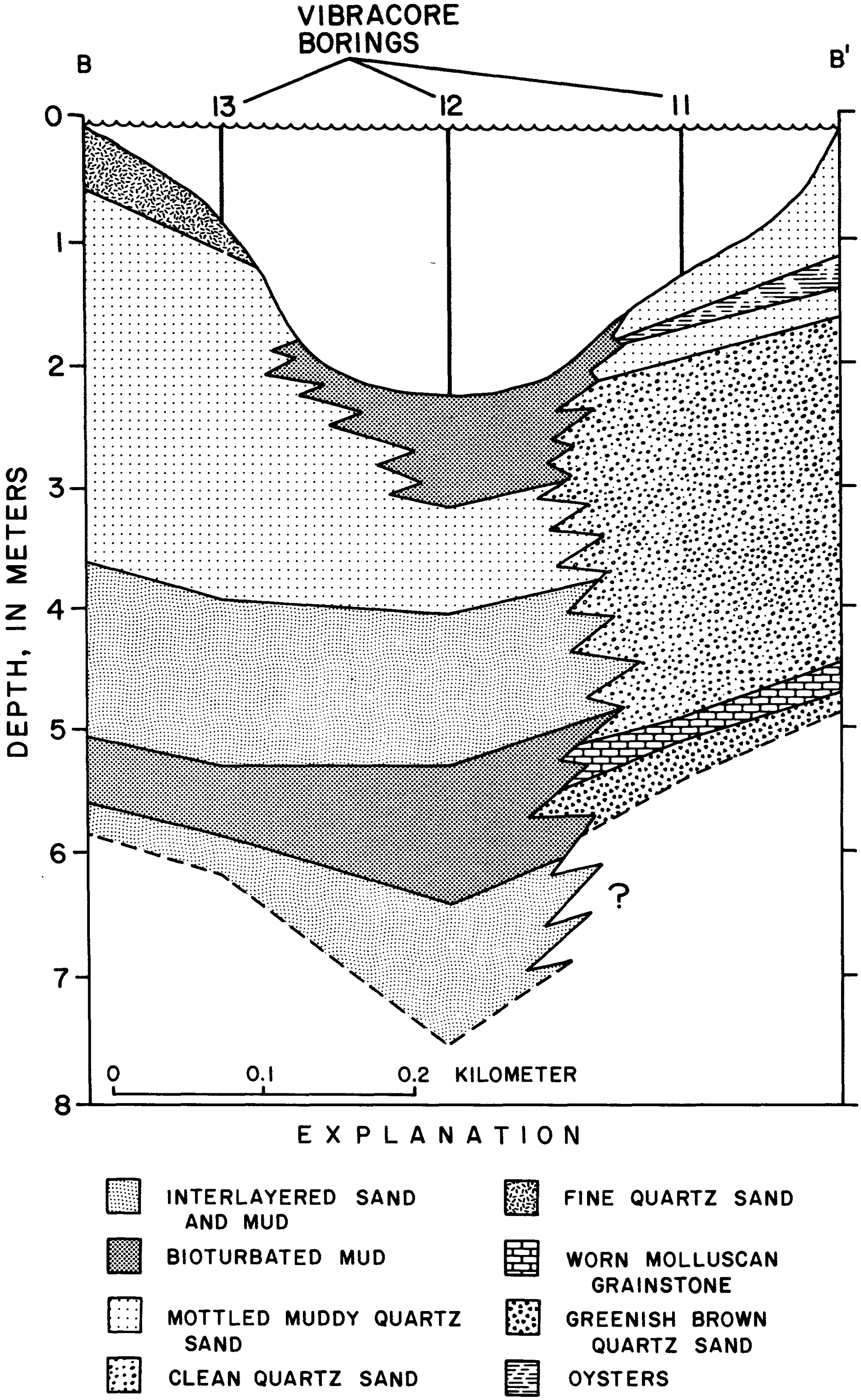

Figure 8.--Cross section along B-B'.

SPATIAL DISTRIBUTION OF SURFACE SEDIMENT

Spatial Trends of Surface Sediment

Grain-size characteristics of surface sediments in the estuarine basin are similar to those of the underlying sediment in the core sequence beneath. Fine-grained sediments dominate the bar at the lower reaches of the estuary, medium to coarse-grained sand dominates the bar in the upper reaches of the Northwest Fork, and mud dominates the main body of the estuary. Diving observations, when the water was fairly clear, revealed patches of fine to medium sand draping the muddy sediment surface in the main body of the estuary.

General trends in the lateral variation of $CaCO_3$ content in the surface sediment are shown in figure 9. These trends are based on 10 surface samples so that local variations are not recorded. An area where shell material was mined between 1930 and 1942 is also shown in figure 9. This activity may well have affected the calcium carbonate grain (shell fragments and other materials) distribution in surficial sediments. Areas of insufficient data are shown blank.

In general, $CaCO_3$ content in the surface sediment diminishes upstream. Of interest is the difference in content between the southwest and the northeast banks of the Northwest Fork. The northeast bank had 5 to 10 percent $CaCO_3$ whereas the southwest bank had 0 to 5 percent. This is likely caused by fine material being selectively removed from the northeast bank.

Grain-Size and Texture Analyses

Figures 10 to 20 show the grain-size distribution curves of thick sand layers from several cores at various depths. All samples represented were taken from sand layers more than 10 cm thick, except for vibracore boring 13 at 436 and 445 cm (fig. 16).

Figures 21 to 26 show grain-size distributions of thin sand lenses and laminae within the mud-dominated sequences. Sample 8-(81-84) is a sand layer, 4 cm thick (fig. 21). In many cases, it was very difficult to determine whether a lamina represents a physical or biogenic structure.

The grain-size analyses reveal that there are two characteristically different grain-size populations. Nearly all samples fit into one of the following two categories: (1) well-sorted fine-grained sediment with a mode between 62.5 and 125 microns; or (2) poorly sorted sediment commonly showing bimodality. The bimodal distributions generally have 1 mode in the size ranging between 250 and 500 microns, generally about 300 microns, and the other between 62.5 and 125 microns, generally about 100 microns. The modes corresponding to finer grain sizes of the bimodal distributions fall exactly within the same size range as the mode for the fine well-sorted sands. A few rather poorly sorted sands have a single mode at approximately 250 microns.

A closer look reveals that in addition to the two aforementioned modes there is another unique particle size at 200 microns. This is more readily identifiable in the northeastern part of the Northwest Fork and in the river

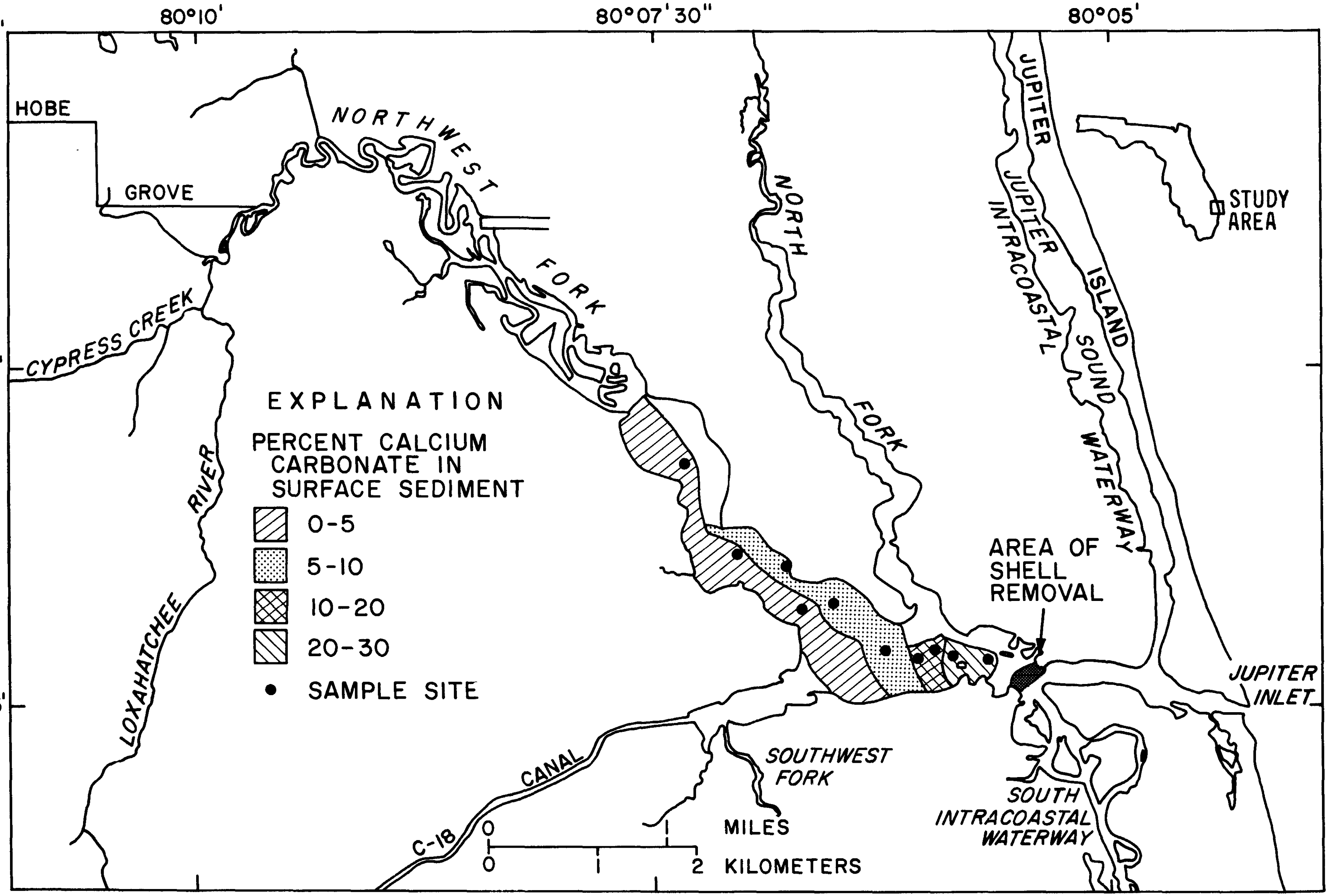

Figure 9.--Percent of calcium carbonate in surface sediment.

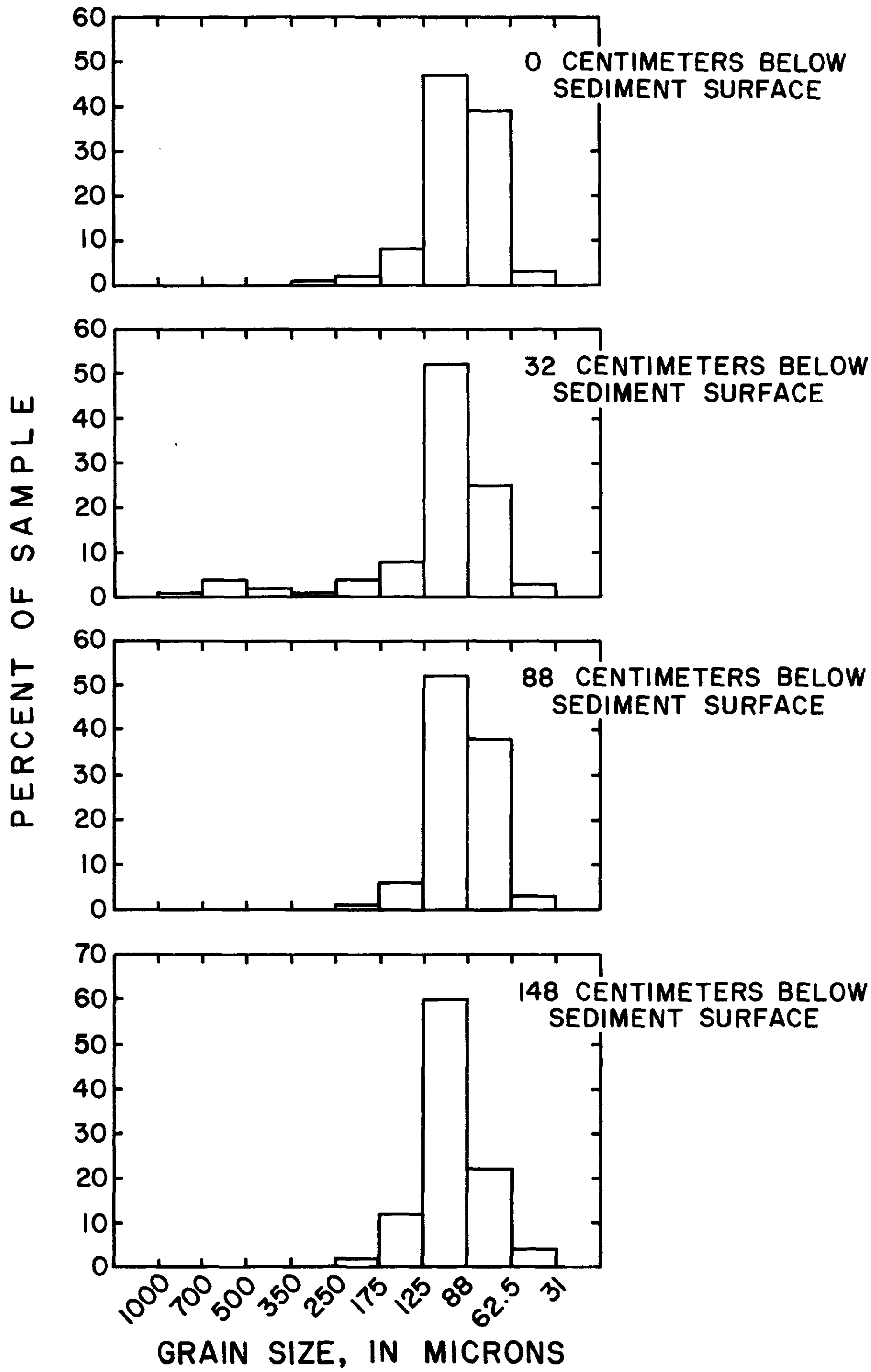

Figure 10.--Grain-size distribution of sand from vibracore boring 1.

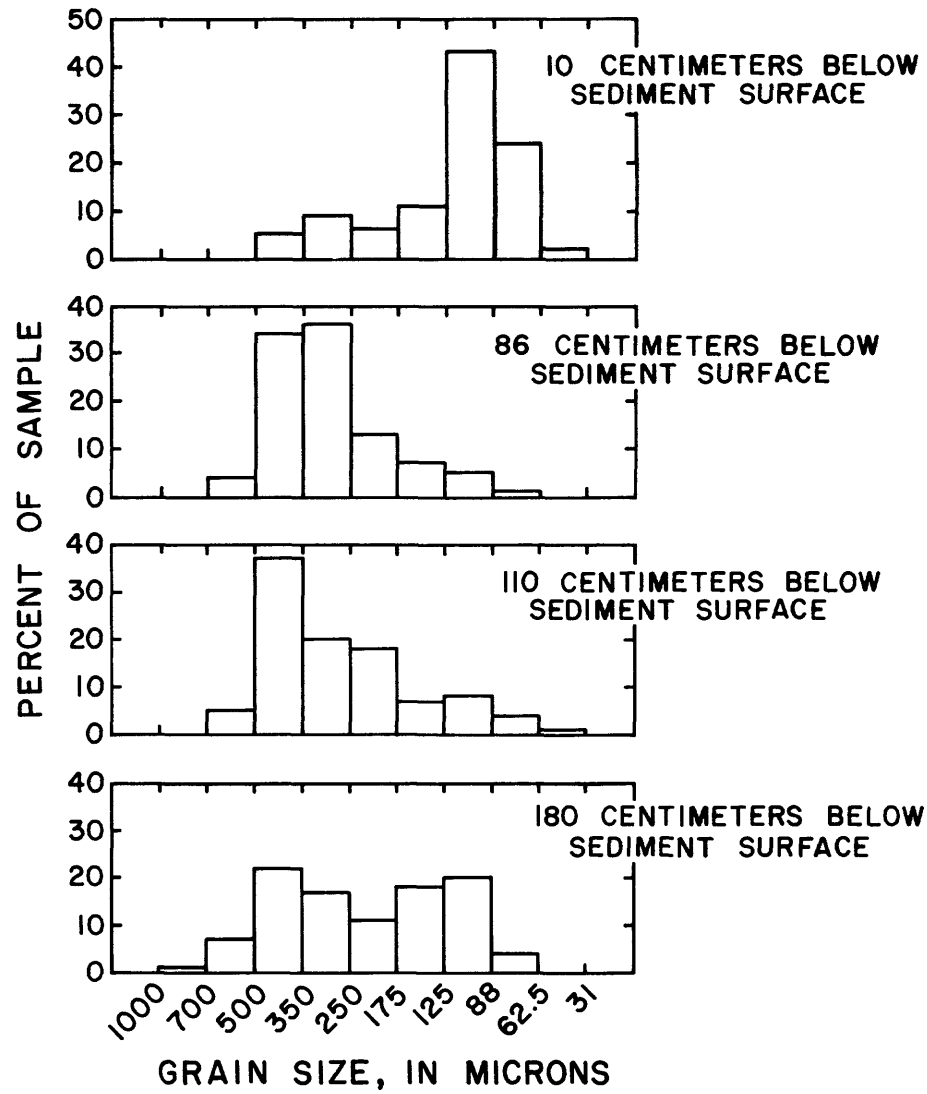

Figure 11.--Grain-size distribution of sand from vibracore boring 3.

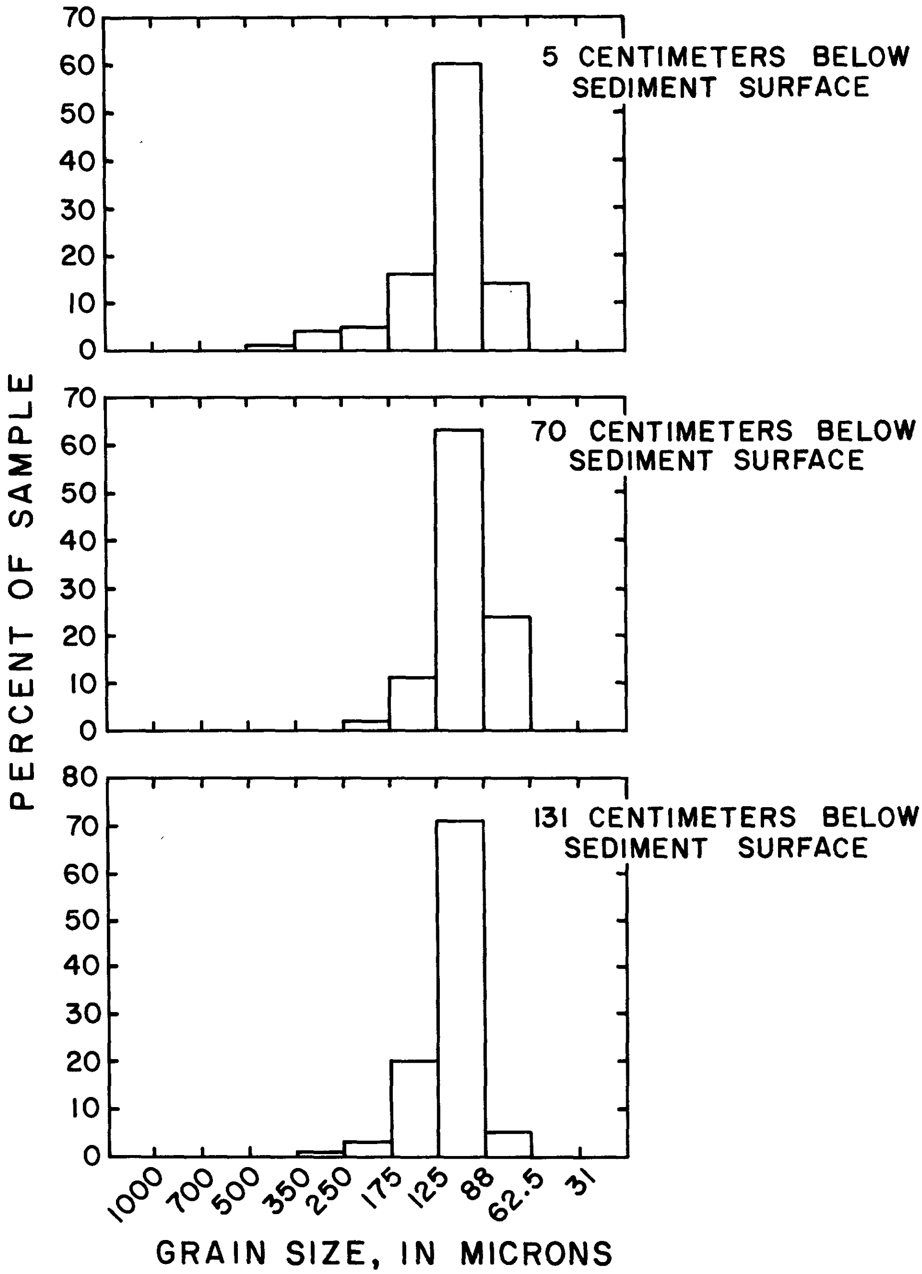

Figure 12.--Grain-size distribution of sand from vibracore boring 4.

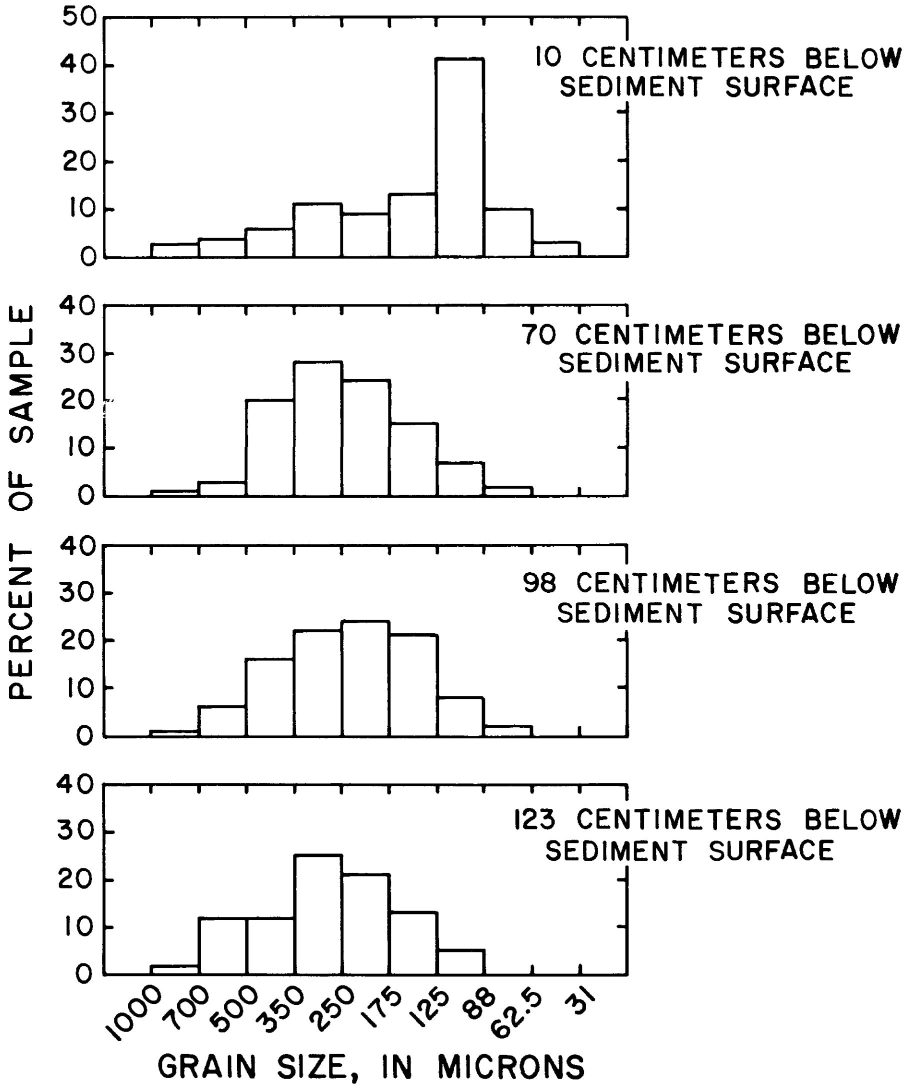

Figure 13.--Grain-size distribution of sand from vibracore boring 5.

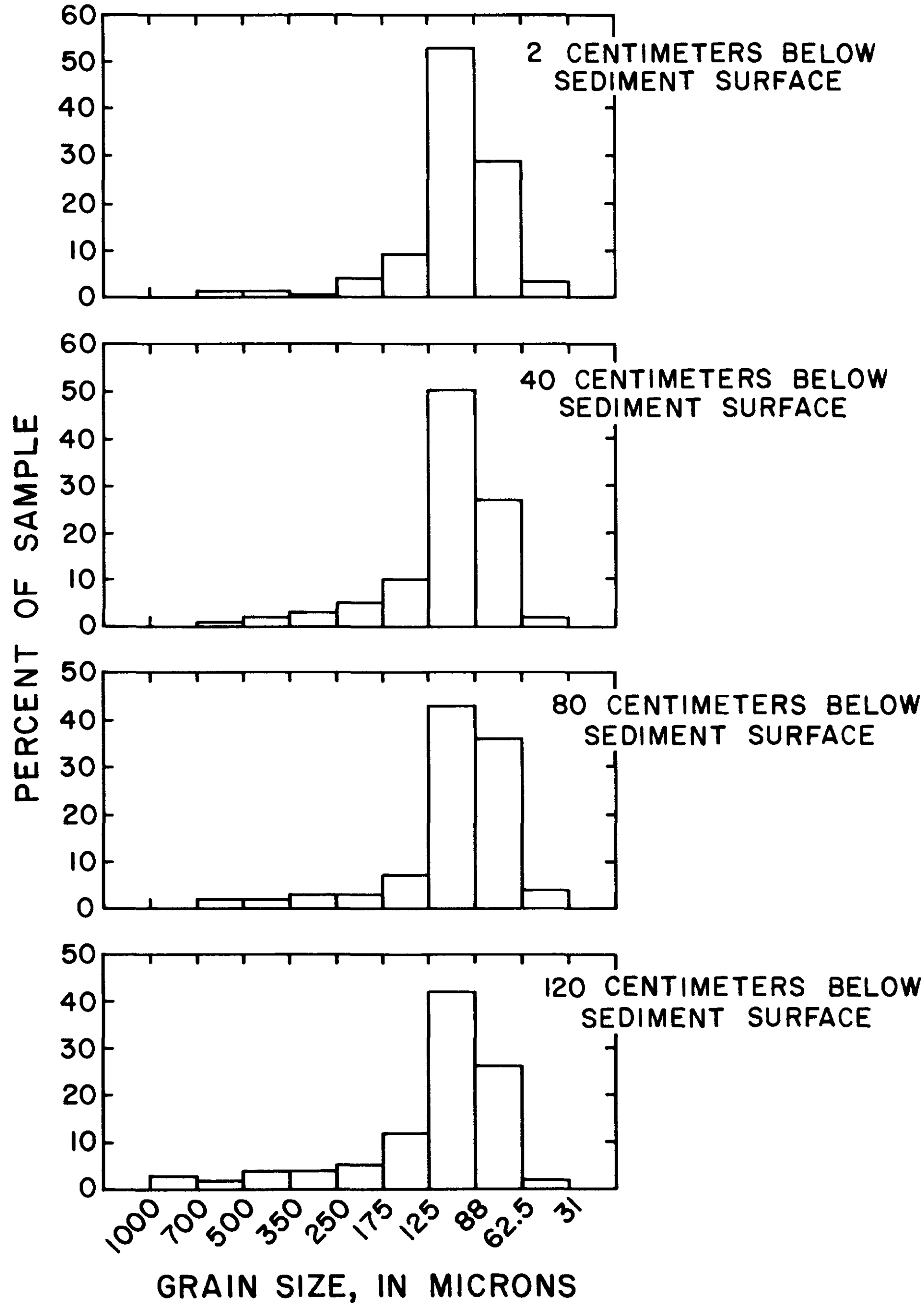

Figure 14.--Grain-size distribution of sand from vibracore boring 6.

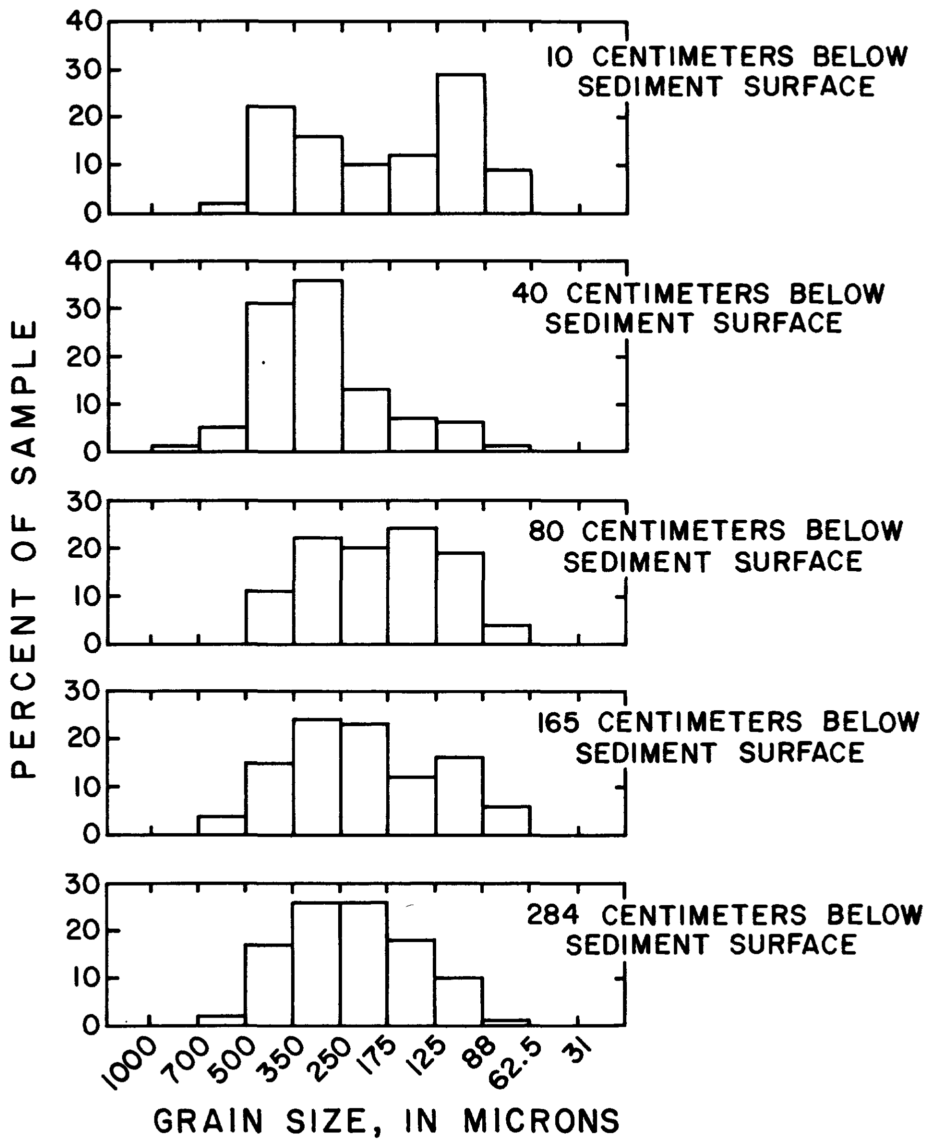

Figure 15.--Grain-size distribution of sand from vibracore boring 11.

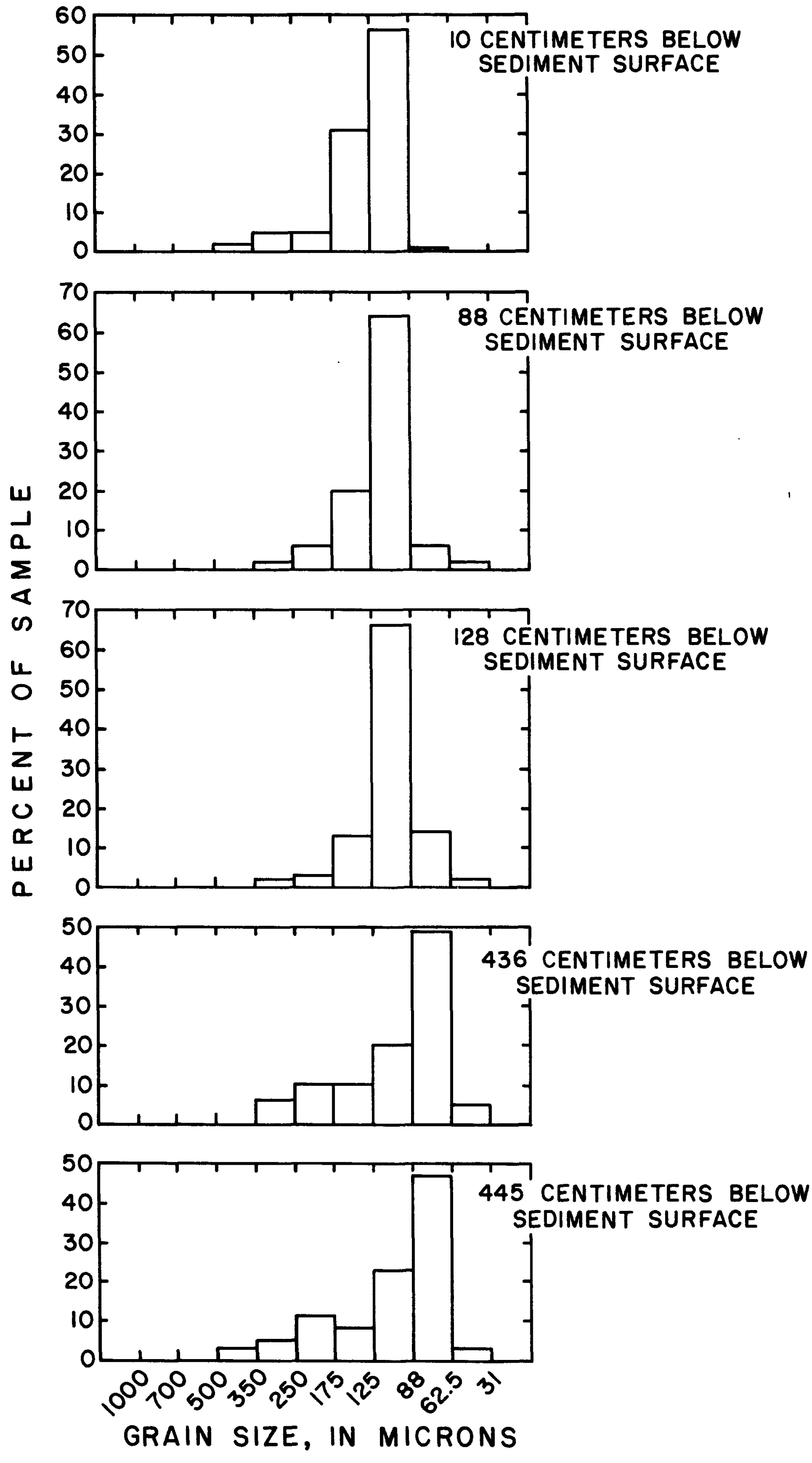

Figure 16.--Grain-size distribution of sand from vibracore boring 13.

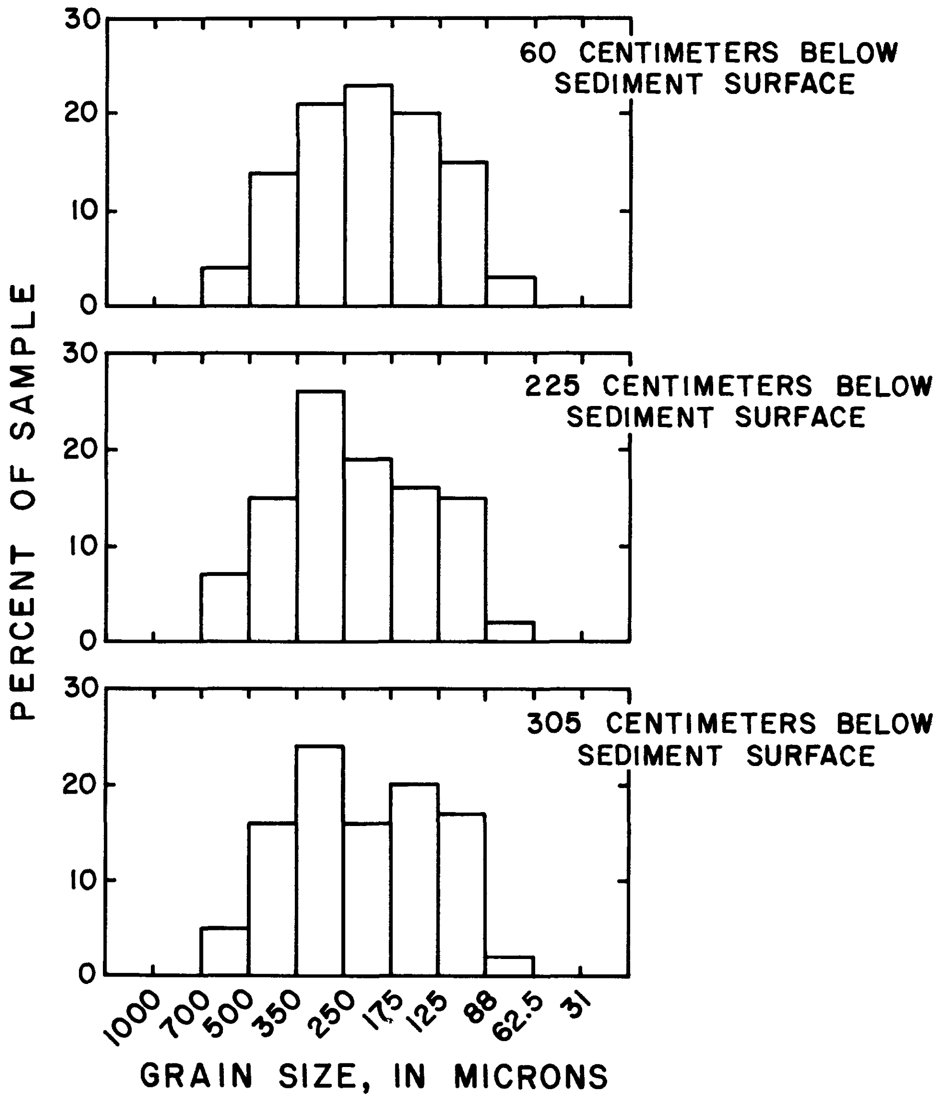

Figure 17.--Grain-size distribution of sand from vibracore boring 14.

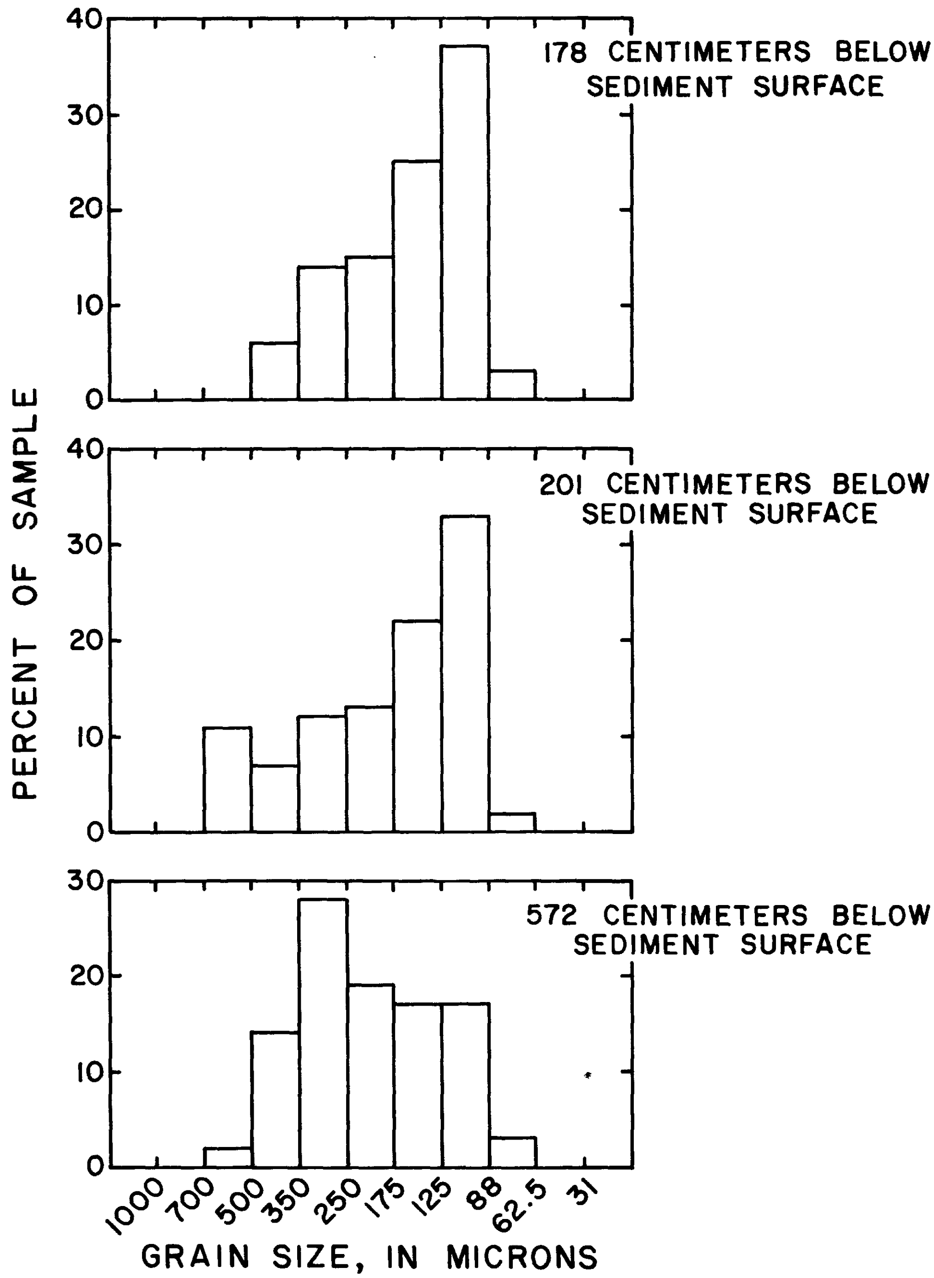

Figure 18.--Grain-size distribution of sand from vibracore boring 15.

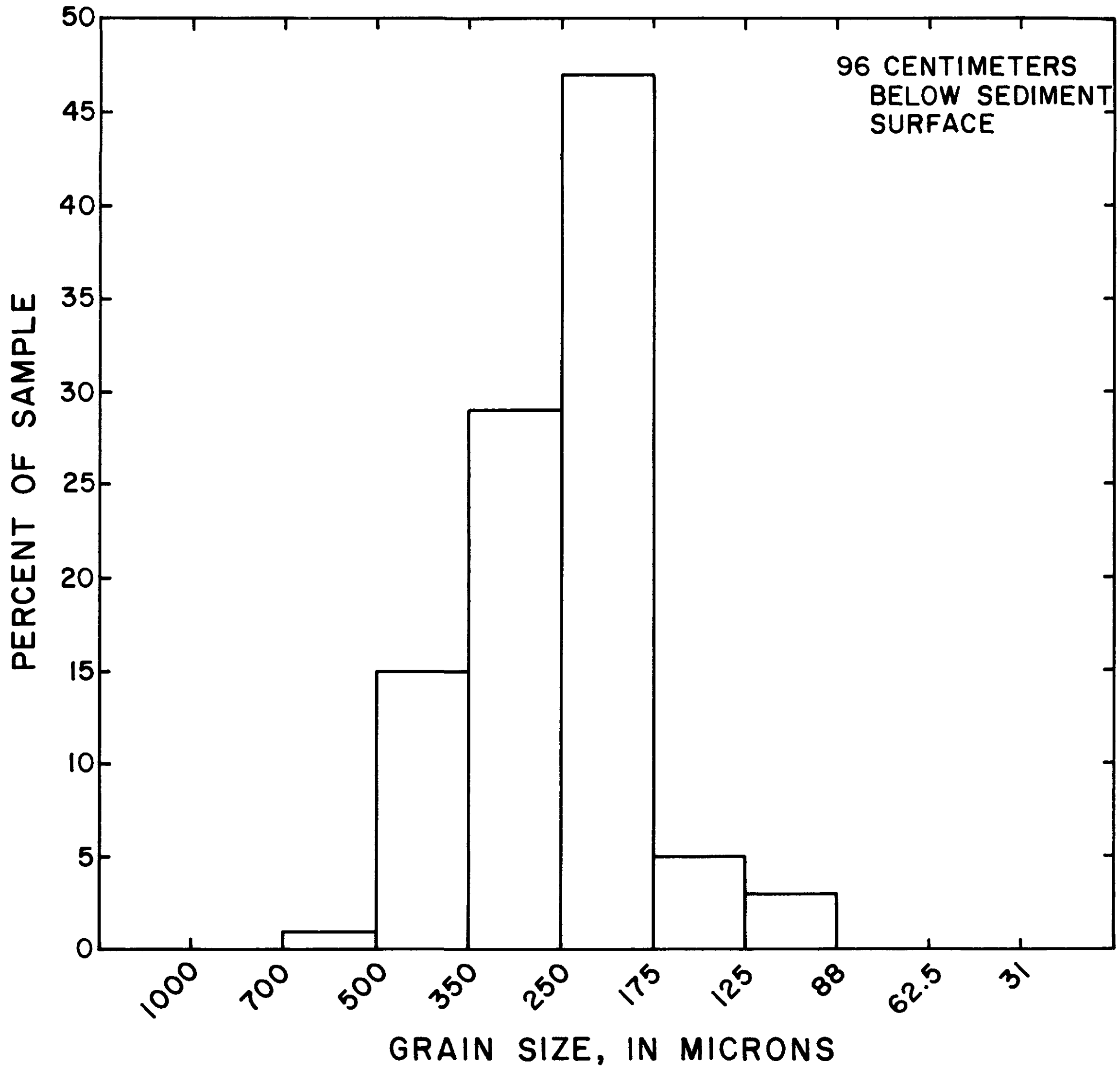

Figure 19.--Grain-size distribution of sand from vibracore boring 19.

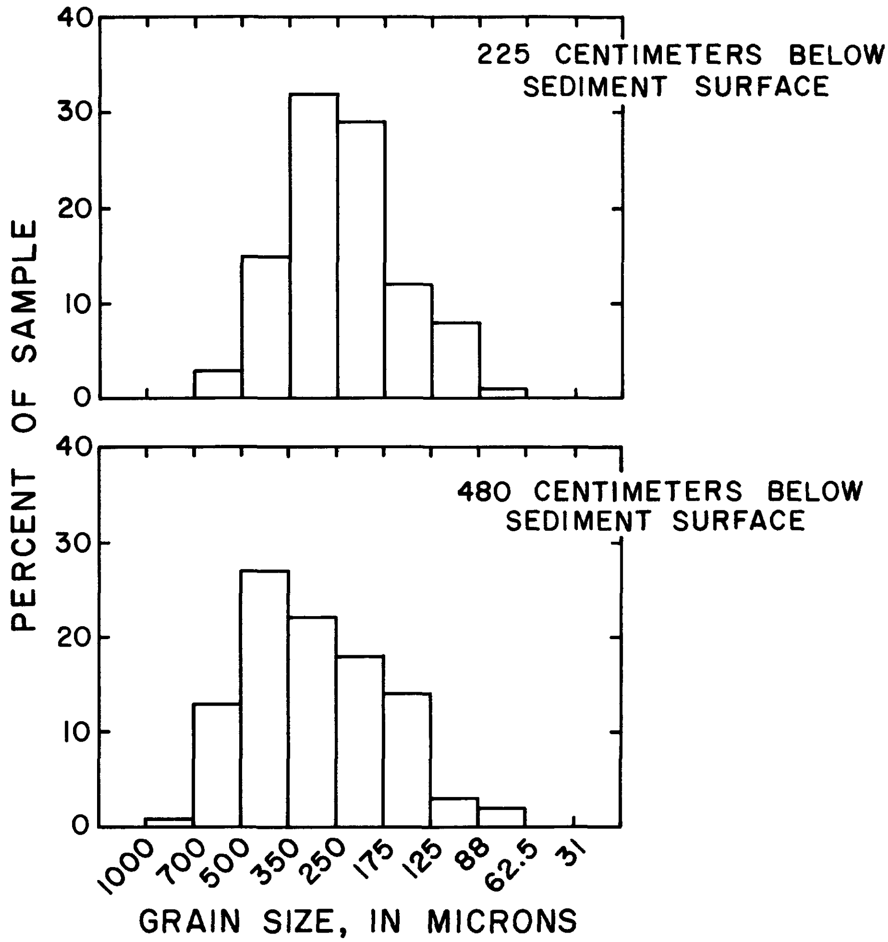

Figure 20.--Grain-size distribution of sand from vibracore boring 20.

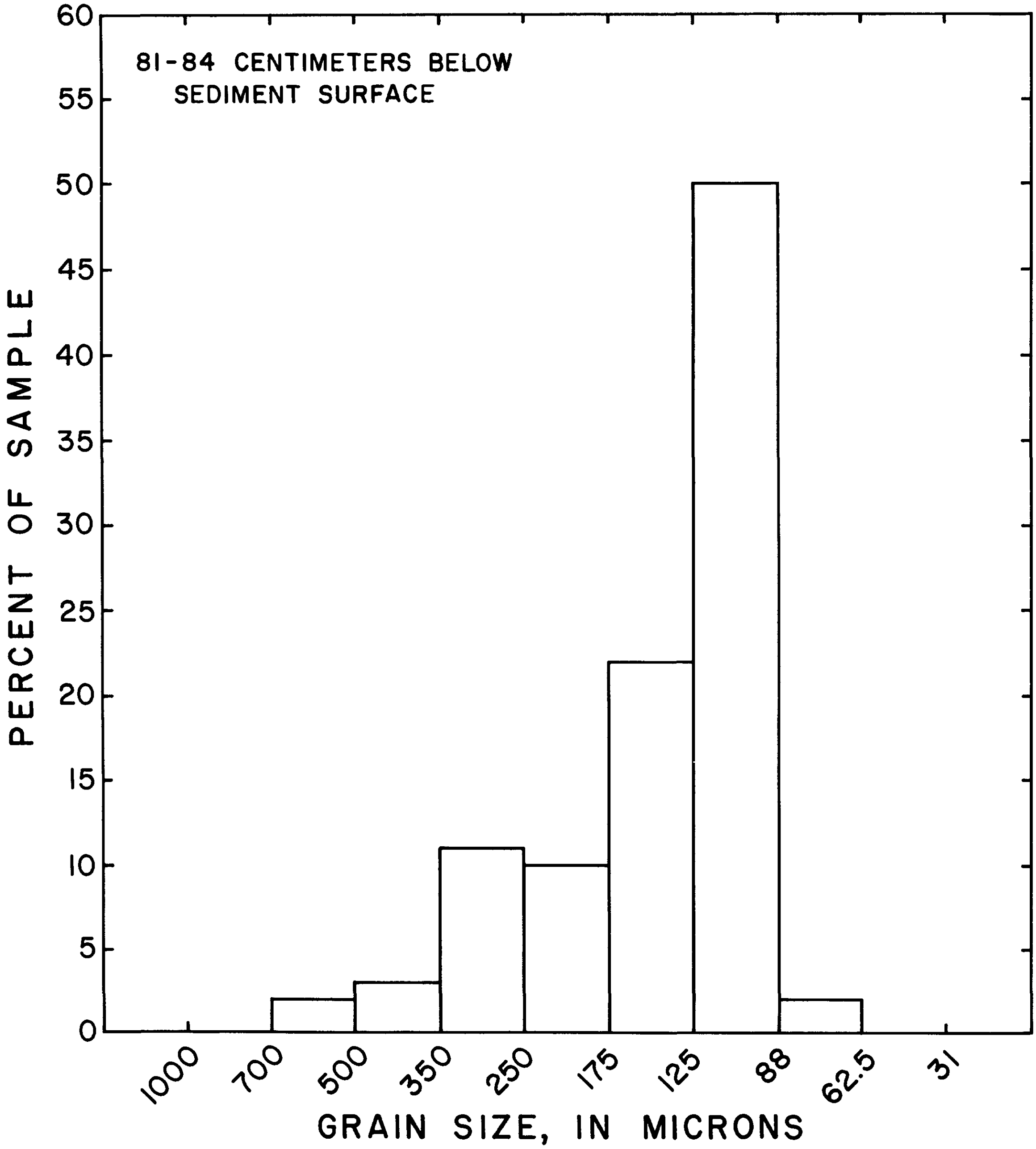

Figure 21.--Grain-size distribution of a 4-cm quartz sand layer from vibracore boring 8.

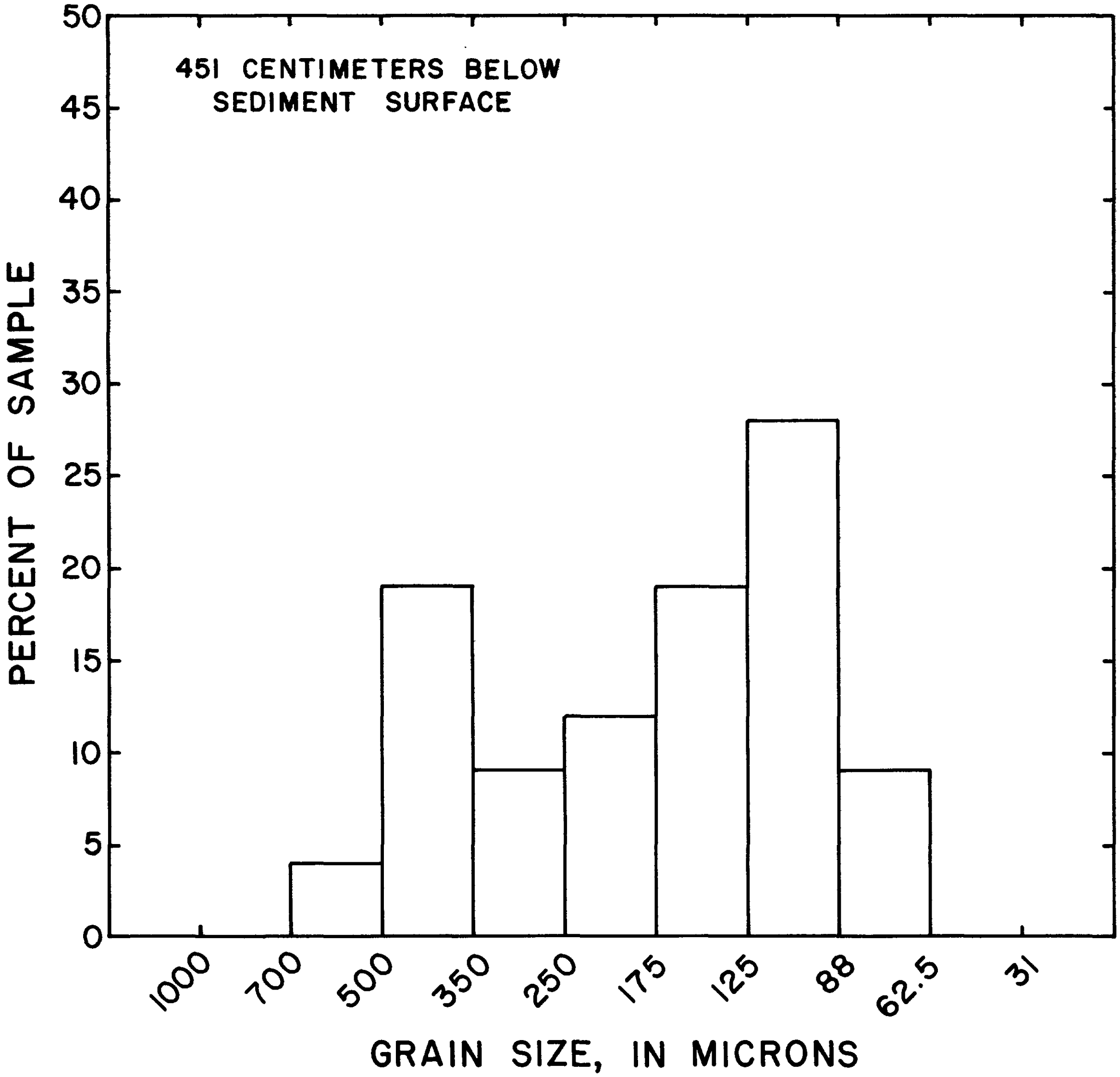

Figure 22.--Grain-size distribution of a sand lamina from vibracore boring 8.

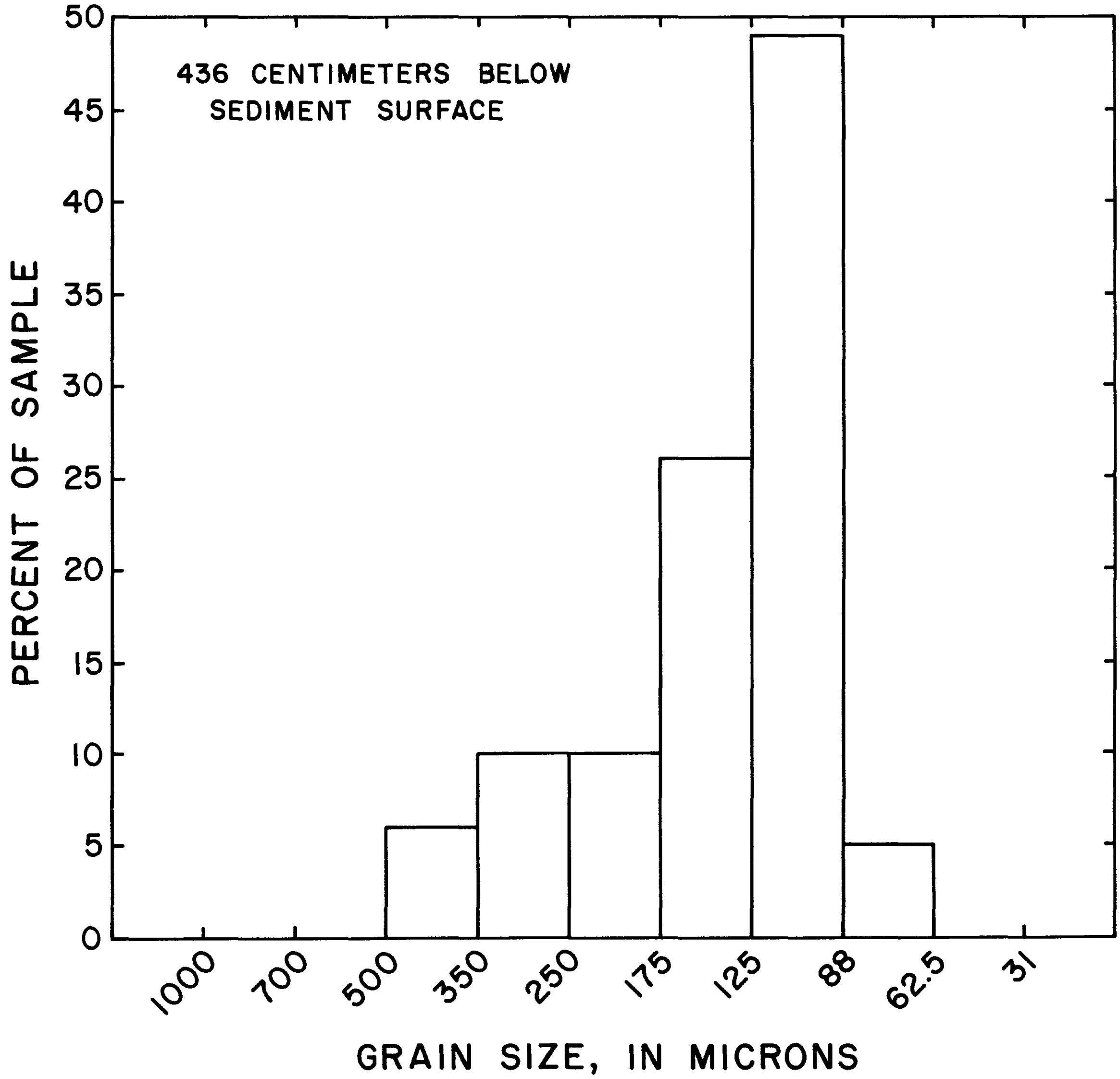

Figure 23.--Grain-size distribution of a quartz sand lamina from vibracore boring 13.

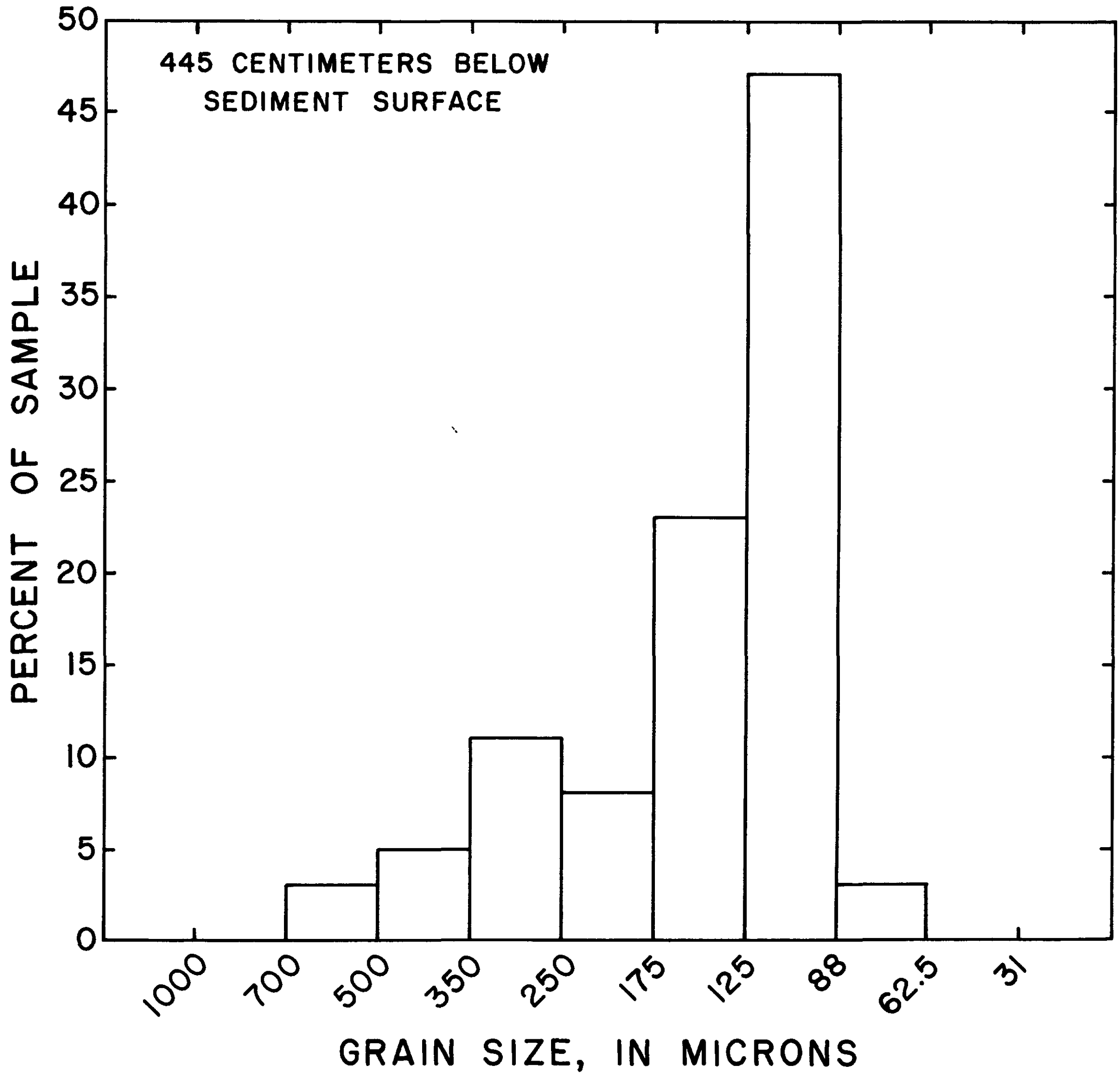

Figure 24.--Grain-size distribution of an infilled horizontal burrow from vibracore boring 13.

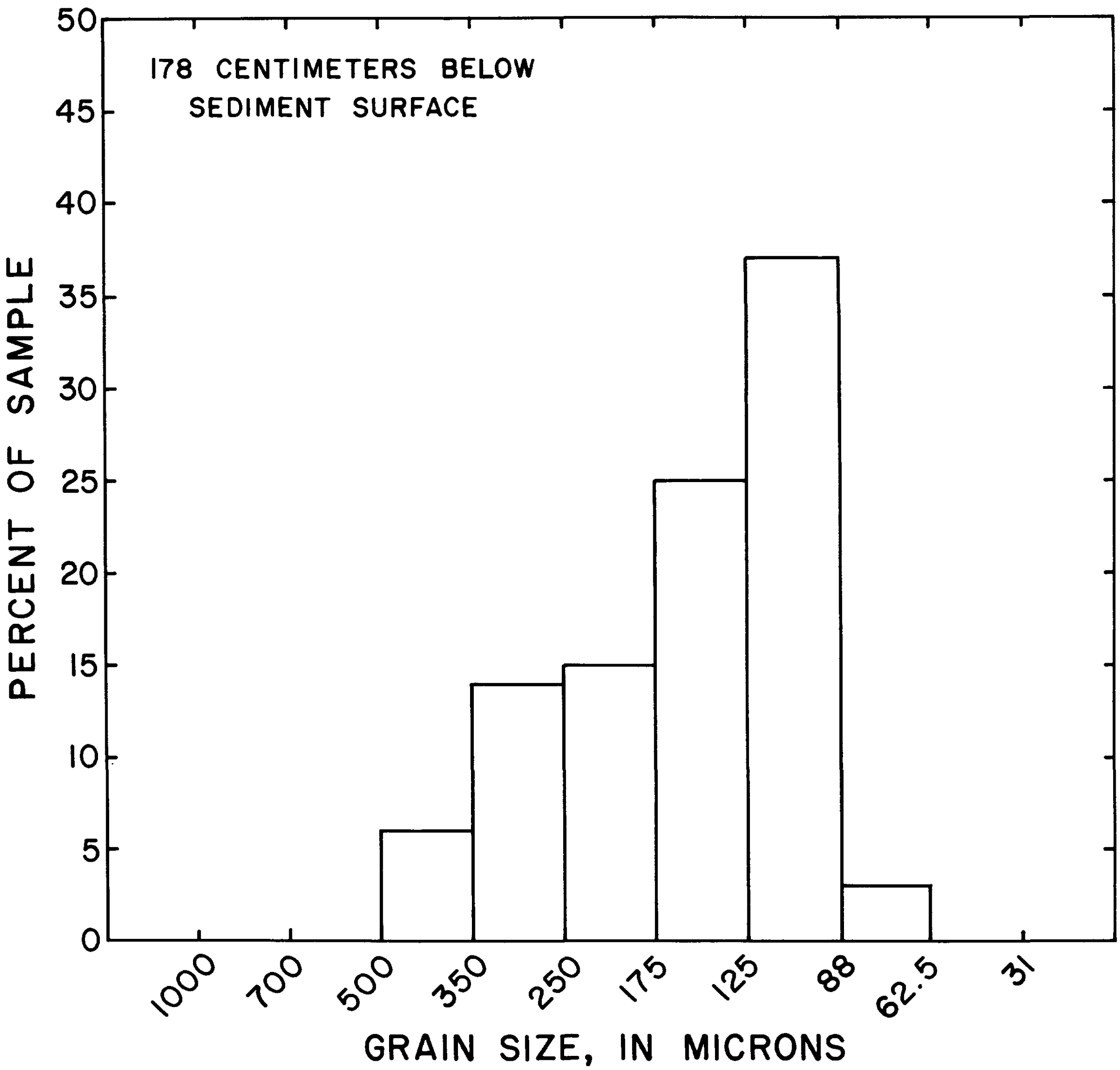

Figure 25.--Grain-size distribution of an infilled horizontal burrow from vibracore boring 15.

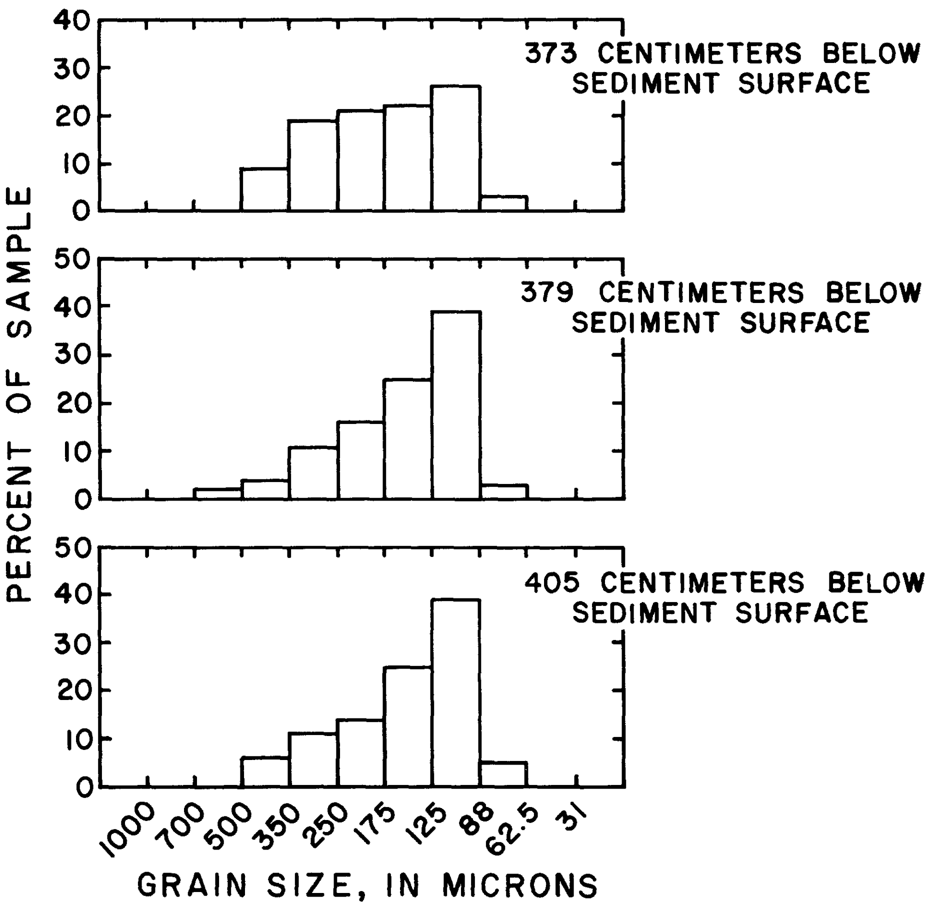

Figure 26.--Grain-size distribution of quartz sand laminae from vibracore boring 17.

delta. Grains of this particular size tend to either dominate the distribution as a mode (figs. 13, 15, 17, and 19) or be conspicuously impoverished (figs. 11 and 21-24) although there are instances where 200-micron particles are just present in varying amounts without displaying those characteristics.

Several cores exhibit distinct vertical trends in grain-size distribution. Vibracore boring 3 at 180 cm (fig. 11) is a good example of an initially symmetrical bimodal and poorly sorted distribution of sediment. This sediment gradually becomes fairly well sorted, finer, and only slightly bimodal at the surface (sample 3-10). Vibracore boring 5 (fig. 13) also shows this trend but to a lesser extent.

Most remarkable, however, is the pronounced lateral variation of the two categories of grain-size distributions discussed earlier. The sediment cores taken near the northeastern bank of the Northwest Fork are dominated by poorly sorted or bimodal grain-size distributions (figs. 15 and 17). Vibracore boring 3 (fig. 11) also shows a tendency toward bimodality but at deeper depths.

Figures 10, 12, 13, and 14 corresponding to vibracore borings 1, 4, 5, and 6, respectively, show that the sandbar or delta at the lower reaches of the estuary consists mainly of fine sand particles between 62.5 and 125 microns. Shields (1936) showed that particles smaller than 170 to 200 microns will tend to move in suspension once there is sufficient bottom shear to entrain them. Greater shear is required to entrain particles below that size than to keep them in suspension. Cohesive forces and the thickness of the laminar sublayer are the primary controls.

Figures 21 to 26 depict grain-size distributions of discrete, thin sand lenses and laminae. Modes of these fall between 62.5 and 125 microns, well within the realm of suspended-sediment movement. Therefore, we can conclude that the sand is being carried in suspension to the tide-dominated sandbar, as well as to the deeper water areas in the Northwest Fork.

The grain-size distribution curves, as just described, do contain a small amount of quartz that is coarser than 200 microns. This indicates that at times bottom currents are sufficiently strong to move some bedload material.

The second sandbar or river delta located at approximately 7 river kilometers upstream of Jupiter Inlet (fig. 2) shows a coarser grain size (figs. 19 and 20). The dominant modes are 200 and approximately 300 microns, indicating bedload as the primary transport mechanism.

The settling data suggest at least two sources for the three dominant grain sizes (100, 200, and 300 microns) in the main part of the estuary: (1) All fractions (100, 200, and 300 microns) are land derived, eroded from banks, and transported down the river whereas (2) the fine fraction (100 microns) also is derived from the oceanside when tidal energy is high. This is not to say that coarse siliciclastic and carbonate sediment is not available from the ocean, but it indicates rather that the prevailing tidal energy conditions in the area where the three forks converge favor the deposition of fine-grained particles. High-energy conditions are required to supply coarse particles to the main part of the Loxahatchee River estuary.

In the above descriptions, samples analyzed have been from sand units or from sandy laminae in interlayered sand and mud sequences. Sands in the river delta, in the main body of the estuary, and along the estuary margins are over 90 percent quartz. Indeed, most samples are over 98 percent quartz.

In the sediments of the river delta and the estuary, a few percent of the grains are biogenic skeletal remains and fecal pellets produced during periods of biological activity in the estuary. These are, however, only a minor contribution to sand accumulation and texture.

Biogenic carbonate grains become increasingly important in the flood tidal delta towards the mouth of the estuary. Yet even here, most samples contain less than 20 percent biogenic grains. Most of these are mollusk fragments that presumably have been carried in through the inlet from offshore or have been reworked from the margins of the inlet channel. This biogenic component though slightly larger than the quartz grains is in hydrodynamic equilibrium with them. The minor component of biogenic material produced on the flood tidal delta is not sufficient to affect the settling size distribution.

Figures 20, 19, and 26 represent samples from vibracore borings taken progressively further into the estuary from the river mouth. They show a fining downstream trend from the river delta. Grain-size distributions of vibracore boring 20 (fig. 20) show a concentration of 250 to 450 microns. A dominant grain size of 200 microns is found in the sample from core 19 (fig. 19) at the prograding edge of the river delta. Farther downstream away from the delta in vibracore boring 17 (fig. 26), 100 microns is the most frequent particle size. Energy conditions determine what size particles will be transported downstream. Provenance and transport will be discussed in more detail in the section on Sediment Dynamics.

FAUNAL CHARACTERISTICS

Microfauna

Foraminiferal assemblages were studied at various depths in the long vibracores, as well as at the surface. Throughout the entire reach of the Loxahatchee River estuary, the genus *Ammonia sp.* dominates, comprising about 75 percent or more of the foraminiferal population.

The most abundant and diverse assemblage in the surface samples in 3S (fig. 3) consisted of *Ammonia sp.*, *Elphidium sp.*, *Triloculina sp.*, and *Quinqueloculina sp.* A few marine planktonic forms were also noted, substantiating the indication that the ocean is a sediment source. A few *Nonion sp.* were found in sample 7S (fig. 3). Upstream from the mouth of the Northwest Fork, *Triloculina sp.*, *Quinqueloculina sp.*, and *Nonion sp.* disappear, and *Elphidium sp.* decreases in number. The foraminiferal assemblages of samples 8S to 12S (fig. 3) consist primarily of *Ammonia*. Upstream from samples 12S (fig. 3), *Ammonia sp.* is the only genus left and rapidly decreases in abundance.

The upstream decrease in the diversity of the foraminiferal assemblage may be due to the increase in species, such as Ammonia and Elphidium, that can adapt most readily to a wide range of salinity. Ammonia and Elphidium are known to exist under hyposaline, marine, and hypersaline conditions and to tolerate these extremes quite well, explaining why those two species (especially Ammonia) are found farther upstream than other species occupying the lower reaches of the estuary.

Below a sediment depth of approximately 30 to 50 cm, the foraminiferal assemblages consist primarily of Ammonia sp. and minor concentrations of Elphidium sp. Increased dissolution of foraminifera with increased depth in cores is attributed to the chemical action of the pore waters.

The presence of planktonic species in the estuary indicates that planktonic foraminiferal tests are being transported into the estuary through the tidal inlet. This must certainly be true for benthic foraminifera as well. Therefore, extreme caution must be used when attempting ecological interpretations based on the microfaunal assemblages in the Loxahatchee River estuary.

Salinities measured in the estuary are not within the tolerance range of some species of foraminifera found in the surface sediment. Therefore, they must have been transported there, a common product of estuarine circulation. An environmental interpretation based on this assemblage, which is not necessarily a biocoenose, becomes difficult.

When examining the foraminiferal assemblages at deeper depths in the core, the same problem arises when ecological inferences are attempted. In addition to that, diagentic processes--mainly preferential dissolution of certain species--have to be considered. An interpretation based on Ammonia and Elphidium alone is highly speculative considering the wide ranges of environmental parameters they can tolerate.

Concentrations of hydrobiids were found in vibracore borings 10, 12, and 17 at 232 to 272 cm, 469 to 532 cm, and 340 to 407 cm, respectively. However, hydrobiid tests were also found in several of the surface samples. It is debatable whether hydrobiid concentrations at depth represent a hydrobiid community that lived at the site or represent a site of accumulation of the dead organisms. Hydrobiid tests filled with air can float large distances before they are incorporated into the sediment. An ecological interpretation based on the hydrobiid concentrations, therefore, would also be quite speculative.

Macrofauna

The shell layer, 4 to 5 m beneath the sediment surface, contains (in order of abundance) Anomalocordia sp., Nassarius vibex, Chione cancellata, Crassostrea virginica (locally found as oyster beds; vibracore borings 1 to 5) and Macoma tenta, a shallow-water sandy-substrate assemblage. Some of these shells show extensive physical abrasion and rounding, suggesting transport and reworking while others do not.

The layered sand and mud sequence contains little shell material. Shells that are present are small, very thin walled, extremely fragile, and generally fragmented. It is very likely that they have been subjected to acidic dissolution. Shells that are identifiable include Nassarius vibex, Tagelus plebeus, Macoma tenta, Chione cancellata, Anomalocordia auberiana, Crassostrea virginica, Mercenaria mercenaria, and Mulina latralis. Several of these shells were found in infilled burrows, indicating that the assemblage represents the biocoenose of a shallow brackish-water environment.

Bioturbation

The estuarine sequence in vibracores from the the Northwest Fork and the lower estuary consists primarily of interlayered sand and mud and bioturbated mud (figs. 7 and 8). The intensity of bioturbation in the estuary has varied through time as evidenced by the degree of preservation of physical structures. Thus, bioturbated mud and interlayered sand and mud record times of high- versus low-benthic organism activity, respectively.

Though physical layering is preserved throughout most of the cores, except for the top 30 to 50 cm, there has been an overall increase in bioturbation towards the top of the estuarine sediment sequence. However, closer examination of the vibracore x-rays reveals that two distinct episodes of biological reworking stand out. A layer of bioturbated mud, approximately 1 m in thickness, is located at a sediment depth of 3 m and records the first episode (figs. 7 and 8). Above and below it are sequences of interlayered sand and mud which lack evidence of biological reworking. The second episode of bioturbation is documented in a 30- to 50-cm thick surface-sediment layer.

This alternation of interlayered sand and mud and bioturbated mud is an indicator of changing paleoecological conditions in the estuary and is mainly attributed to the working of the inlet. We know that the inlet has opened and closed many times in recent history. This phenomenon is likely to have occurred throughout the entire existence of the estuary. Interlayered sand and mud is a record of primarily physical processes active in the estuary. Bioturbated mud, on the other hand, in addition to recording similar physical processes, superimposes bioturbation upon the physical record. The fact that poorly defined and distorted layering and laminations are still visible in places in spite of intensified bioturbation suggests that physical processes during episodes of low- and high-biological activity are almost the same. The intensity of reworking by organisms is believed to be related to the working of the inlet as mentioned earlier. Times of high-biological activity correspond with a predominantly open inlet and tidal flushing whereas times of low-biological activity indicate a predominantly closed inlet and stagnant conditions. The Loxahatchee River estuary throughout its history, therefore, has alternated between a more or less lifeless and stagnant system isolated from the ocean, and one where open circulation allowed for free exchange with saline ocean waters inducing biological activity. The top 30 cm of bioturbated mud records a drastic increase in biological reworking, as compared to the rest of the sequence, and is believed to be directly related to man's efforts in maintaining an open inlet at Jupiter over the last 4 decades.

RADIOCARBON ANALYSES

The radiocarbon ages are plotted with respect to present sea level and compared to the former sea level (based on sea-level curves presented by several authors; fig. 27). We selected the sea-level curve presented by Scholl and others (1969) as best representing conditions in south Florida. The Scholl curve goes back 6,000 years but can be extrapolated to compare the basal dates of samples 15-432 and 17-479 of 7800±70 and 6900±80 years, respectively. A direct comparison with Scholl's curve can be made in all other instances.

The four dates obtained from oyster shells in samples 2-77, 3-49, 3-100, and 3-110 (table 2) are distributed on or around the sea-level curve and, therefore, suggest brackish conditions for at least the last 4,500 years. If, in fact, Scholl's curve is extrapolated in a more or less straight line, as indicated by the dashed line in figure 27, the two basal dates would push brackish conditions back as far as 7,800 years ago. Samples 11-30, 5-20, and RC1-25 indicate that sedimentation in the main body of the estuary has not kept pace with sea-level rise during the past 1,800 years. The younger samples plot progressively farther below sea level. These samples are taken in or just beneath the near-surface bioturbated zone that extends to about 30 cm. The samples may contain a mixture of older and younger material and, thus, represent a maximum age for that depth.

Sample 7-112 plots below the sea-level curve, but the reason is not certain. The peat from sample 18H-60 also plots below the curve, but this may be because the precise elevation of the sample site is not known. An increase in elevation only slightly more than 30 cm puts this date above sea level where it belongs.

Net-sedimentation rates based on the radiocarbon dates have been calculated and are represented in figure 28. The net rate is shown to decline from 0.69 mm/y about 7,000 years ago to approximately 0.20 to 0.25 mm/y 1,000 years ago. Even though this trend is associated with a decline in the rate at which sea level has been rising over the past 7,000 years, sedimentation rates nevertheless have not kept up up with rises in sea level. This is best seen by comparing samples 17-479 and RC1-25 relative to sea level (fig. 27). Whereas sample 17-479 plots in the vicinity, sample RC1-25 lies far below the sea-level curve. Both sites are relatively close together (fig. 4) and are associated with the same sediment type--an interlayered quartz sand and mud sequence. It should be noted, however, that both samples 15-432 and 17-479 may well have been deposited above sea level, if the latter was subject to higher rates of sea-level rise prior to 6,000 years B.P. as Shepard (1964) suggests for stable areas, such as Texas and Florida. The shell hash (15-432) may then represent a deposit reworked above sea level.

Sedimentation rates are a net accumulation over a period of time. This rate represents a sum of the episodes of accumulation, erosion, and nondeposition. This is evaluated in the latter part of the section on Sediment Dynamics.

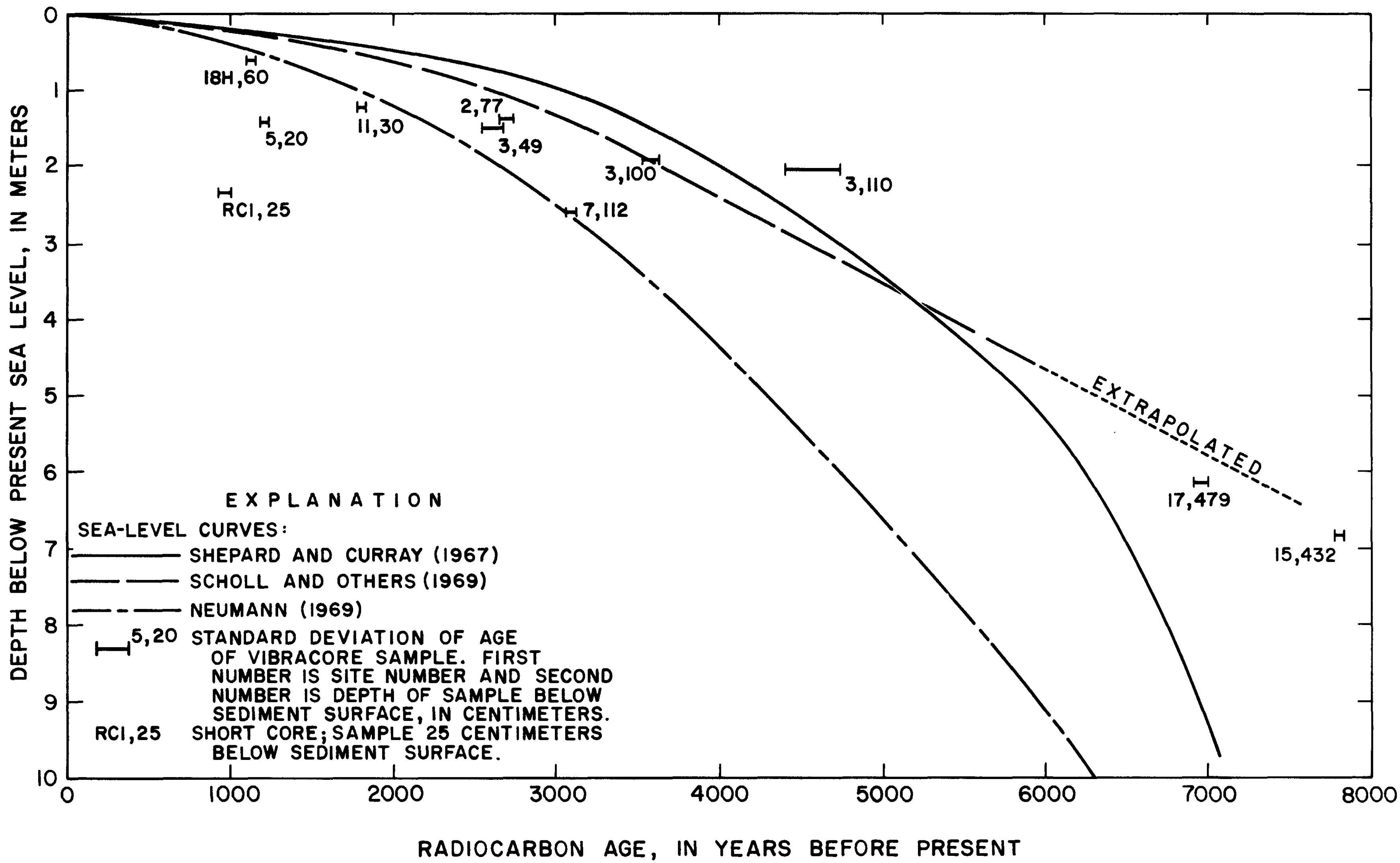

Figure 27.--Carbon-14 dates.

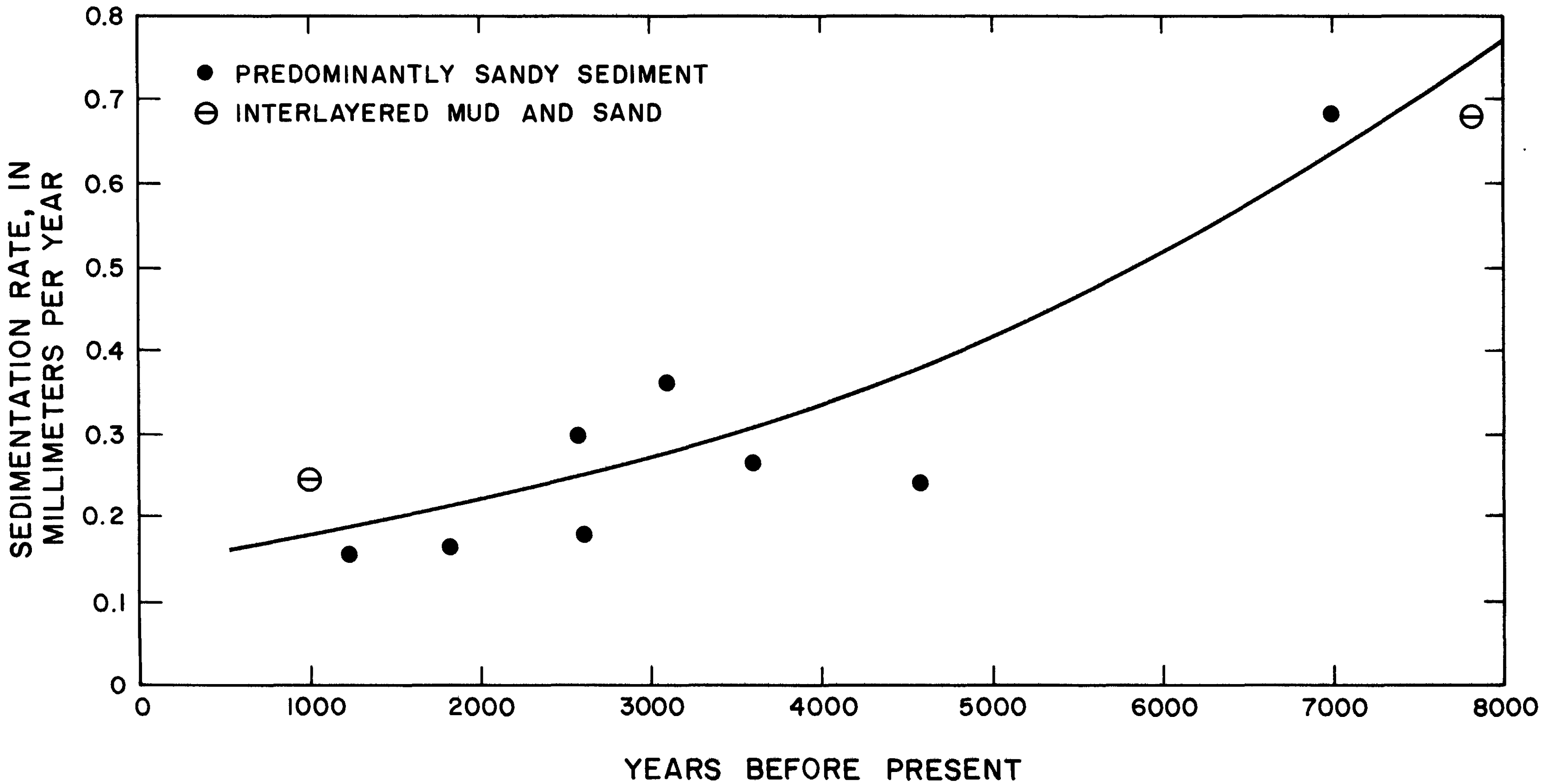

Figure 28.--Sedimentation rates based on depth below the sediment surface of the dated sample.

PORE WATER

The pH measurements show that acidic conditions prevailed in the deeper muddy sediment at the two upstream sites, C-3 and C-4 (table 3). If indeed pore water mixing with ground water is minimal, acidic pore water and the subsequent dissolution of foraminifera at depth observed in vibracore boring 15 can be attributed to microbial activity. Furthermore, again assuming the pore exchange to have been minimal and considering that salinity decreased (fig. 29) whereas alkalinity increased downcore, the enrichment of CO_3 and HCO_3 in the pore water (increase in alkalinity) must come from postdepositional dissolution of carbonate material since the contribution of alkalinity from ocean water becomes less important with depth as evidenced by a decline in salinity with depth. It is debatable whether the salinity values at depth represent average paleosalinities or whether some exchange with ground water or overlying ambient water has occurred. The predominance of mud would suggest that such exchange was minimal.

HYDROLOGY

An attempt was made to fit the Loxahatchee River estuary into a classification scheme devised by Pritchard (1967) based on the extent to which saltwater and freshwater mix. Pritchard recognizes three types of estuaries: (1) saltwedge estuary; (2) partially mixed estuary; and (3) vertically homogeneous estuary.

Salinity profiles and current velocities during flooding tide and high tide (figs. 30 and 31) show that the Loxahatchee River estuary is very well stratified in the entire Northwest Fork during intermediate discharge rates and can be regarded as a saltwedge type for at least part of the year. The results in this particular part of the study, however, must be treated with caution because measurements of salinity and current velocities at different stations do not correspond to the same tidal stages. Tidal stages for each measurement are recorded in table 4 under "Remarks." Furthermore, the results are not representative of high discharge rates in the estuary, but they are rather intermediate. Table 5 shows discharge rates at S-46 in C-18 during the rainstorms in the latter part of March 1982. The discharge rate on April 1, 1982, when measurements were made, was only 41 percent of the maximum reached on March 29.

The halocline in the Northwest Fork occurs between a depth of about 1 meter during flooding tide, as well as during high tide. During low or flooding tides (fig. 30), the tidal delta promotes mixing of freshwater and saline water so the stratification in this region is not as pronounced. The river delta effectively traps saline waters in the Loxahatchee River (fig. 31) where bottom-water salinities in excess of 20 ppt (parts per thousand) can occur. Saline water spills over the delta into the river during high tide (fig. 31) and sinks to the bottom where it remains trapped.

Measured bottom-current velocities are high enough to transport material of up to 0.5 mm throughout the Northwest Fork. Bottom currents twice as fast would theoretically be capable of eroding sediment. Peak discharges and resulting bottom-current velocities in the Loxahatchee River estuary can be high enough to start eroding sediment that was deposited earlier.

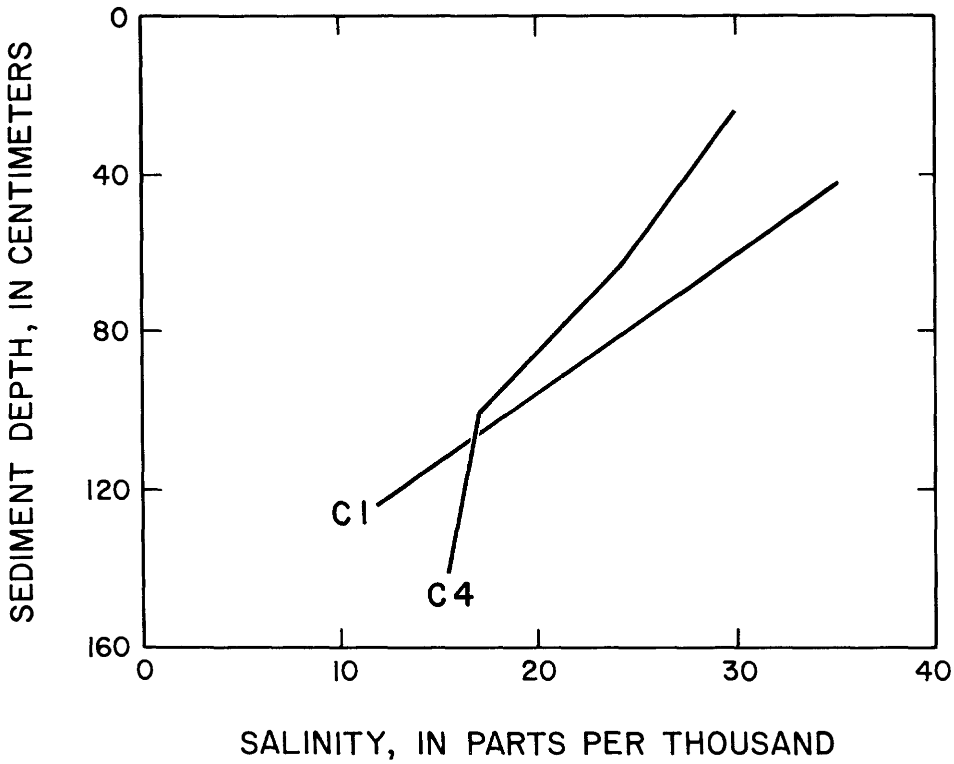

Figure 29.--Pore-water salinities at two sites in the Loxahatchee River estuary.

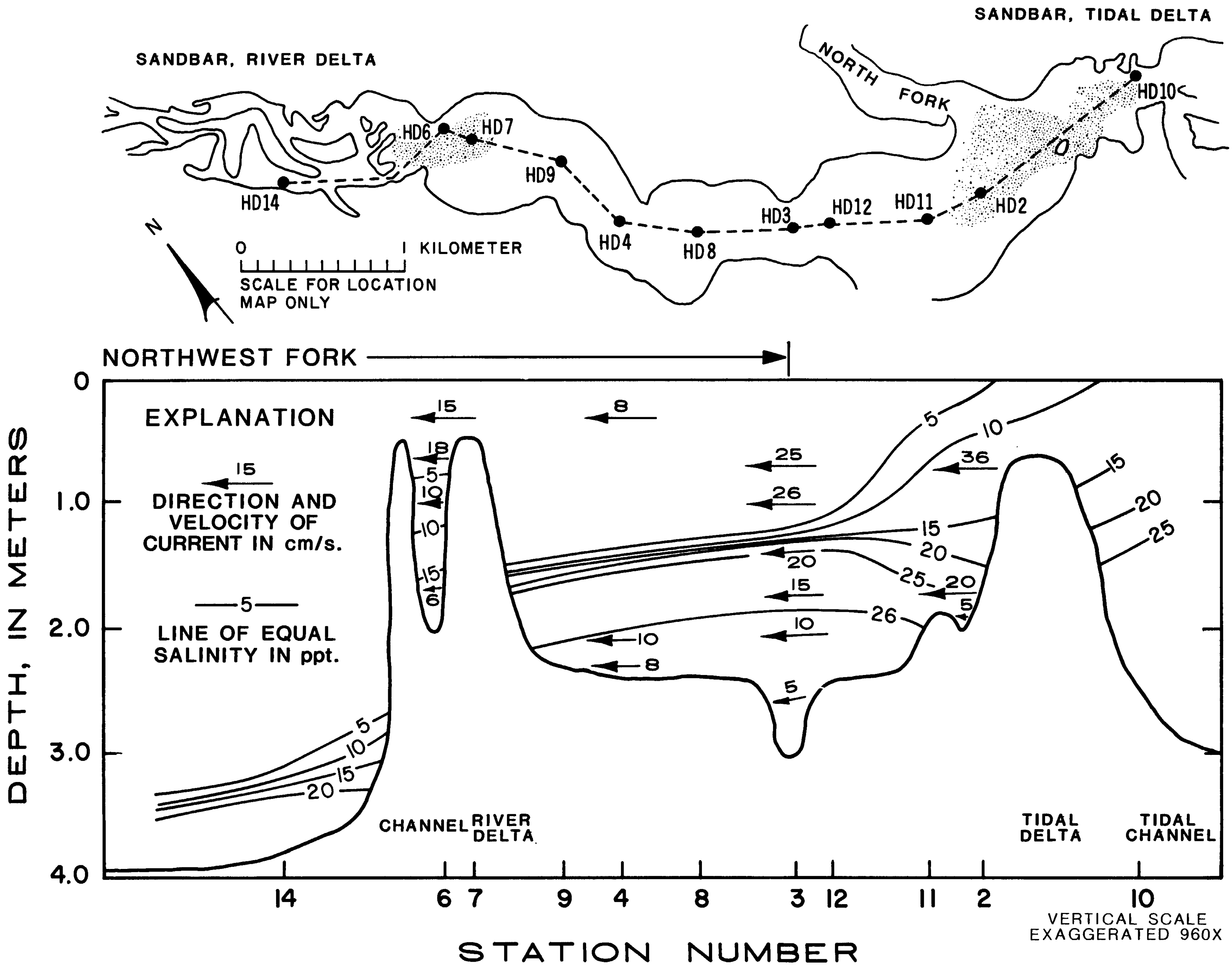

Figure 30.--Salinity profile and current velocities during flooding tide.

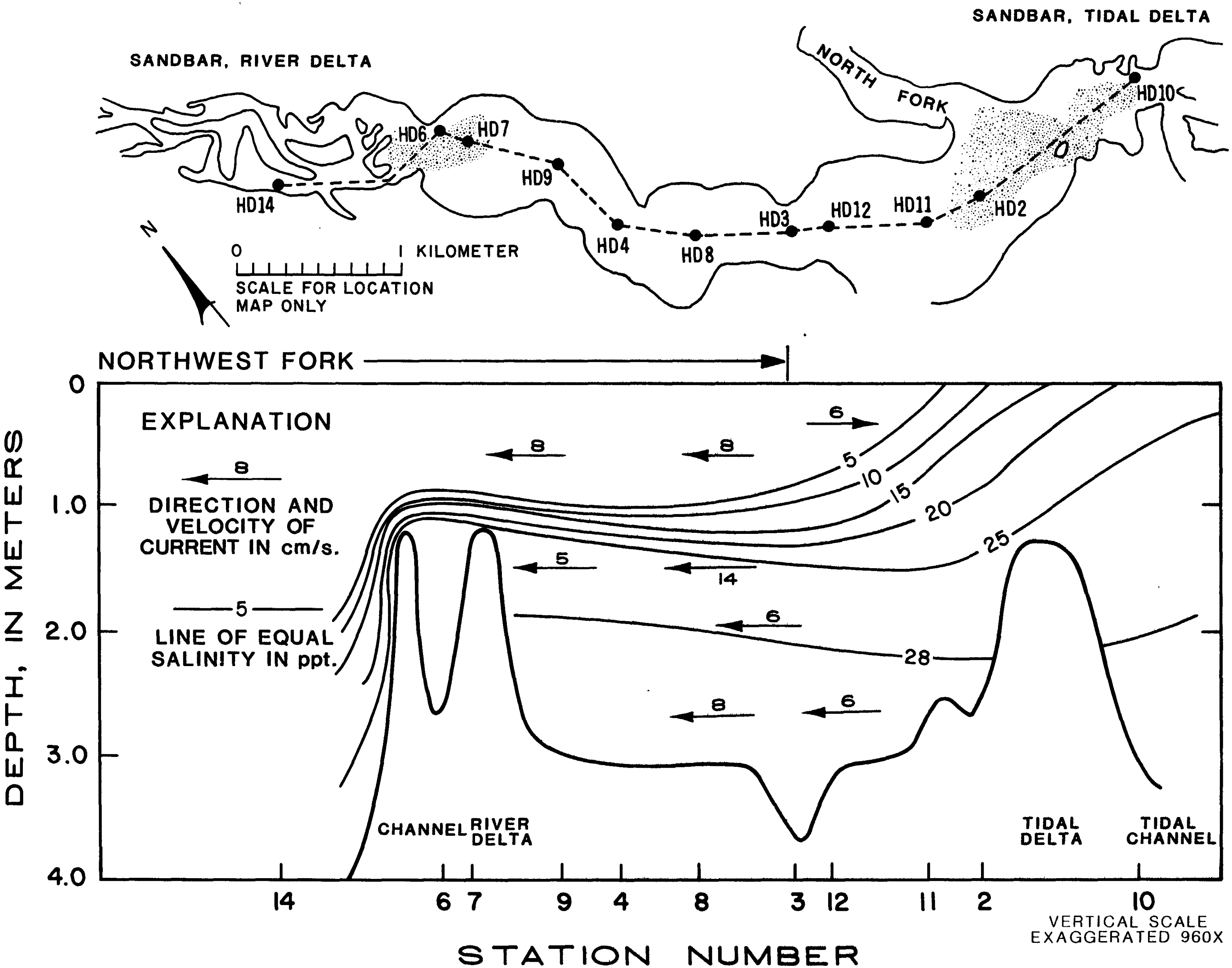

Figure 31.--Salinity profile and current velocities during high tide.

Table 3.--Pore-water chemistry, Loxahatchee River estuary

Station No.	Sediment depth (cm)	Alkalinity (meq/L)	pH
C-1	40	6.84	7.05
	120	5.00	7.28
C-2	25		6.35
	55		6.88
	105		7.00
	145		7.24
C-3	30		6.89
	70		5.85
	110		6.93
C-4	22	16.4	7.08
	62	17.4	6.79
	102	17.9	6.12
	142	14.5	5.10

Table 4.--Hydrographic data measured on April 1, 1982

Station No.	Water depth (ft)	Depth of measurement (ft)	Conductivity (umhos)	Salinity (ppt)	Temperature (°C)	Current velocity (cm/s)	Remarks
HD1	4	1	0.00	0.00	24.24	--	Flooding 1 hour after low tide.
		2	3.20	1.80	24.15	--	
		3	7.44	4.35	23.90	--	
		4	38.97	25.78	23.70	8	
HD2	6	1	15.80	9.73	24.02	--	Flooding 1 hour 15 minutes after low tide.
		2	17.80	11.40	23.90	36	
		4	24.40	15.52	23.70	--	
		5	39.16	25.90	23.48	20	
		6	--	--	--	5	
HD3	9	1	1.30	.70	24.20	--	Flooding 1 hour 35 minutes after low tide.
		2	5.32	3.10	24.30	25	
		3	6.54	3.88	24.40	26	
		4	40.60	26.78	23.90	20	
		5	--	--	--	15	
		6	43.48	28.79	24.20	10	
		8	43.47	28.70	24.20	5	
		9	43.35	--	--	--	
HD4	7	1	.80	.44	24.40	8	Flooding 1 hour 45 minutes after low tide.
		2	.80	.44	24.40	--	
		3	2.90	1.70	23.90	--	
		4.5	41.00	27.70	23.20	--	
		6	41.80	28.20	23.90	10	
		7	--	--	--	8	
HD5	6	1	1.40	.80	24.56	--	Flooding 2 hours after low tide.
		4	1.40	.80	24.56	--	
		5	1.40	.80	24.56	--	
		6	1.60	.90	24.38	--	

Table 4.--Hydrographic data measured on April 1, 1982--Continued

Station No.	Water depth (ft)	Depth of measurement (ft)	Conductivity (umhos)	Salinity (ppt)	Temperature (°C)	Current velocity (cm/s)	Remarks
HD6	6	1	0.70	0.40	24.80	15	Flooding 2 hours 15 minutes after low tide.
		2	1.00	.70	24.00	18	
		3	10.80	6.60	23.57	10	
		4	17.57	11.00	23.50	6	
		5	24.20	15.58	23.40	6	
HD7	4	1	2.90	1.57	25.35	--	Flooding 4 hours 10 minutes after low tide.
		2	3.40	1.90	24.00	--	
		3	30.00	19.20	23.30	--	
		4	39.12	25.90	23.33	4	
HD8	9	2	7.00	4.00	25.40	8	Flooding 4 hours 35 minutes after low tide.
		3.5	23.30	14.00	24.00	--	
		4	--	--	--	14	
		5	42.90	28.40	24.20	--	
		6	--	--	--	6	
		7	43.45	28.50	24.35	--	
		8	--	--	--	8	
		9	43.70	29.00	24.20	--	45 minutes before high tide
HD9	6	1	1.80	1.00	25.40	--	Flooding 30 minutes before high tide.
		2	--	--	--	8	
		3	4.00	2.10	25.40	--	
		4	39.63	26.10	23.20	5	
		6	42.10	28.10	22.82	0	
HD10	9	Surface	26.30	--	--	--	High tide
		1	39.40	24.85	25.40	--	
		3	41.70	26.60	25.40	--	
		7	45.70	29.40	25.40	--	
		9	46.00	29.70	25.40	--	

Table 4.--Hydrographic data measured on April 1, 1982--Continued

Station No.	Water depth (ft)	Depth of measurement (ft)	Conductivity (umhos)	Salinity (ppt)	Temperature (°C)	Current velocity (cm/s)	Remarks
HD11	7	1	13.50	7.90	25.80	--	Just past high tide; no sign of bottom current; boundary between 2 and 3 feet.
		3	32.00	19.90	25.30	--	
		5	39.77	25.30	25.30	--	
		6.5	40.70	26.00	25.20	--	
HD12	9.5	1	8.60	4.85	26.10	--	10 minutes past high tide
		2.2	Boundary	--	--	6 ebb	
		3	30.25	19.18	24.16	--	
		5	39.05	25.08	25.04	--	
		7	43.43	28.56	24.35	--	
		9	44.00	29.21	24.29	6 flood	
HD13	8	1	5.42	2.04	25.82	--	
		2	6.75	3.75	26.60	--	
		3	20.82	12.72	24.32	--	
		5	39.11	25.20	24.68	--	
		7	42.92	28.23	23.99	--	
HD14	18	18	30.90	20.20	23.90	--	Sharp salinity in ppt interface at 9 to 10 feet; 2 hours 30 minutes after low tide.

Table 5.--Discharge rates (24-hour periods) at Canal 18, structure 46 in the Southwest Fork, during and after rainstorms in late March 1982

Date	Discharge (m/s)
March 25	0
26	126
29	1,109
30	975
31	623
April 1	457
2	296
3	238
4	127
5	424
6	145

SEDIMENT DYNAMICS

The sandbar, 3 km inland from Jupiter Inlet, is essentially a flood-tidal sand delta. Sand is being provided from the inlet and the seaward parts of the system and is carried inward to this point where the estuary broadens. Silt and fine sand are being deposited where current velocities decrease. The sandbar has migrated landward over the last 40 years as documented by aerial photography (McPherson and others, 1982). This migration is also indicated in the sediment sequence of core 3 (fig. 11) where 300 to 500-micron sand predominates at depth, and a pronounced 100-micron peak occurs near the surface. In other words, the tidal sandbar, which consists mainly of less than 200-micron material, has prograded over preexisting coarser sand since most of the sand near the surface is less than 200 microns in size and reflects predominance of transport by suspension.

From the grain size and geometry of the sediment body, we conclude that the decreasing currents in the channel, as the estuary widens, cause the fraction of the sediment moving as bedload to be deposited on the seaward side of the delta. The finer sand, however, is carried on to the delta. Transport of finer sand occurs on the delta both during day-to-day as well as winterstorm situations. We have observed active movement of sediment on part of the sandbar surface when there was little influence by wind stress or waves. The fine sand does not bypass the delta or spread into the Northwest Fork during day-to-day processes.

The sandbar at the upper reaches of the Northwest Fork is simply a sand delta at the mouth of the constricted or channelized part of the Loxahatchee River. The sediment in this sandy river delta is dominated by medium to coarse-grained sand that tends to move downstream as bedload. The sand is derived from bedload transport down the river during times of high discharge. The bedload sediment is deposited on the delta in association with decreasing current velocities as the flow is no longer confined laterally. About 25 percent of the sand on this river delta is less than 200 microns in size and probably has been transported in suspension. It is likely that significantly more sand in suspension (some fine sands) bypasses the delta during major discharge periods and spreads into the Northwest Fork where it settles out from suspensions to form the fine quartz sand drapes observed during diving. The fine quartz sand forming draping laminae on the surface is considered to eventually become discrete laminae at depth.

The sand laminae could also be derived from the oceanside after bypassing the tidal delta in suspension during high-energy flood currents. Day-to-day currents are sufficient to carry the fine sands on to the tidal delta, but storm conditions, flood surges, or very strong estuarine circulation are necessary to sweep sand from this delta into the Northwest Fork.

The sediments on both of the sandbars or deltas contain very little mud, indicating that the major phases of sedimentation are high-energy events that exclude mud from being deposited, and that lesser energy periods have sufficient wave or tidal action to prevent mud from settling. The river delta does have a small amount of mud mixed with the sediment and is visible as mottling patterns in the sediment. This represents mud that has briefly rested on the bottom and has been carried down into burrow tubes away from an area where it can be physically reworked. On the flood tidal delta, mottled sands containing a significant component of mud are observed only in cores 5 and 6 on the inner flank of this delta. Mottling observed in both deltas is a reflection of individual major pulses of sedimentation not producing thick sediment sequences, and that there are fairly long periods of quiescence between major depositional events during which organisms can thoroughly rework the sediment which was deposited.

Within the main body of the estuary, the organic-rich muds containing thin layers, laminae, and lenses of sand reflect two kinds of sedimentation. The fine-grained organic-rich muds accumulate during quiet periods and represent a mixture of detritus that is carried down from the river, fine-grained material brought into the estuary through Jupiter Inlet, and material that is produced in the estuary (nonskeletal organic matter, diatoms, and foraminifera).

The sand laminae, lenses, and layers represent periods when sand is being swept across the river or tidal delta in turbulent suspension and carried into the estuary. Peak discharges from the river should carry suspended sand into the Northwest Fork by way of surface freshwater flows, and the sand would then settle to the bottom through the denser underlying saline water. Sand from the tidal delta would be carried in by bottom currents that could cause bottom reworking. If there were strong estuarine circulation during peak river discharge, bottom currents might be sufficient to erode and transport sediment. The tidal delta, however, creates a sill that should tend to dampen the development of extremely strong estuarine circulation during most conditions.

The tidal delta that partly blocks the estuary creates an estuarine basin (Northwest and Southwest Forks) that is a potential sediment sink in which rapid accumulation of fine-grained sediment could occur. Carbon-14 analyses, however, indicate that there is an extremely slow rate of sedimentation (an average of 0.25 mm/y over the last 1,000 years). Therefore, either very little fine-grained sediment is available to the deeper parts of the estuary, or physical processes are reworking and removing part of the fine-grained sediment from the estuary.

The lower rates of sedimentation in the Loxahatchee River estuary are in part related to its setting. The rivers that feed it drain a swamp environment from which only organic material and some quartz sand can be derived. There is, however, evidence that sediment is being provided to the Loxahatchee River estuary at much higher rates than it is actually accumulating. We have taken several cores which penetrated over a meter of very soft organic-rich mud with essentially no sand component in canals adjacent to the estuary. Sedimentation rates in these canals are at least 1.5 cm/y and may be as high as 3.0 cm/y, nearly 100 times the rate of sediment accumulation documented in the main body of the estuary. This demonstrates that there are large volumes of fine sediment available to the estuary, and that there are high rates of sedimentation in the true sediment sinks. This also suggests that the main body of the estuary has other dynamic processes inhibiting rapid rates of sediment accumulation.

We have recorded various bottom conditions on several diving trips. Several times we observed an extremely turbid zone, 20 to 60 cm above the bottom. The top of this turbid zone was generally distinct. On one visit, we found the water column from the surface to the bottom to be relatively clear with visibilities of 4 feet. The bottom surface had a gently undulating morphology and was covered with entrances to burrow tubes throughout most of the estuary. The higher areas of the undulating bottom were muddy, but the lower areas commonly had very thin laminae of sand at the surface. This suite of diving observations demonstrates that though sediment-laden waters are present in the estuary during much of the year, when conditions clear, there is sand on parts of the bottom surface. This either means that mud is being swept from the system or that new layers and laminae of sand are provided frequently to the estuary.

The thin sand layers, laminae, and lenses in the organic-rich mud are predominantly made of quartz sand grains that are finer than 200 microns in size. We conclude that this sand is spread across the estuary as a suspended load. There is, however, a small percentage of the sand that is significantly coarser than 200 microns and either represents bedload movement or periods when there are highly turbulent waters moving across the estuary, keeping these coarser sizes suspended in the water column. In general, we conclude that the latter is the case because many of the thin quartz laminae lie on top of thin layers of mud in which there is no apparent evidence of erosion.

In addition to the very thin sand laminae, there are occasional thicker sand layers (to as much as 3 cm). These thicker sand laminae and layers may well represent a winnowed concentration of a thicker sequence of sand and mud formed by active bottom winnowing and reworking of the substrate. It is, in fact, very difficult to recognize erosion surfaces in a sediment system that is dominated by sediments transported in suspension because deposition, as well as erosive surfaces, will tend to be essentially horizontal and not have ripples or other bed forms in which truncation would be recognizable. If this is the case, there may be fairly high rates of sedimentation within the estuary, but infrequent physical reworking events will eliminate much of that sequence and produce a long-term slow rate of net-sediment accumulation.

The sand that forms the thin layers and laminae in the estuary could be derived either from riverine discharge carrying sediment downstream into the estuary or from estuarine circulation which would carry sand from the lower reaches of the estuary inward. It is also possible that extreme wave action during major hurricane conditions could cause both reworking of sediments from the estuary margins and deltas and provide a circulation to move sediment well out into the estuary proper. At the present time, we are unable to positively differentiate between these three possibilities. Whichever is the case, the sand layers are a product of a catastrophic kind of sedimentation that was not directly observed during our study.

The aforementioned evaluation of sediment dynamics in the Loxahatchee River estuary has been largely based on observations of processes during present-day conditions and, therefore, apply only for periods during which Jupiter Inlet is open allowing free exchange with the ocean and estuarine circulation. Undoubtedly there were periods when the inlet was closed, and the dynamics of the system were drastically different.

SUMMARY

The Loxahatchee River estuary, a small (544 km^2) shallow-water body in southeastern Florida, empties into the Atlantic Ocean at Jupiter Inlet. Historical evidence indicates that the estuary periodically closed and opened to the sea as a result of natural causes. Originally, freshwater and tidal flows maintained the inlet open some of the time. Near the turn of the century, some flow was diverted by construction of the Intracoastal Waterway and the Lake Worth Inlet and by modification of the St. Lucie Inlet. Subsequently, Jupiter Inlet remained closed much of the time until 1947, except when periodically dredged. After 1947, it was maintained open by dredging.

After 1900, man began to influence the estuary by dredging and by altering drainage in the basin. Generally, ground-water levels have been lowered, thereby altering the quantity, direction, and pattern of freshwater inflow.

In the main body of the estuary away from sandbars, the sedimentary sequences were dominated by bioturbated mud, or mottled muddy sand, to depths of about 30 cm below the sediment surface and by interlayered sand and mud with high-organic content below the bioturbated zone. The biological reworking of the near surface sediment is interpreted as the result of increased marine influences, possibly associated with "permanently" opening and maintaining Jupiter Inlet since the late 1940's and with altered freshwater runoff.

Sedimentation rates based on radiocarbon dates have decreased from 0.69 mm/y about 7,000 years ago to about 0.25 mm/y 1,000 years ago. Although this trend is associated with a decrease in the rate at which sea level has been rising, sedimentation rates nevertheless have not kept up with rises in sea level. Although not recognizable in the sedimentary sequence, periods of erosion and nondeposition might explain the apparent anomalously low-sedimentation rates.

Other evidence indicates that sediment is being provided to the estuary at much higher rates than it is actually accumulating, and this suggests that dynamic physical processes of circulation and flushing are inhibiting rapid sediment accumulation. The sources of the sediment that accumulate in the estuary include: (1) fine-grained suspended material brought into the estuary through Jupiter Inlet; (2) biological material produced in the estuary; (3) fine-grained suspended material, including sand and detritus, carried down the river or other tributaries; (4) medium to coarse sand transported as bedload; and (5) fine, medium, and coarse sand suspended during highly turbulent storm periods.

The thin sand laminae in the organic-rich mud of the mid-estuary sediment sequences were deposited primarily from a suspended load. Somewhat thicker sand layers in the mud probably represent catastrophic conditions of highly turbulent transport. The tidal sandbar, about 3 km from Jupiter Inlet, is being built by sand transported from the ocean primarily in suspension. The river delta bar at the upstream reach of the Northwest Fork embayment is built primarily by bedload transport of sand down the river during periods of large freshwater discharges although about 25 percent of the sand in this bar was probably transported as suspended load from upstream.

SELECTED REFERENCES

Cary Publications, Inc., 1978, The Loxahatchee Lament: Jupiter, Florida, 360 p.

Howard, J. D., Elders, C. A., and Heinbokel, J. F., 1975, Animal-sediment relationships in estuarine point bar deposits, Ogeechee River-Ossabaw Sound, Georgia, Mar. 7:181-203.

Inter-Agency Committee on Water Resources, 1957, Subcommittee on Sedimentation: Report no. 11.

McPherson, B. F., and Sabanskas, Maryann, 1980, Hydrologic and land-cover features of the Loxahatchee River basin, Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-1109.

McPherson, B. F., Sabanskas, Maryann, and Long, W. A., 1982, Physical, hydrological, and biological characteristics of the Loxahatchee River estuary, Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 82-350.

Neumann, A. C., 1969, Holocene sea level history of Bermuda recorded by deep peat sequences (Abstract): VIII Cong. Union Int. pour Etude de Quaternaire.

Parker, G. G., Ferguson, G. E., Love, S. K., and others, 1955, Water resources of southeastern Florida: U.S. Geological Survey Water-Supply Paper 1255, 965 p.

Pritchard, D. W., 1967, Observations of circulation in coastal plain estuaries, in Lauff, G. H., ed., Estuaries: American Association for the Advancement of Science, Publication 83, Washington, D.C., p. 37-44.

Scholl, D. W., Craighead, F. C., Sr., and Stuiver, M., 1969, Florida submergence curve revised, its relation to coastal sedimentation rates: Science, v. 163, p. 562-564.

Scholl, D. W., and Stuiver, M., 1967, Recent submergence of southern Florida, a comparison with adjacent coasts and other eustatic data: Geological Society American Bulletin 78, p. 437-554.

Shepard, F. P., 1964, Sea level changes in the past 6,000 years: Possible archeological significance: Science, v. 143, p. 574-576.

Shepard, F. P., and Curray, J. R., 1967, Carbon-14 determination of sea level changes in stable areas: Progress in Oceanography, v. 4, p. 283-291.

Shields, A., 1936, Anwendung der Aehnlichkeitsmechanik auf die Geschiebebewegung: Berlin Preuss, Versuchsanstalt fur Wasser, Erd und Schiffbau, no. 26, ref. in Bagnold, R. A., 1966, An approach to the sediment transport problem from general physics: U.S. Geological Survey Professional Paper 422-1.

U.S. Army Corps of Engineers, 1966, Survey report on Jupiter Inlet, Florida: Jacksonville, Florida.

Vines, W. R., 1970, Surface water, submerged lands, and waterfront lands: Area Planning Board, Palm Beach County, 182 p.

Shepard, F. P., 1964, Sea level changes in the past 6,000 years: Possible archeological significance: Science, v. 143, p. 574-576.

Shepard, F. P., and Curray, J. R., 1967, Carbon-14 determination of sea level changes in stable areas: Progress in Oceanography, v. 4, p. 283-291.

Shields, A., 1936, Anwendung der Aehnlichkeitsmechanik auf die Geschiebebewegung: Berlin Preuss, Versuchsanstalt fur Wasser, Erd und Schiffbau, no. 26, ref. in Bagnold, R. A., 1966, An approach to the sediment transport problem from general physics: U.S. Geological Survey Professional Paper 422-1.

U.S. Army Corps of Engineers, 1966, Survey report on Jupiter Inlet, Florida: Jacksonville, Florida.

Vines, W. R., 1970, Surface water, submerged lands, and waterfront lands: Area Planning Board, Palm Beach County, 182 p.

*U.S. GOVERNMENT PRINTING OFFICE: 1984-746-138/10009 Region 4.