NORDA REPORT

THE GEOLOGICAL ENVIRONMENT WEST OF ST. CROIX

T. L. HOLCOMBE
A. M. EINWICH
F. A. BOWLES
J. EGLOFF, JR.

SEA FLOOR DIVISION
NAVAL OCEANOGRAPHIC LABORATORY

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FOREWORD

This report, commissioned by the Chesapeake Division, Naval Facilities Engineering Command (CHESNAVFACENGCOM), contains results of an intensive geological study of one small area west of the island of St. Croix, U.S. Virgin Islands. Although primarily intended as a reference volume for engineers and scientists who operate and maintain the St. Croix Tracking Range, the publication will also be of interest to students of northeastern Caribbean geology, and to marine geologists in general.

C. G. DARRELL, CAPTAIN, USN
COMMANDING OFFICER
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Geological and geophysical data collection efforts over the past 15 years were augmented in early 1976 with 12 kHz bathymetry, together with 3.5 kHz and low-frequency seismic reflection data, collected on N/S and E/W gridlines at 300 meters (m) line spacing, plus extensive bottom photographs and several video-tapes. These data were collected by USNS LYNCH and the submersible ALVIN. All available data were assembled, and, where appropriate, synthesized into this report.

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A small plateau (Frederickstad Plateau), with a gently tilted, low-relief surface, lies west of the island slope of St. Croix at 800-1,200 m depth. The plateau is dissected by three submarine canyons. Rock outcrops are largely confined to the walls of the canyons, whereas the rest of the plateau is underlain by at least a surface veneer of unconsolidated carbonate ooze. The unconsolidated sediments are predominantly silty calcilutites with an 85% average carbonate content. Two of the canyons (Shepard Canyon, Sprat Hall Canyon) are clearly erosional in origin, whereas one (Frederickstad Canyon) appears to have been associated with a prograding sedimentation regime in which a plain and natural levee were formed. Whether turbidity currents, sand flows, or other downslope sediment movements are active in eroding the canyons at present remains an open question.

The engineering properties, sensitivity (2-8), and cohesion (56-89 g/cm^2 of surficial sediments are, as a whole, rather uniform over the area. Void ratios range from 1.31 to 1.83, and porosity ranges from 56.5 to 64.7%.

Three stratigraphic units are identifiable in the seismic sections of the area based on their acoustic character. Little is known of the lithology and time-stratigraphy of the acoustic units in the absence of stratigraphic control. A NE/SW syncline underlies the Plateau and controls the location of Frederickstad Canyon. Structural activity seems to have ceased prior to, or during deposition of, the early part of the youngest stratigraphic unit, although minor structural movements probably occurred more recently.

The area is seismically active today, and may be expected to undergo occasional moderate earthquakes. Destructive earthquakes, although rare, are an ever-present possibility.

EXECUTIVE SUMMARY

This report represents a geological study of that portion of the St. Croix Ridge which lies beneath the St. Croix tracking range west of the island of St. Croix in the Caribbean. The study was prepared for CHESNAVFACENGCOM in support of their continuing program of range operation and maintenance.

Geological and geophysical data collection efforts over the past 15 years were augmented in early 1976 with 12 kHz bathymetry, together with 3.5 kHz and low-frequency seismic reflection data, collected on N/S and E/W gridlines at 300 meters (m) line spacing, plus extensive bottom photographs and several videotapes. These data were collected by USNS LYNCH and the submersible ALVIN. All available data were assembled, and, where appropriate, synthesized into this report.

A small plateau (Fredericksted Plateau), with a gently tilted, low-relief surface, lies west of the island slope of St. Croix at 800-1,200 m depth. The plateau is dissected by three submarine canyons. Rock outcrops are largely confined to the walls of the canyons, whereas the rest of the plateau is underlain by at least a surface veneer of unconsolidated carbonate ooze. The unconsolidated sediments are predominantly silty calcilutites with an 85% average carbonate content. Two of the canyons (Shepard Canyon, Sprat Hall Canyon) are clearly erosional in origin, whereas one (Fredericksted Canyon) appears to have been associated with a prograding sedimentation regime in which a plain and natural levee were formed. Whether turbidity currents, sand flows, or other downslope sediment movements are active in eroding the canyons at present remains an open question.

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This study was carried out with the support of CHESNAVFACENGCOM under Contract No. N62477-76-PQ-6-0002. Bathymetry and seismic reflection data were collected by the U.S. Naval Oceanographic Office (NAVOCEANO) ship USNS LYNCH. Earlier bathymetry was obtained from the files of NAVOCEANO and the Defense Mapping Agency Hydrographic Center (DMAHC). Dive narratives and photographs from dives made by the submersibles ALVIN and ALUMINAUT and bottom photographs collected by the R/V OCEANIC were made available by CHESNAVFACENGCOM. P. Grim and B. Grant of the National Geophysical and Solar-Terrestrial Data Center provided assistance in an inventory of the data holdings of other oceanographic institutions. J.E. Matthews provided assistance in preparing the section on Regional Setting. Discussions with R.F. Dill, J.E. Matthews and W.C. Ward on the geology of the St. Croix area have been most helpful. L. Thigpen edited and typed the final manuscript. S. Madosik assisted with data compilations and illustrations.

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THE GEOLOGICAL ENVIRONMENT WEST OF ST. CROIX

I. INTRODUCTION

Significant geological and geophysical data have been collected from the sea floor beneath the St. Croix tracking range (17°40'-17°47'N, 64°53'-65°04'W). This data collection supported engineering efforts associated with the installation, operation, and maintenance of tracking range arrays. The data gathering, conducted principally by the Naval Oceanographic Office, began in 1962, when bathymetry was collected by the USS SHELDRAKE, and when gravity cores were taken by the USNS SAN PABLO. Additional bathymetry and bottom photographs from the array sites were collected by the USS SHELDRAKE and R/V OCEANIC in 1965, and dives were made by the submersible ALUMINAUT in 1966. In 1976, detailed bathymetry, together with 3.5 kHz and low-frequency seismic reflection data, were collected by USNS LYNCH, and dives were made by the submersible ALVIN to obtain videotapes, bottom photographs, and bottom samples from the vicinity of the array sites. A significant improvement in the quality of the data collected in 1976 over that collected in 1962-1966 resulted because: (1) more exact navigation made higher-density bathymetry and seismic reflection surveys feasible; and (2) the precise bottom-tracking by the ALVIN provided accurate locations where photographs and samples could be taken.

The data compiled after the 1962-1966 surveys were laboratory analyses, charts, and logs. A bathymetry chart and analyses of physical and engineering properties of cores (Ridley et al., 1963) were produced as a result of the 1962 survey. An updated bathymetry chart was produced after the 1965 bathymetric surveying. Descriptive logs were compiled from the 1965 bottom photograph analyses, and in situ bottom character descriptions were made from the ALUMINAUT in 1966. Although these contributions are valuable, they are not geological studies.

The purpose of this report is to synthesize the fragmented data collection and analysis efforts of 1962-1966 and to combine the results with the 1976 data to produce a comprehensive geological report. Notes regarding data quality are included within the report as an aid to engineering applications. The intent is a single report which outlines the knowledge of the sea floor beneath the St. Croix tracking range using the existing data. First, a brief summary of the regional geology will set the stage for focusing on the sea floor of the subject area in detail. This will be followed by a description and consideration of the physiography, surficial sediments, subsurface geology, and seismicity. Finally, the discussion will consider those features of the sea floor which are particularly applicable to maintain the tracking range. Throughout the report, the emphasis is on illustration. The volume of material permits inclusion of only a fraction of the data, but representative photographs and sections are presented, and maps provide the necessary data integration. An annotated bibliography refers to earlier data reports upon which this study is based, and to collateral references on the geology of the island of St. Croix and its vicinity.

II. REGIONAL SETTING

The island of St. Croix and the St. Croix tracking range are situated atop an EW submarine ridge, the St. Croix Ridge. This ridge joins the main structure of the Greater Antilles south of Puerto Rico, and extends eastward to the northern end of the Aves Ridge, a distance of about 175 km (Figure 1a). Elevation of the St. Croix Ridge ranges from a maximum of +350 to +360 m on the island of St. Croix to a minimum of −1,800 to −2,000 m between St. Croix and the Aves Ridge. The crest of the St. Croix Ridge is broken as if faulted west of St. Croix, where at least three gently tilted, plateau-like crestal regions are separated by abrupt depth discontinuities, which may be fault scarps. One of these scarps separates the island of St. Croix from the dissected plateau, where the tracking range array sites are located. Structural trends on the ridge crest are predominantly NE/SW, but more northerly and easterly trends also occur (Figure 2). The island of St. Croix is an integral part of the fault-block ridge crest, and displays predominant NE/SW structural trends. On the island, a NE/SW-trending graben, filled with Tertiary sedimentary strata, separates two elevated blocks where older sedimentary and metasedimentary rocks are exposed (Cederstrom, 1950; Whetten, 1966).

The southern flank of the St. Croix Ridge is an eastward extension of the southern island margin of the Greater Antilles. Steep EW-trending escarpments and ridges make up a 20- to 30-km-wide belt of island slope which extends down to the floor of the Muertos Trough (Figure 1a). Resolution of subsurface acoustic horizons is poor, probably because structural disturbance has "jumbled" the sediments and destroyed the continuity of reflective horizons. The structure is thought to be largely compressional, resulting from a regime of plate convergence (Case, 1975; Garrison et al., 1972; Matthews and Holcombe, 1974), which has probably been active since Miocene time. Slumping and other gravity-induced tectonic effects may also have been a factor in producing the structural deformations (Figure 2).

The broad, shallow, eastern end of the Muertos Trough (Figure 1a) forms the depressed northern margin of the Venezuelan Basin and adjoins the base of the southern flank of the St. Croix Ridge. Depth increases westward from~ 3,500 m south of the eastern end of the ridge to~ 5,000 m south of Puerto Rico. Much of the depth increase may be sedimentological rather than structural, for a broad wedge of sediments appears west of the Aves Ridge; its greatest thickness occurs immediately west of the ridge, thinning westward. The floor of the Muertos Trough is smooth to gently undulating.

North of the St. Croix Ridge, the Anegada Trough (Figure 1a) separates the ridge from the Virgin Islands Shelf. The trough separates into basins divided by sills or ridges. A steep escarpment separates the crest of the St. Croix Ridge from the basins of the Anegada Trough. Turbidite plains occupy the floors of the basins. The largest of these basins (30 by 120 km), the Virgin Islands Trough (Figure 1a), lies immediately north of the island of St. Croix and the St. Croix tracking range. Its plain lies at a depth of~4,500 m. This basin is directly downslope from St. Croix. Thus, much of the sediment contribution to the turbidite plain may originate on the island of St. Croix and on the crest of the St. Croix Ridge. The Anegada Trough is the site of a major active transcurrent fault which is defined by seismicity (Donnelly, 1964; Sykes and Ewing, 1965). Possibly the NE-trending faults on the St. Croix Ridge are secondary structures that resulted from the primary transcurrent movement along the Anegada Trough.

There is evidence (Matthews, 1970) that the St. Croix Ridge was originally the southern flank of the Puerto Rico/Virgin Islands platform, and that St. Croix was separated by the formation of a post-Eocene graben (Virgin Islands Trough). Therefore, it is presumed that crustal structure and rock types beneath St. Croix are similar to those of the remaining Virgin Islands and Puerto Rico. On the basis of seismic reflection data, Officer et al. (1959) concluded that the eastern Greater Antilles Ridge was composed of a thick wedge of material with a 7.0 km/sec. seismic velocity. Talwani et al. (1959) were in general agreement, and, by gravity modeling, derived a 3.0 gm/cc density for the material. Matthews and Shuey (1971), with the use of a magnetic model utilizing gradational susceptibilities to model long wavelength anomalies across the structure, concluded that this thickened crustal ridge of material was composed of serpentinized peridotite, which represented a hydrated upper mantle.

Serpentine pebbles and coarse sand were brought up on the core-catcher during core operations in the eastern Muertos Trough, downslope from the St. Croix Ridge (J.E. Matthews, personal communication). The Antilles Ridge was the site of Upper Cretaceous volcanic eruptions of keratophyres and spilites, and these were intruded by plutons (generally composed of diorite, quartz diorite, or granodiorite) during the Upper Cretaceous and lower Tertiary periods. On the island of St. Croix, the predominant rocks (Late Cretaceous/epiclastic-volcanic/ and tuffaceous sedimentary strata) are different from the volcanic rocks of the eastern Greater Antilles Ridge, but were probably formed in an adjacent or juxtaposed marine environment (Whetten, 1966). The continuity of structural fabric over the St. Croix Ridge would lead one to expect that rocks similar to those underlying the island of St. Croix might also underlie submarine portions of the St. Croix Ridge. The general rock types can be summarized in terms of their density and magnetic susceptibility by the following suggested values.

Rock Type	Density gm/cc Assumed	Susceptibility 10^{-3} emu/cc Measured
Serpentine	3.0	0.01-0.05, 0.03*
Volcanic	2.5	0.01-0.04, 0.02*
Intrusive	2.65	0.2*
Sediment	2.0	Zero

*Denotes average value

The gravity and magnetic values in the St. Croix vicinity have been presented by Shurbet et al. (1956), Bowin (1972), and Garrison et al. (1972), respectively. The magnetic map is not detailed and only shows regional positive anomalies of 250 gammas centered just south of the island, with an associated negative anomaly to the north of the island (Figures 3a, 3b). This is similar to the anomaly pattern associated with the St. Croix Ridge to the west, and is easily modeled by a volcanic and intrusive-capped pedestal of serpentine. A small, 100 gamma, positive anomaly just north of the island's eastern tip might result from a diorite intrusion similar to those which occur on St. Croix. The gravity map is based upon land stations and contains more detail (Figure 4). The average simple bouguer field over the island is + 150-160 mgal, except over the southern-central part of the island where a minimum of + 140 mgal results from the tertiary sedimentary basin. A density contrast of 0.5 gm/cc between the Tertiary sediments and the Cretaceous volcanics predicts a 2 km depth for the basin. The diorite intrusion in the eastern part of the island produces a +170 mgal anomaly. There are no gravity or magnetic surveys of the region of sufficient detail to interpret such small-scale geographic variations as faults, dikes, or the configuration of intrusions or structures.

III. PHYSIOGRAPHY

A. GEOMORPHOLOGY

The physiography of the St. Croix tracking range is summarized by a bathymetry map (Figure 5), a physiographic map (Figure 6), topographic profiles (Figures 7 and 8), and 3.5 kHz seismic sections illustrating physiographic character (Figures 9-13).

As previously noted, west of the island of St. Croix, the St. Croix Ridge is characterized by a flattened crest that is broken by escarpments into plateaus which occur at different levels. The first plateau west of St. Croix, here termed the Frederiksted Plateau, lies at a depth of 800-1,200 m (Figure 5). The Frederiksted Plateau is approximately 30 km long, 20 km wide, and its long dimension is N/S. It is separated from the island of St. Croix by a N/S-trending island slope of about 750 m relief and 5-30° slopes, and may be a fault scarp. The St. Croix tracking range occupies approximately the northern half of this plateau.

The surface of the northern Frederiksted Plateau is regionally flat to gently sloping terrain, partly dissected by canyons. Where the plateau is flat, its surface is generally smooth, and continuous shallow subbottom reflectors, which are conformable with the bottom, indicate undisturbed surficial sediments. Where the plateau slopes, its surface is irregular or undulating, and shallow subbottom reflectors are locally disrupted, indicating gravity or tectonically-induced disturbances of sediments. Near the St. Croix Island slope, the bottom surface (excluding the canyons) slopes westward away from the island slope at about 2-5°. The remainder of the Frederiksted Plateau within the study area slopes away from the island slope gently W/SW at about 1-3°. The northern edge of the plateau surface, however, is tilted gently S/SE at about 2-4°.

The northern edge of the Frederiksted Plateau ends at the rim of a steep (10-30°) escarpment which separates it from the deep (~4,500 m) Virgin Islands Trough. Although the escarpment generally trends E/W, its upper slopes are indented in the northern portion of the study area; they trend NE/SW in the NW corner of the study area, and NW/SE in the NE portion of the study area. The steep NE/SW and NW/SE escarpment intersects with the SSE-tilted plateau and produces NW/SE and NE/SW ridges at the northern edge of the plateau which come together in the shape of an inverted vee. Opposite the NE indentation, the island slope is continuous with the escarpment leading down into the Virgin Islands Trough.

Many small submarine canyons originate on the western island slope of St. Croix and coalesce downslope to form larger canyons. Three large canyons dissect the plateau's surface. One of these, the Frederiksted Canyon (Figure 5), drains all the slope canyons which originate south of an E/W line extending westward from Frederiksted Pier. The Frederiksted Canyon extends westward, then curves southwestward across the Frederiksted Plateau. North of Frederiksted Pier, the slope canyons coalesce into two larger canyons, the Shepard Canyon and Sprat Hall Canyon (Figure 5); both curve northward and extend over the edge of the plateau and northward down the escarpment, where they merge into a single canyon. Several smaller canyons extend westward down the island slope west of Sprat Hall, turn abruptly northward, and extend directly down the steep escarpment leading into the Virgin Islands Trough. On the island slope, relief of the canyons is small (generally less than 20 m). On the plateau, the Frederiksted Canyon varies in relief from 20 to 100 m, becoming generally larger and deeper downslope. The Shepard Canyon increases from 20 to 180 m relief downslope, and reaches maximum relief at the northern edge of the plateau. Its relief again decreases on the escarpment. The Sprat Hall Canyon reaches a maximum relief of 60 m at the plateau's edge. The width of the Frederiksted Canyon varies from .75 to 1.2 km, while the width of the Shepard Canyon ranges from 1 to 2 km. Canyon slopes average 5-15°.

Except for its upturned northern edge, the gradient of the Frederiksted Plateau extends away from the island slope gently downslope to the W and SW. The Frederiksted Canyon is conformable to the plateau's gradient. It swings left (SW) with increasing distance from the island slope. The canyon is leveed, with the right (N) bank being 50-100 m higher in elevation than the left (S) bank. Deep-sea channels and submarine canyons which are leveed and asymmetrical (with the right bank being of higher elevation than the left bank) have been observed throughout the northern hemisphere in the Atlantic (Heezen et al., 1969; Rona et al., 1967), Pacific (Menard, 1955), and elsewhere. Left-hooking of channels has been observed on the continental rise off Oregon and Washington in the Pacific. Menard (1955) has suggested that the coriolis effect causes the left-hooking because of preferential deposition on the right bank in the Northern Hemisphere; this would also explain why the right banks are higher than the left banks.

The occurrence of a natural levee on the higher right bank and the conformity of overall gradients between the Frederiksted Canyon and the Frederiksted Plateau (possibly including the left-hooking, although leftward curvature could instead be the result of structural control) suggest that the entire plateau, except for the northern edge, has been part of a sedimentation regime which has favored sediment deposition over sediment erosion. Thus, the Fredericksted Canyon has been a principal conduit for sediment-laden currents.

The implications of such an interpretation are many. One is that the Fredericksted Plateau and Canyon are part of a prograding surface of deposition built up by sediments which originated on the island shelf and the slope of St. Croix, or on the island itself. Thus, the youngest sediments underlying the plateau might be a mixture or alternating sequence of pelagic, neritic shelf, and terrigenous sediments. Another implication is that the sediments underlying the northern Fredericksted Plateau, except for the northern edge, consist of a geologically young section which has accumulated in sufficient thickness to be the predominant influence in accounting for the present shape of the plateau's surface. One would therefore expect the sediments and rock strata, if any, which crop out in the walls of the Fredericksted Canyon to be geologically young. The plateau was probably a marine environment during the time when the sediments were deposited that shaped the plateau's surface. The plateau was probably similar in depth and structural disposition, with respect to the island of St. Croix and the island slope, during deposition of these sediments, as it is today.

Shepard and Sprat Hall Canyons interrupt a gradient west of Shepard Canyon which is as continuously downslope toward the west as if there was once a continuous east-to-west downsloping away from the western island slope of St. Croix. Thus, this appears to be a case of "submarine stream capture" by canyons whose heads have eroded their way southward across the Fredericksted Plateau from the steep rim of the escarpment bordering the plateau on the north. This period of erosion probably postdates most of the sediment deposition which resulted in the formation of the prograded surface of the plateau. Prior to "capture" of the northern half of the island slope drainage, the Fredericksted Canyon probably drained the entire western island slope. Now, however, only the southern half of the island slope drainage is via the Fredericksted Canyon.

In summary, it appears that the history of the Shepard and Sprat Hall Canyons is one of erosion, whereas that of Fredericksted Canyon is one of prograding, but with maintenance of a channel.

Present-day turbidity/current, sand flow, or other downslope movements of terrigenous and island shelf sediments, if any, are probably confined to the canyons. This may explain why surficial sediments on the plateau are relatively uniform in composition, poorly sorted, and almost devoid of terrigenous components (see section on surficial sediments).

B BATHYMETRY

The bathymetry map (Figure 5) of the St. Croix tracking range (17°40'-17°47'N, 64°54'-65°04'W) has been compiled from new bathymetry data collected by the USNS LYNCH in January 1976, using a 12 kHz standard echo sounder and a precision depth recorder. The survey grid consisted of N/S and E/W lines spaced about 300 m apart. Many of the E/W lines are limited to the eastern portion of the surveyed area. A single vertical beam, single-channel echo sounder with an effective beam half-width of about 30° was used to take depth measurements. Navigation was done by acoustic ranging using the tracking range acoustic arrays.

Positioning inaccuracy results because the normal incidence reflection from a sloping bottom is along a path which deviates from the vertical by an amount equal to the bottom slope. Over most of this area, deviation from the vertical is less than 50 m because slopes are generally less than 5°. However, on steep scarps and canyon walls, positioning of the sounding relative to the ship could exceed 500 m in the horizontal component for slopes of 30° (Figure 14).

The map is contoured in units of 1/400 sec. of two-way travel time, with a contour interval of 10/400 sec. Echo-time accuracy of the map is probably better than ±.005 sec. Conversion of echo-time to depth is a function of sound speed in the water column. Assuming a sound speed of 1,500 m/sec, invariant with depth, conversion of echo-time to depth yields depths in terms of "uncorrected" meters (1 sec = 750 "uncorrected" meters). Depths corrected for actual sound velocity would be systematically greater than the "uncorrected" depths by an amount ranging from 1 to 10 m in this area. The reader is referred to Krause (1962) for an in-depth discussion of the accuracy and resolving power of recorded echo-sounding.

Because of the depth and positioning inaccuracies inherent in the instrumentation and in conversion of echo-time to depth, the 300 m line spacing approaches saturation density. Little, if any, accuracy or resolution of detail would be gained by collecting data with a 12 kHz, wide-beam, single-channel bathymetry system at closer trackline spacing.

IV. SURFICIAL BOTTOM CHARACTER AND SEDIMENTS

A. DISTRIBUTION OF BOTTOM CHARACTER

The surficial bottom character in the St. Croix tracking range area is summarized by a selection of bottom photographs illustrating quiet-water, sediment-covered sea floor (Figures 15-20), bottom-current features (Figures 21-25), sedimentary rock outcrops (Figures 26-30), and other features (Figures 31-35). Stratification in surficial sediments is illustrated by 3.5 kHz seismic sections in Figures 36 and 37. Areal distribution of the basic bottom types, sediment-covered bottom, and areas of rock outcrop, is shown in Figure 38.

Generally, unconsolidated sediments underlie the greater part of the area, which is flat to gently sloping, and includes the Fredericksted Plateau and the elevated areas between the canyons. Outcrops of sedimentary rock and occurrence of "float" are mostly confined to the canyons and the steeper slopes (Figure 38). The canyon walls are locally terraced, indicating alternating resistant and more easily eroded stratified rocks. On a smaller scale, alternating rock strata on the average of a few centimeters thick occur within Shepard and Sprat Hall Canyons. Joint and fracture lineations generally exhibit preferred orientations of NE/SW and NW/SE. The orientation of the upper sections of Shepard and Sprat Hall Canyons may be controlled by structural planes of weakness.

Bottom currents measured by ALVIN are normally in the range of 3-13 cm/sec., although in some areas, currents are negligible. Present-day current speeds are sufficient to transport silts and clay sediments, but insufficient to erode (see Hollister and Heezen, 1973). Therefore, at least some of the present-day suspended sediments may be transported out of the area. Scour, sediment trails, and bent-over stalked organisms show evidence of currents. Two directional measurements indicate NE/SW currents; another indicates WNW/ESE. One "feather" displays a circular mark which indicates variability in current direction (see companion report on Meteorology and Physical Oceanography). On the bottom, current direction probably varies considerably as controlled by small-scale bottom geometry.

The occurrence of hard, stratified sedimentary rock in terraces on canyon walls suggests that the canyons are predominantly erosional features. The "cleaned-out" appearance observed at several locations on canyon bottoms suggests that turbidity currents or other downslope movement of sediments may still occur episodically.

Bottom photograph surveys were conducted at all array sites except Site 2. Photographs were made in stereo pairs by the R/V OCEANIC in 1965; individual photographs were made at time intervals of about 12 seconds during lowerings of 1- to 2-hour durations. RAYDIST navigation was used for position control of the surface ship. However, no positioning of the bottom cameras relative to the ship was employed. Therefore, camera positioning is approximate. In a scan of the photographs, the occurrence of basic bottom types (smooth, sediment-covered outcrops of stratified rock, etc.) were noted by D. Pullen in 1966.

Descriptions of bottom character were also reported from the ALUMINAUT dives of October 1966. Although no navigation was available and an exact location is not possible, the canyon for which E.H. Linger furnished an excellent description can be located approximately as a part of Sprat Hall Canyon.

In March 1976, photographs were taken at 6-second intervals and videotapes were made during a series of dives by the submersible ALVIN, which was attended by the surface ship LULU. Precise tracking was done by the St. Croix Range Station. In addition, written logs were kept by the following observers: R. Dill, W. Gardner, A. Sutherland, Lt. T. Ballew, LCDR D. Wells, J. Williams, and D. Magnuson.

As part of this study, the photographs and dive narratives have been examined for the occurrence of bottom character from the geologist's viewpoint. Descriptions have been compiled from all sources; areas are identified by array numbers and source of data (Figure 38).

Arrays 1 and 4 (ALVIN, ALUMINAUT): Arrays 1 and 4, located on the lower island slope, display similar bottom characteristics. The areas are best characterized as smooth and practically featureless. The bottom, a mottled, light tan color (Figure 19), is silty, showing finer sediments here than further offshore. Evidence of burrowing organisms and plants (such as sea pens) is seen only occasionally. Depressions, although few, are more frequent than elevations or mounds. Estimates of unconsolidated sediment thickness as observed on this run range from 7-10 cm atop probable bedrock at the Array 4 site, to as much as a meter or more, as evidenced from pits and holes. Several bluffs exposing unconsolidated or semiconsolidated sediments are seen, as well as ridges having smooth and softly rounded edges. Only two small rock outcrops are noted. No current heading is evident, and bent sea pens occur only to the north of Array 4 where there is a current heading of about 240° at 5-6 cm/sec. To the south, current ranges from negligible to about 2.5-5 cm/sec.

Array 3 (ALVIN): Array 3, next closest to the shoreline, is situated on a flattened ridge which slopes gently to the northwest between Sprat Hall and Shepard Canyons. This area is similar to those around Arrays 1 and 4, and is also best described as practically featureless, consisting mostly of soft sand with hillocks. A large number of conical mounds (Figure 18) of unknown origin are present; these are 15 cm high with a 30 cm base diameter. Small indentations and hills with a peak-to-peak roughness of no more than 7-8 cm were also observed. The bottom is mostly flat, or only slightly sloping, with sporadic sparse, fine growth "like midget eel-grass." The most predominant large bottom organism is the tulip sponge, whose occurrence in the area is estimated to be about one every 30 m. Only a few fish are seen. There are no current ripples or any other current indications.

Array 5 (OCEANIC, ALVIN, ALUMINAUT): Array 5 is located on the divide between two shallow canyons that merge to the northwest with Fredericksted Canyon. Steep NW/SE cliffs occur 50 m N and NE of the array. They are a part of the steep-sided, step-like terraces (Figure 28) of consolidated sediment seen frequently on canyon slopes in this region. The far wall of the small canyon exhibits 60° slopes, also of exposed consolidated sediments, and a relief of 7 m. The latter wall is described as being composed of very white, consolidated sediments, and has indications of manganese encrustation. Several large boulders are present on this slope.

The southern slope of the array ridge also shows exposed rock in the form of partially sediment-covered rock ledges whose two angular orientations give evidence of possible fracturing. Much of the float on this slope is angular.

The array sits on soft, calcareous sediments, which dominate the area except for the rock outcrops. Much of it is a quiet, tranquil bottom covered with imprints, tracks and burrows (Figure 17). However, possible ripple marks are located near the top of both sides of the ridge. Current measurements at and around the array site are among the highest recorded in the surveys (10-13 cm/sec.) Current evidence is also shown by an undercut cliff (Figure 34) and scoured boulders (Figure 25) which appear on the shallow canyon slopes to the NE.

Array 6 (OCEANIC, ALVIN): Array 6 sits atop a flat strip of the Fredericksted Plateau that slopes down NW and separates Fredericksted and Shepard Canyons. The area lies SW of Array 3 and is separated from it by the steep walls of Shepard Canyon, which extend northwestward, then continue sinuously in a northward direction NNW of the array. To the south, the eastern end of Fredericksted Canyon trends approximately E/W and separates Arrays 5 and 6.

The array site is described as being flat or having only a 2° to 3° slope; rock outcrops are noted to the WNW and NE. To the NW, ALVIN encountered a ridge and several rock outcrops, with isolated rocks widely scattered over the sloping areas in between. To the west, the OCEANIC survey depicts several rock ledges, either exposed or thinly sedimented, which display two orientations — WNW/ESE, and NNE/SSW. This may reflect a joint system or fracturing, as indicated by much float and shattered rock fragments. At this position, the seismic and 3.5 kHz records show a slight disturbance that may represent faulting.

To the NE, ALVIN transited over a rocky ridge before its descent into the canyon, which has walls comprised of a series of step-like terraces. These are described as follows. First, an escarpment with an approximate 7 m dropoff, sloping at 30° to 40°, is followed by a flattened area sloping to the north at 5° to 7°. Then a series of steps 1.5-2 m wide and 30 cm deep appears, succeeded by a 3- to 5-m drop to smooth bottom. More terraces are seen, after which a sharp bedrock escarpment drops from 8-10 m, with a slope estimated at 50° to 60°. Following an area "like a roadbed," another 10-m cliff completes the descent to the canyon bottom, where a small declivity occurs and drops down a step on the other side over rocks. No other rocks are mentioned; apparently the other canyon wall is sediment-covered.

The bottom around the array site is calcareous, soft or silty clay, with hillocks, and has a slope of less than 2°. Much bottom life occurs over most of the area, including sea fans, whips, and corals (Figure 23). Their parallel orientation and bending indicate currents in many places as do "wash-out" areas to the north and depressions scoured around isolated rocks (Figure 22). No predominant direction was noted, although measurements ranged from 5-10 cm/sec. A measurement of 7 cm/sec. was recoded at the site, with current scour around one array leg. The canyon bottom was clean-swept (Figure 25).

Array 7 (OCEANIC, ALVIN): Array 7 is located on the eastern edge of the Fredericksted Plateau near the western slope of southern Shepard Canyon. The array is on a 6° to 8° slope. About 100 m SE of the array, the ALVIN found that the slope increases and the bottom forms a series of sedimentary steps or terraces that are likened to a "contoured farming area" (Figure 28). Lower down, terraces composed of limestone are covered with thin, calcareous sediments. Still further downslope, the terrace edges become more rough and irregular, and a boulder is seen. Partway up the slope on the other side of the canyon, a sheer, two-tiered cliff about 3 m high is noted. Photographs from the OCEANIC show thinly-sedimented rock ledges on both sides of the canyon. Two orientations are again observed; one of these usually parallels the slope. Float occurs on both slopes.

At the array site, the bottom is described as calcareous and nondescript, and has a current of 2.5-5 cm/sec. A few mounds are seen (Figure 20), and, sporadically, a fan-type coral. To the east, the cable is occasionally buried under about 3 cm of sediment, and on the canyon floor, the current runs from 5-8 cm/sec.

Array 8 (OCEANIC, ALVIN, ALUMINAUT): Array 8 is on the SW slope of Sprat Hall Canyon. An example of imprecise location of the OCEANIC photographs is shown here by the appearance of different bottom characteristics at track intersections; while one track shows a sediment floor, the other depicts rock ledges at the same point (Figure 38). In another discrepancy, the compass indicates a slope direction for a cliff opposite that shown in the contour chart; however, LYNCH 3.5 kHz and seismic records in the vicinity display a small hill which slopes in both directions.

One small outcrop occurs less than 50 m NW, another about 135 m W, and several others within 400 m S of the array. A steep scarp also lies to the S. A rock sample was obtained at the southernmost location observed; Figure 35 is a photograph of the locality. The rock formation appears lobate and massive, and has an overall rough-textured aspect. The sample is a porous, manganese-coated, calcareous rock. Its bioclastic character, with detrital shells and small shell fragments, is reminiscent of a coquina.

East of the array, still on the SW slope of the canyon, rock cliffs, ledges, and terraces occur. The OCEANIC report gives approximate measurements for the terraces (or ledges) as 70 cm high and 100 cm wide with a 40° slope. A minimum height of 3 m was observed. The photographs show thin-bedded and clean-swept or lightly sedimented ledges oriented parallel to the slope, followed by a rock cliff at least 5-7 m high with estimated slopes of 40° to 70°. Large individual rocks, both bare and thinly covered, are present, as is much rock float scattered down the incline. The latter is estimated in the OCEANIC descriptions as being 7.5-10 cm high with a 20 cm cross-section.

Although there is no navigation, accounts by the ALUMINAUT observers clearly place them in the canyon E of Array 8, even though their exact location is not known. One canyon wall is described as a vertical or slightly undercut cliff, so straight it could be a fault; the other wall shows horizontal bedding. The bottom of the canyon is strewn with rubble; boulders line the sides. In a few places, the side walls have caved in, leaving piles of debris and obvious scars. Proceeding upslope in the canyon, the rock is alternately hard and soft material, forming ledges. Fractures and folded strata with a dip of about 75° occur about 20 m above the bottom, and near the top, the wall is badly fractured. On top of the cliff, a flat bottom with isolated boulders is encountered, then followed by another vertical wall. Continuing up the canyon, many outcrops and boulder-filled ledges are observed. At one point, the top of a wall resembles semiconsolidated marl or clay, and a possible slump scar is noted. Scattered boulders and rubble are scoured on all sides, indicating a current.

ALVIN observers portray the array site as flat and composed of fine-grained, calcareous, unconsolidated clay about 30 cm thick. South of the array, the bumpiness of the bottom and the proximity of "tulips" are indicative of rock close to the surface, and they suggest a terrain of sediment-covered float.

The bottom of the canyon and its NE slope as seen by the OCEANIC camera are sediment-covered.

Although some of the area shows no visible current evidence, measurements and estimates range from 3 to 6 cm/sec. Parallel bending of whips and tulips, together with the parallel alignment of sharp ridges atop elongated hillocks, attest to the presence of current throughout (Figure 25). Current variability in one locale is shown by a fan-shaped furrow made in the sediment by a whip in response to changing currents (Figure 21).

Array 9 (OCEANIC, ALVIN): Array 9 is located on a gradual eastward slope near the western wall of Shepard Canyon, where it widens and goes over the rim of the escarpment to the N. On the slopes above, or SW of the array, float is encountered, with maximum measurements of 25 by 60 cm. Further upslope are rock exposures with prominent regular bedding that resembles "rows" which are 20 cm high and have a 1 m spacing between the "rows" (Figure 26). Above these are large, single rocks, some about 1 m high, 2 m wide, and 3 m long; one boulder was estimated to be 3 m high and 5 m wide.

ALVIN crossed the canyon to the N where the canyon widens and its walls begin to descend toward the Virgin Islands Trough. Coming down from the array, the first rock outcrop occurs at about 200 m. A series of scarps and cliffs follow (Figure 30), displaying a diversity of stratified rock types (Figure 27). Upper beds are massive and partly sedimented, giving way lower down to alternating blocky and thin beds (Figure 29). Still further downslope, bedding types are mixed; some of those observed show a possible joint system (Figure 33). A steep escarpment borders both sides of the canyon bottom. On the opposite wall (north-facing), a change in the character of the bottom takes place; where sedimented areas on the western slope had been smooth, they are now strewn with rubble

(Figure 32). This slope, starting with a steep escarpment between 75° and 90°, is composed of rough granular sediment, and rock outcrops of all types (irregular, or blocky and porous) are observed. As the slope decreases upward, the canyon influence lessens and the sediment cover on the rocky slope increases until there is no more evidence of rock.

In a more southerly crossing of the eastern wall of the canyon, OCEANIC also reports a series of rock ledges (Figure 24) and outcrops with a variety of bedding types (Figure 31) that end at the canyon bottom as a rocky cliff about 30 m high. Here, too, float is frequent. Although the sediment cover on the ledges in this area seems to increase downhill for a time, clean-swept ledges also occur. This slope area also contains another example of two different bottom types shown at a track intersection.

On the whole, the edges of most ledges and outcrops are oriented parallel to the slopes. An occasional side canyon seems to follow the orientation of the possible joint system.

The sediment area around the array is described as sand and stiff clay, with no slope. The current here measures at 13 cm/sec coming from 230°. At a heading of 75° magnetic, ALVIN found less and less current and a silty, sandy clay. Outbound on the cable (E), more sediment activity is noted; parts of the cable are often buried.

As previously noted, the eastern slopes of S`iepard Canyon are more rubble-strewn. The top of the ridge to the west is more heavily sedimented, and tulip sp' iges are noted bending in a direction of 120° in response to a slight current.

Array 10 (OCEANIC, ALVIN): Array 10 is located to the W of a gentle, N/S divide on the Frederiksted Plateau. There are no rock outcrops reported by either survey. Around the array, the bottom is flat and composed of fine, silty, and calcareous material which is milky-white to light-brown in color. There are very few features; near the array, the bottom is a little more hummocky, with indications of bottom creatures. Occasional sponges and evidence of starfish activity are seen (Figure 16). About 1,000 meters E of the array, "tulips" pointing 100° show a slight current; most current measurements averaged 5 cm/sec.

Array 11 (ALVIN): Array 11 is on the very flat terrain of the northeastern part of Frederiksted Plateau. The areas observed are totally sedimented, smooth, featureless, and silty. Observers report only a few mounds and holes, and very little growth; they assume it suggests a very thick sediment layer. They also observe that the number of bottom organisms seems to increase eastward as if the sediment layer becomes thinner in that direction. There are no rocks of any kind in the sector. Current varies from 1.5 cm/sec. in the NW to 9 cm/sec. at the array site. Eastward, evidence for current consists of about 2-3 cm of scour around the base of a deep-sea fan, occasional burial of the cable, and beer cans along the cable "looking as if someone tied them there."

Frederiksted Canyon Area (OCEANIC): A survey of both walls of part of Frederiksted Canyon and the Frederiksted Plateau slope to the NE was made. Surprisingly, the orientation of many of the ledges of exposed and semiexposed rock on the slope of the plateau do not parallel the general slope trends, but run NE/SW or perpendicular to it, and probably reflect underlying structural trends. A small, westward-dipping, noselike ridge marks the place where two smaller canyons coalesce and join Frederiksted Canyon. The surveys across the canyon show ledges which parallel the slopes, and also show another orientation that probably indicates some sort of structural control, or possibly erosion on a joint system. Much sediment lies on the ledges and almost buries the float and the boulders. The northern slopes show large, rounded holes (Figure 15); an occasional sharp upper edge suggests that some of the indentations may be small slump marks. The southern slopes show possible ripple marks

B. SEDIMENT COMPOSITION AND TEXTURE

Locations of the sediment samples collected in the vicinity of the St. Croix tracking range are shown in Figure 39. The samples were taken during two surveys run in 1962 and 1965. Results of the sediment analyses appear in Informal Report Nos. 0-34-63 and 0-15-66, respectively (Ridley et al., 1963; Ostereicher, 1966). Most of the samples were collected with a Kullenberg (gravity) corer; also collected were hydroplastic (gravity) cores and surface grab samples. The longest cores obtained measured only 131 and 116 cm; the remaining cores were all less than 100 cm in length.

Aside from one isolated grab sample, no other sediment samples have been collected in the area. Thus, there is essentially no new data or major discussion to add to that already given in the reports. For the purpose of both continuity and convenience, however, portions of the text from reports 0-34-63 are included in this report. The sediment grain size data in report 0-15-66 are similar to those in report 0-34-63. Thus, the remarks in report 0-34-63 dealing with sediment generalities are applicable to the sediments collected in 1965.

The results of the grain size analyses are plotted in Figures 40-43. The sediments in the sampling area show a substantial degree of uniformity, both areally and with depth. The most predominant sediment type in the area is silty mud, accounting for 53 of the 108 samples analyzed. Clayey silt (22), silty sand (16), and sandy silt (11) make up the bulk of the remaining samples. The average median diameter for most of the samples analyzed lies in the medium silt-size grade or .031 to .015 mm; average silt percentages are shown in Figures 40 and 41. Of those samples having median diameters outside the range of medium silt, most fall just within the lower limit for coarse silt (0.031 - 0.0625 mm).

Sand-sized material (> 0.0625 mm) occurs in all samples; average sand percentages are shown in Figures 42 and 43. Sand is most abundant within the range of 0.50 to 0.0625 mm (or medium-to-fine sand). Particles coarser than this usually account for considerably less than 1% of the total sediment. Thus, silt and sand-sized particles dominate in the size distribution of these samples. However, only three samples can be classified as sands; these occur at sites C4A (surface), TR5 (25-30 cm), and C28 (7-15 cm) (Figure 39).

Although the median diameters exhibit a rather narrow range, the actual range of particle sizes is quite broad. Sorting values are poor in all cases, showing a wide dispersion of sizes about the median. The carbonate content of these sediments appears to be the primary reason for the lack of good sorting.

The carbonate content of the sediments from the St. Croix tracking range area is high, averaging 85% of the total sediment and ranging from 67 to 95%. Micro-organic remains in the form of tests, plates, and spicules comprise most of the carbonate material, and, consequently, the bulk of the total sediment in the sampling area. Because these forms are chiefly silt-sized, the reason for the textural characteristics previously outlined becomes clear: sorting values display the range of this organic debris, the size of which is solely dependent on the characteristics of the individual organism. Under the low energy conditions of the ocean floor, little selective sorting is imposed on the heterogeneous assemblage.

At stations C5 and C6, located in shallow water along the coast (Figure 39) the corer failed to penetrate. At C4A, slight penetration yielded the only calcareous sand sample obtained. At stations C5 and C6, only bits of coralline fragments were recovered. A second attempt at C6 resulted in a 116 cm core of silty sediment with no large fragments. The evidence suggests that coarse, calcareous debris is present at least surficially nearshore (possibly as outcropping ledges), although its distribution may be spotty. Thin-graded layers, indicative of current deposition, were noted in the top 13 cm of core C14.

It was reported in report 0-34-63 that there are no apparent trends in the particle size distribution of the sediments in the sampling area. However, a correlation between grain size and physiography is suggested when the data are compared with the bathymetry (Figures 40-43). Silt percentages are higher in the central portion of the map area and lower on the flanks of the shallower areas of the northern rim of the Plateau and the structural high at the southern edge of the map area. Sand percentages are reversed; they are higher in the northern and southern areas and lower in the central. Considering that currents at the bottom are strong enough for transporting fine sand, silt, and clay, it is possible that currents are preferentially removing silt and clay-sized material from northern and southern areas, and depositing them in the central area. An alternative explanation is that production of biogenic, sand-sized carbonate is more prolific in the northern and southern areas than in the central area.

There is no obvious tendency for coarser material to be found nearer shore. This, the ubiquitous poor sorting, and the high percentages of biogenic carbonates suggest that terrigenous sediments are not now reaching the Fredericksted Plateau. This is further evidence that present-day turbidity current flows, if any, are confined to the canyon systems which drain the area.

C. ENGINEERING PROPERTIES

Engineering studies were made on 11 of the 14 Kullenberg cores collected during the 1962 survey. Core numbers C6, C13, and C15 (Figure 39) were slightly desiccated and could not be used for engineering tests. These tests were run only on those portions of the cores from which it was felt that no moisture had been lost after the core was collected. The top 30 cm seemed to be especially dry and loose in most of the cores. Results of the engineering tests are synthesized in Figure 44. Summary sheets for analysis of each core are included in report 0-34-63 (Ridley et al., 1963).

Four primary engineering tests were made on the cores taken from the St. Croix area. These include wet unit weight (g/cm^3); water content (percent of dry weight); cohesion (g/cm^2), both natural and remolded; and grain-specific gravity. The first three tests depend completely upon having the in situ water contents remaining unchanged during core storage. Cohesion, or the capacity to resist shearing stresses, was measured with a laboratory vane apparatus. Cohesion was determined in both the natural and remolded states to obtain the sensitivity or the ratio of the natural cohesion to the remolded cohesion. As a whole, cohesion and sensitivity are uniform over the area (Figure 44). Slightly higher cohesion values (94 to 108 g/cm^2) are found in the NW corner of the area (C1, 10, and 17) as compared with the other quadrants where cohesion ranges between 56 and 89 g/cm^2. Sensitivity varies from medium (2 to 4) to very sensitive (4 to 8) with no apparent relationship to the other measured parameters. These values indicate that the sediments lose between 50 and 87.5% of their natural strength when remolded. Unit weight and moisture content vary only slightly throughout with values from 1.61 to 1.76 g/cm^3, and 44 to 68%, respectively. Grain-specific gravity is essentially uniform — varying from 2.73 to 2.79.

The void ratio and porosity are calculated values based on the moisture content, unit weight, and grain-specific gravity. These values range from 1.31 to 1.83, and 56.5 to 64.7%, respectively.

V. SUBSURFACE GEOLOGY

A. ACOUSTIC STRATIGRAPHY

Seismic reflection data were collected on the USNS LYNCH in January 1976 during the same survey when the bathymetry data were collected. Track coverage and spacing are, therefore, identical to that of the bathymetry. The instrumentation consisted of a single-channel, 30-kilojoule, single-element sparker system, and the unprocessed signal was amplified and recorded on a dry-paper precision seismic recorder. The distribution of subsurface sedimentary strata is illustrated by the selected seismic sections in Figures 45 through 48, and by geologic cross-sections in Figures 49 and 50.

Three stratigraphic units are identifiable in the seismic sections of the subject area. These units are termed units A, B, and C, in descending order. A fourth unit, termed unit D, is that unit which occurs below acoustic basement. Sequences, rather than reflectors, have been delineated because discontinuities and discordances associated with individual reflectors make correlation difficult. Resolution of individual reflectors is further limited because each sound-source pulse produces a wave train rather than a single wavelet.

Unit D represents the uppermost part of the section that lies below the deepest seismically recorded reflectors, i.e., below "acoustic basement." Its thickness is obviously unknown. Because it is beyond the limits of penetration, little can be said about it other than speculations arising from interpretation of the geophysical data (see section on regional setting). However, its upper limit is consistent throughout the area, and its structure is conformable with the overlying strata, leading one to assume that its surface represents a significant lithologic discontinuity.

Unit C is characterized by a series of strong internal reflectors in a section which is variable in thickness. It ranges in thickness from 0.3 to 0.8 seconds (two-way travel time.)* The unit thins over the NE/SW scarp zone in the south-central area, the subsurface structural expression which extends to the northeast, and beneath the uptilted northern rim of the plateau; but it does not appear to thicken appreciably near the island slope. However, near the island slope, the thickness of unit C is not clearly resolved due to limitations in penetration of the section by the seismic system. The NE/SW scarp is the north flank of an ENE/WSW-trending anticline that extends through the southeastern part of the area (Figure 6). Some normal faulting, downthrown to the NW, may be associated with the NW flank of the anticline. The thickness of unit C is 0.3-0.4 sec. over the NW flank of the anticline and beneath the northern rim of the plateau, and typically 0.5 - 0.6 sec. in the intervening structural low. Along the western part of the northern rim, the unit thins, but beneath the eastern portion of the northern rim, the unit thickens northward away from the ENE/WSW structural high.

Unit B is more uniform in thickness, being 0.1-.25 sec thick over the entire area. It does not thicken appreciably in the central structural low, nor approaching the island slope. Unit B does not have prominent internal reflectors, nor a reflector which defines its uppermost limit. It has been delineated because of its distinctive acoustic character, which consists of a peculiar, fine-textured internal acoustic reflectivity (see Figures 45-48).

Unit A, containing the uppermost strata, averages 0.1-0.3 sec. in thickness, with the minimum and maximum extremes being less than .05 and more than .6 sec. The section is thin (.1-.2 sec.), and relatively transparent beneath the upturned northern edge of the Fredericksted Plateau and beneath the gentle NE/SW scarp zone in the south-central part of the area. Between the two thin areas, a thicker section (.2-.3 sec.) occupies the structural low which underlies the flat part of the Fredericksted Plateau and the Fredericksted Canyon. The thicker area of the section is characterized by less transparency and the occurrence of one or more internal reflectors. A particularly strong and widespread reflector occurs near the base of unit A in the thicker, structurally negative area. Unit A thickens in a wedge-shaped fashion in the eastern part of the area, near the base of the island slope, where internal reflectors, including the prominent one near the base of the section, also occur.

Very little is known of the lithology and stratigraphy of acoustic units A through D. In the absence of stratigraphic control, the most reasonable extrapolations of the time-stratigraphy would be based on correlation with rock units which are exposed, or known to occur in the subsurface, on the island of St. Croix.

* Sediment thickness data are here expressed in units of two-way acoustic travel time (the time required for sound to travel through the sediment interval, be reflected, and return to the upper surface of the sediment interval). Relating two-way travel time to linear distance is dependent on sound speed in the sediments, which varies vertically and horizontally in the sediment section. In most areas sound speed as a function of level in the sediment section is poorly known at best. However, considering sound speeds typical of the upper sediment section (1.5-2.5 km/sec), a valid, though very imprecise, proportionality between two-way travel time and linear distance would be 1 second = 1,000 m thickness.

The rocks represented by unit D are less distinctly stratified than unit C; it is plausible that they could correlate with the Cretaceous Caledonia Formation on St. Croix. The Caledonia Formation is composed of epiclastic volcanic rocks of varying lithology. However, the lithologic variation is between beds of alternating rock type which are on the order of inches in thickness, "giving a homogeneous aspect to the entire formation" (Whetten, 1966). Such beds would probably also be acoustically homogeneous.

Unit C compares favorably in thickness with the late Cretaceous Judith Fancy Formation of St. Croix. The Judith Fancy Formation represents the upper part of the Cretaceous section, which is composed of stratified tuffaceous sedimentary rocks. Lithologic discontinuities are present, and three separate members of the formation are mappable on St. Croix (Whetten, 1966). Variable lithology in stratified rocks could acoustically yield such internal reflectors as observed in unit C.

Unit B could represent pre-A Tertiary strata deposited beneath the area, although the estimated thickness of unit B is substantially less than the thickness of the pre-Miocene strata in the central graben of St. Croix, which has been estimated from a gravity survey to contain about 2 km of Tertiary sediments (Shurbet et al., 1956). Only the upper part of the pre-Miocene Tertiary deposits has been sampled on St. Croix. It consists predominantly of dark, clayey strata, but includes a few streaks of limestone overlain by a conglomorate in the lowest part of the sampled section (Cederstrom, 1950). The clay is predominantly montmorillonite (Whetten, 1966).

An alternate, equally reasonable interpretation is that Units B and C together comprise the pre-A Cenozoic sedimentary section.

As seen in the previous section of this report, the top of unit A at the ocean floor consists of poorly-sorted, calcareous ooze containing silt, sand, and mud, with the bulk of the samples being classified as silty mud. These surficial sediments of the plateau are apparently recent authigenic, biogenic, marine sediments. Such deposition has probably continued during the time interval represented by units A and B. Beneath the structural low, the thicker accumulations of unit A may represent a turbidite/continental-rise-like sequence of deposits that may be, in part, terrigeneous. Several rock samples have been obtained from the walls of Shepard and Sprat Hall Canyons (see Figure 38), from the middle and lower levels of unit A. One sample from the west wall of Sprat Hall Canyon is a porous, bioclastic calcarenite that appears to be composed of a heterogeneous assortment of calcareous shell fragments and other debris.

Widespread, large-scale, turbidite deposition is a Plio-Pleistocene ice-age phenomenon which resulted when lowered sea level brought coastlines of continents and islands to the edge of the continental shelves. Thus, the greater part of unit A turbidite deposition may be Plio-Pleistocene. Outside the zone of turbidite deposition and before the turbidites were deposited, rates of deposition were probably much slower. The time of deposition of the lowermost part of unit A may extend into pre-Pliocene time. It is possible that the strong reflector which occurs near the base of unit A could correlate with the lower Miocene Kingshill Marl on St. Croix.

B. STRUCTURE

As previously noted, the principal structures consist of a major ENE/WSW anticline and syncline, and several subsidiary folds. These are positioned on Figure 6, and they are clearly apparent in Figures 45-48. The NW flank of the ENE-trending anticline partially coincides with the escarpment seen in the south-central part of the area, and the synclines underlie Fredericksted Cayon and the thick wedge of sediments within unit A. The time of the structural movements cannot be accurately determined. Indeed, the movements could have occurred slowly over a long period of time. The principal part of the movement was probably accomplished by the end of B time, although fault movements have probably continued into the early part of A time, as seen by the upper limits of propagation of fault displacement (Figures 45-48).

Unit C appears to have been involved in the large-scale deformation which produced the basic structure, and also to have undergone structural deformations on a smaller scale that locally distorted and disrupted the major litholcgic interfaces.

The Cretaceous rocks on St. Croix "were folded between Maastrichtian and late Oligocene time" (Whetten, 1966). Since that time, tensional structures have developed, resulting in the formation of the central graben. Thus, a pre-A history of structural movement, followed by faulting and tilting of strata which continued to be active as late as early A time, is compatible with structural activity on St. Croix.

Faulting along a N/S line probably produced the western island slope of St. Croix. When such movement occurred is not definitely determined, but it is to be noted that unit A thickens in wedge-shaped fashion eastward toward the island slope, whereas units B and C do not appear to be so affected. This would seem to tentatively fix the time of movement in early A time. This movement could be associated with the general elevation of the island of St. Croix, which has been occurring since late Oligocene time (Whetten, 1966). It is possible, although it does not seem likely, that the faulting occurred earlier, and that the contrasts between B and C, and unit A, record a change in depositional environment rather than a structural event.

VI. SEISMICITY AND SEISMIC RISK

Along the NE margin of the Caribbean plate, shallow focus seismicity in the last 25 years has been concentrated along the landward slope of the Puerto Rico Trench north of Puerto Rico and the Virgin Islands, and along the island margin east of the Lesser Antilles. Intermediate and deep-focus seismic events have occurred beneath the Puerto Rico/Northern Virgin Islands area, and directly beneath the Lesser Antilles Island area (Figure 51; Sykes and Ewing, 1965).

In the northern Lesser Antilles, the seismicity pattern is that of a sloping seismic zone, shallow on the east and deepening westward (Sykes and Ewing, 1965), as is typical of presumed plate convergence along island arcs. In the Puerto Rico area, intermediate and deep-focus earthquakes tend to have occurred south of the shallow focus seismicity, but there is considerable scatter in the focal points; thus, a southward-dipping seismic zone is not clearly delineated (Sykes and Ewing, 1965; Khudoley and Meyerhoff, 1971).

A trend of shallow-focus earthquakes extends along a NE/SW line through the Anegada Passage, the Virgin Islands Trough, and across the St. Croix Ridge to the Muertos Trough (Figure 51). This trend delineates the Anegada fault zone which is therefore presumed to be tectonically active; the linearity and minimum width of the seismic zone suggests a vertical or near-vertical fault plane, which would imply transcurrent, transtensional or tensional movement, rather than plate convergence. Hess and Maxwell (1953) previously proposed major strike-slip movement along the Anegada Fault on the basis of geological evidence which suggested that fragmented, now-isolated belts of mid-Cretaceous metamorphic rocks were part of a continuous linear trend. More recently, questions have been raised regarding the amount and sense of displacement (Donnelly, 1964; Whetten, 1966; and J.E. Matthews, personal communication), but not that displacement has occurred.

Available historical records of seismicity in the area have been compiled for the period 1530-1960 by Robson (1964). Such records are incomplete and subject to inaccuracies because they are limited to those earthquakes which were felt and reported in early seismological literature or West Indian newspapers. During the period 1777-1923, there were 32 earthquakes felt in the northern Virgin Islands which were large enough to deserve mention in newspaper accounts and other records. One event, the great earthquake of 1867, was highly destructive to the islands of St. Thomas and St. Croix; a tsunami (sea wave) was generated which caused damage to ships and shore areas throughout the Lesser Antilles. The epicenter for this earthquake was probably beneath the north wall of the Virgin Islands Trough (Reid and Taber, 1919). During the 1777-1923 period, only four earthquakes affecting St. Croix are mentioned in the records examined by Robson. To what degree this might be due to fragmentary reporting of earthquakes on St. Croix is not known; however, the large concentration of seismicity recorded north of the northern Virgin Islands is noted (Figure 51). Possibly the structural discontinuity along the Anegada Passage acts as an attenuator to transmission of seismic energy from the main Puerto Rico/northern Virgin Islands crustal block.

An account by Reid and Taber (1919) reveals the devastating effects of the great earthquake of 1867 on the island of St. Croix:

> In St. Croix the shock was nearly as severe as in St. Thomas; there were two severe shocks, one immediately after the other, lasting about three minutes, and many minor shocks; nearly every plantation suffered some injury to the dwelling house, the mill or the works. The waves broke upon the northern and western coasts of the island with great violence, washing many vessels and boats ashore, sweeping away some smaller houses and doing great injury to others. The U.S. ship Monongahela had a most thrilling experience in the harbor of Fredericksted, on the west coast. Her commander, Commodore Bissell, sent the following report to Rear Admiral Palmer:
>
> *U.S.S. Monongahela (2 rate),*
> *St. Croix, Nov. 20, 1867*
>
> *Sir: — I have to state with deep regret that the "Monongahela" under my command is now lying on the beach in front of the town of Fredericksted, St. Croix, where she was thrown on the 18th instant by an influx of the sea, the effect of the most fatal earthquake ever known here. The shock occurred about 3 o'clock p.m. Up to that time the weather was serene. No indication of a change showed by the barometer which stood at 30° 15'. The first indication we had of the earthquake was a violent trembling of the ship resembling the blowing off of steam from the boilers. This lasted some 30 seconds, and immediately after the water was observed*

receding rapidly from the beach. The current changed almost immediately and drove the ship towards the beach carrying out all the cable and drawing the bolts from the kelson without the slightest effect in checking her terrific speed towards the beach.

Another anchor was ordered to be let go but in a few seconds she was in too shoal water for the anchor to be of any avail.

When within a few yards of the beach, the reflux of the tide checked her speed for a moment, and a light breeze from the land gave me a momentary hope that the jib and foretopmast staysail might pay her head off shore and thus in the reflux of a wave be taken in water sufficiently deep to float, and be then brought up by the other anchor. These sails were immediately set and she paid off so as to bring her broadside to the beach.

When the sea returned in the form of a wall of water 25 or 30 feet high it carried her over the warehouse into the first street fronting the bay. The reflux of this wave carried her back toward the beach leaving her nearly perpendicular on a coral reef, where she has now keeled over to an angle of 15°. All this was the work of only some three minutes of time.

Soon after the waters of the bay subsided into their naturally quiet condition, leaving us high and dry on the beach.

During her progress towards the beach she struck heavily two or three times.

The first lurch carried the rifle gun on the forecastle overboard. Had the ship been carried some ten or fifteen feet further out she must inevitably have gone on her beam end, resulting, I fear, in her entire destruction and in the loss of many lives. Providentially only three (3) men were lost, these were in the boats at the time the shock commenced. The boats that were down were swamped with the exception of my gig which was crushed under the keel killing my coxswain, a most valuable man. During this terrible scene the officers and crew behaved with coolness and subordination...

Gentlemen ashore who were looking at the ship when the shock occurred declare that the bottom of the bay was visible where there was before and is now thirty or forty fathoms of water...

Very respectfully, Your obedient servant,

S. B. Bissell, Commodore, Commanding

Rear Admiral J. S. Palmer, Commanding N. A. Squadron

It is a satisfaction to know that the "Monongahela" was later floated off

Experiments with sensitive seismograph nets in the Virgin Islands and eastern Puerto Rico area have demonstrated that "microearthquakes" occur with a frequency of 10-15 micro-events per day (Murphy et al., 1970). The events recorded seem to integrate with the pattern of larger events recorded on the worldwide seismograph network. Several events originated in the Anegada Passage, and one event occurred about 15 km west of Sandy Point, St. Croix (17°40′N, 65°02′W).

In a study of large earthquake occurrences, Kelleher et al. (1973) noted that while severe earthquakes (>7 magnitude) have occurred all along the circum-Pacific belt, including the Caribbean, large events tend to occur at regular intervals of time at any given location. Kelleher et al. (1973) believe that the recurrence interval for large earthquakes in the circum-Caribbean region may be as long as several hundred years.

VII. DISCUSSION

In the following discussion, this report is summarized and the principal conclusions are presented. References to engineering considerations are interspersed in the discussion.

The St. Croix tracking range occupies the northern half of a small plateau which sits atop the St. Croix Ridge west of the island of St. Croix. The top of the St. Croix Ridge is broken as if faulted, and is tilted into a series of blocks which occur at different levels. The island of St. Croix appears to be an integral part of this structure. To the S of the St. Croix Ridge and at the northern edge of the Venezuelan Basin is the Muertos Trough. North of the St. Croix Ridge, a steep escarpment faces the Virgin Islands Trough.

Geomagnetic, gravity, and seismic reflection data are compatible with the interpretation that the St. Croix Ridge consists of a foundation of serpentinite which is capped by intrusive rocks, volcanics, and sedimentary strata.

The older sedimentary rocks of St. Croix consist of epiclastic volcanic and tuffaceous sedimentary rocks different from the volcanic rocks of the northern Virgin Islands/eastern Greater Antilles, but the St. Croix rocks may be sedimentary derivatives of these volcanics. Similar strata may also underlie the submarine portions of the St. Croix Ridge. It has been proposed that the St. Croix Ridge was once part of the Greater Antilles Platform, the two elements having been subsequently separated by rifting or transtensional movement which opened up the Virgin Islands Trough.

West of St. Croix, the Frederiksted Plateau occurs at a depth of 800-1,200 m and includes the area of the tracking range. The surface of the plateau is regionally flat to gently sloping, and is partly dissected by canyons. Many small submarine canyons originate on the western island slope of St. Croix and coalesce downslope to form larger canyons. One of these (Frederiksted Canyon) extends westward across the plateau and then southwestward. Two others (Shepard and Sprat Hall Canyons) extend northwestward, then northward over the escarpment which forms the south wall of the Virgin Islands Trough.

The flat and gently sloping areas of the Frederiksted Plateau are generally sediment-covered. Rock outcrops are mostly confined to canyon walls, steeper portions of the island slope, and the north escarpment. Surface sediment grain size, composition, and engineering properties do not vary greatly over the flat and gently sloping areas. Therefore, the suitability of the flat and gently sloping areas as a foundation for moored and bottom-mounted instrumentation probably does not vary significantly with location. The steeper areas are less suitable in general, as they are subject to the geologic hazards associated with steep slopes and canyons, although suitability varies greatly with locality. Hard rock outcrops could provide the opportunity for establishing a firm foundation for bottom-mounted hardware.

Dredging, jetting, and plowing are probably suitable methods for shallow submarine excavation in the flat to gently sloping sediment-covered areas, and probably some of the steeper slope areas as well. The occurrence of hard, cliff-forming horizontal strata at the upper rims of Shepard and Sprat Hall Canyons, and the impression of divers that in certain areas thin, unconsolidated sediments overlie firm "bedrock," suggests that deeper excavations in the flat to gently-sloping areas might encounter hard sedimentary strata. Some areas where hard rock crops out in the canyons would require drilling and blasting, even for shallow excavation.

Bottom currents in the tracking range area are predominantly in the range of 5-10 cm/sec. — fast enough to transport silt, clay and fine sand, but not fast enough to erode. Current speed and direction is highly variable with time, location, and morphology (see companion report on oceanography and meteorology). It is probable that net deposition is taking place over most of the area, considering that a veneer of sediment covers rock outcrops, and surface samples exhibit poor grain-size sorting. Rates of pelagic deposition are unknown, but they are probably on the order of a few centimeters per thousand years.

Surficial sediments are thought to be predominantly authigenic, pelagic, biogenic carbonates. Holocene terrigeneous sediments, if any, are apparently confined to the turbidity-current drainage system and, therefore, bypass the area. In pre-Holocene time, however, deposition of terrigeneous sediments via turbidity currents probably contributed to the sedimentary sequence associated with the Frederiksted Canyon.

Areas of steep slope underlain by unconsolidated sediments are susceptible to slump, creep, and other mass downslope gravity-induced movement. The island slope is probably the area most susceptible to slumping, particularly toward the N where slopes are steepest. Mass downslope movement of material on the island slope could result in breakage or burial of cables.

The subsurface stratigraphic section is divisible into litho-stratigraphic units, based on acoustic character, termed units A, B, C, and D, in descending order. Little is known of unit D because it lies near the limits of acoustic penetration. Unit C, generally 0.3 - 0.6 sec. thick, has strong internal acoustic reflectors, and is apparently structurally disturbed. Unit B is acoustically semi-transparent with characteristic fine-textured stratification and thickness which does not vary extremely (0.1 - 0.25 sec). Unit A is relatively thick (0.2 - 0.3 sec.) and has internal reflectors where it fills the ENE/WSW-trending syncline, whereas it is thin (0.1 - 0.2 sec.) and acoustically transparent on the limbs of the syncline.

The location and morphology of Frederiksted Canyon and levees, and the disposition of the underlying sediments with respect to the structure, suggest that infilling of the syncline proceeded until sediments spilled over the northern rim of the Frederiksted Plateau. Then, with sediments available as eroding tools, Shepard and Sprat Hall Canyons probably underwent headward erosion, capturing drainage that was formerly part of the Frederiksted Canyon system.

The study area is in the vicinity of the seismically active boundary between the North American and Caribbean lithospheric plates. Seismicity clearly defines a sloping seismic zone beneath the Lesser Antilles; therefore, plate convergence is indicated. Intermediate-focus earthquakes occur beneath the Puerto Rico/Virgin Islands area, but here, a sloping seismic zone is not clearly defined.

The St. Croix tracking range area is seismically active, hence, subject to earthquakes. Micro-earthquakes probably occur with daily frequency. These events, however, are only apparent with the most sensitive measuring and recording apparatus. Events large enough to be felt occur at frequencies measured in years.

Moderately strong earthquakes (intensity IV-VI, modified Mercalli scale) do not occur very often. Judging from available records kept over about a 200-year period, only three or four events believed to be of this magnitude have occurred. However, the accuracy and completeness of the historic records of seismicity for St. Croix is open to question.

Major earthquakes (intensity VII or more) are rare in this area. Only one has occurred in the 200-year period of record, the earthquake which occurred in 1867 (intensity VIII or IX). Nevertheless, the occurrence of a truly destructive earthquake is an ever-present possibility, if the record of historic seismicity can be applied to the present. According to Kelleher et al. (1973), areas of the Caribbean margin that have not experienced a destructive event in recent years are those areas which are subject to the greatest seismic risk at present. The most likely location of epicenters for earthquakes occurring near St. Croix is along the Anegada Fault Zone, which coincides with the Virgin Islands Trough and crosses the St. Croix Ridge between St. Croix and Puerto Rico. Seismicity could occur along secondary faults anywhere along the St. Croix Ridge. The low-lying coastal areas and port facilities of St. Croix are vulnerable to destruction or damage by tsunami, as well as by earth motion, in the event of a major earthquake. Offshore, a major earthquake could trigger slump or other mass downslope movement on steeper sediment-covered slopes; set off turbidity currents; or result in tilting, shifting, or downslope movement of moored or bottom-mounted sea floor structures.

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MARINE GEOLOGY AND GEOPHYSICS

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Adey, W. and R. Burke (1976). Holocene Bioherms (Algal Ridges and Bank-Barrier Reefs) of the Eastern Caribbean. Geol. Soc. Am. Bull., v. 87, p. 95-109.

Discusses areal distribution of eastern Caribbean Holocene bioherm reefs and algal ridges which are locally active at present. Patterns of reef growth are related to the rise of sea-level in early Holocene time. Contains a map and cross-sections of reefs encircling St. Croix. Based on data collected from boreholes and the wall of a ship channel cut through the reef.

Cederstrom, D.J. (1941). Notes on the Physiography of St. Croix, Virgin Islands. Am. Jour. Sci., v. 239, p. 553-576.

An account of the geomorphology of St. Croix. A description of the topography, rocks, and structure is followed by a physiographic interpretation which includes uplift and peneplanation in the early Tertiary, and two later cycles of uplift and renewed erosion. Emergence which exposed the reefs on the Kingshill Marl resulted in the formation of a consequent NE to SW drainage pattern, much of which has since been "captured" by N- to S-flowing streams. Several stands of sea level, both higher and lower than the present level, are recorded in raised and submerged terraces.

________ (1950). Geology and Groundwater Resources of St. Croix, Virgin Islands. USGS Water Supply Paper 1067, 117 p.

A report on the general geology of St. Croix, followed by an extensive treatment on the subject of occurrence, quality and use of water resources. Contains definitive stratigraphic descriptions of the Tertiary marls, reef limestones, clays, and basalt conglomerate which underlie the central plain of St. Croix. Treatment of structure, geomorphology, and stratigraphy of the late Cretaceous volcanics is sketchy. Occurrence of fringing reefs and bank or terraces at 12-20 m and 24-40 m is noted, and reefs, banks, raised sea cliffs, beach sands, and upraised alluvium deposits are discussed in terms of Pleistocene fluctuating sea level.

Jordan, D.C. (1975). A Survey of the Water Resources of St. Croix, Virgin Islands, U.S. Geological Survey Caribbean District Open-File Report.

An excellent reference volume on rainfall distribution, runoff, ground water, water quality, and ultimate potential water supply. Includes a brief sketch of geology, geography, and history of water supply.

Ostereicher, C. (1966). Environmental Studies in Support of Atlantic Underwater Tactical Ranges. U.S. Naval Oceanographic Office Informal Manuscript Report No. 0-15-66.

The results of an environmental survey conducted by NAVOCEANO off the west coast of St. Croix, Virgin Islands, and the southeastern coast of Puerto Rico are discussed in this report. Oceanographic parameters measured during the survey include ocean currents, temperature, salinity, and sound velocity. In addition, 13 cores and eight grab samples were taken for use in describing the sea floor environment. Sediment size and composition data are provided on 12 cores and one grab sample.

Reid, H.F. and S. Taber (1919). The Virgin Islands Earthquakes of 1867-1868. Bull. Seis. Soc. Am., v. IX, p. 9-30.

A compilation of all documentation of the effects of the great earthquake of 1867 which devastated St. Thomas and St. Croix. The epicenter for this earthquake was estimated to be in the Virgin Islands Trough between the islands. It is suggested that faulting accompanying tectonic separation of the St. Croix Ridge from the northern Virgin Islands platforms is a plausible explanation for the origin of the earthquake.

Ridley, E., N. Stiles, and G. Nielson (1963). Oceanography - West Coast of St. Croix, Virgin Islands, U.S. Naval Oceanographic Office Informal Manuscript Report No. 0-34-63.

Grain size, chemical and engineering property (cohesion, porosity, specific gravity of grains) analyses of 14 gravity cores collected in 400-1,500 m water depth immediately west of St. Croix show that surface-sediment composition and physical properties are relatively uniform over the area sampled. Carbonate percentages are high, and silt is the predominant grain size.

Shurbet, G.L., J.L. Worzel, and M. Ewing (1956). Gravity Measurements in the Virgin Islands. Geol. Soc. Am. Bull., v. 67, p. 1529-1536.

From 21 gravity stations on St. Croix, 10 on St. Thomas and gravity measurements made from submarines, together with seismic and other geophysical data, the authors constructed a N-S crustal section across St. Thomas and St. Croix. Crustal thickness was inferred to be about 29 km beneath St. Croix. Simple bouguer anomaly patterns on St. Croix define the central Tertiary basin, where sediment thicknesses of up to 2 km are implied.

Starr, R. and R.G. Bassinger (1971). Marine Geophysical Observations of the Eastern Puerto Rico-Virgin Islands Region. Trans. Fifth Carib. Geol. Conf., Geol. Bull. No. 5, Queens College Press, p. 25-28.

Results of a combined bathymetric, seismic reflection profile and total magnetic field intensity investigation of the area south and east from Puerto Rico to the Virgin Islands. The submarine St. Croix Ridge, which extends westward from that island, consists of an irregular row of discontinuous highs with northeast-trending spurs. West of 65°35'W, the ridge changes character; it comprises three seamounts and is much shallower. Seismic reflection profiles of the ridge in the east show southerly dipping strata on the northern ends of the spurs, but no reflectors are apparent on the main crest of the ridge. Associated with the ridge east of 65°35'W is a slight linear east-west magnetic high with a corresponding magnetic low to the north.

Vaughan, T. (1923). Stratigraphy of the Virgin Islands of the United States and of Culebra and Vieques Islands, and Notes on Eastern Puerto Rico. Washington Acad. Sci. Jour., v. 13, p. 303-317.

From stratigraphic evidence, Vaughan summarizes the late Cretaceous and Cenozoic paleogeography and geologic history of the Virgin Islands area. Ages of the sedimentary strata of St. Croix are correctly identified (late Cretaceous, Oligocene-Miocene, and Quaternary), based on paleontologic evidence.

Whetten, J.T. (1966). Geology of St. Croix, United States Virgin Islands. Geol. Soc. Amer. Memoir 98, p. 177-239.

This is the most detailed and comprehensive report on the geology of St. Croix, which makes it an excellent reference publication. Includes discussion of the geomorphology, stratigraphy, age, structure, and geologic history of St. Croix rocks. Large geologic map in color is based on two field seasons plus previous geologic work. Emphasis is placed on the lithology, stratigraphy, environment of deposition, petrography, structure and provenance of the late Cretaceous epiclastic volcanic and tuffaceous sedimentary rocks, together with gabbro and diorite intrusions, contact aureoles and scattered dikes, which underlie the Northside and East End Ranges of St. Croix. Geology of these areas was not emphasized in previous geologic work. Contains description of dredge sample obtained in 800-1000m of water 3 km west of Sandy Point, St. Croix. The dredge material is well-sorted, fine sand, made up principally of biogenic detritus.

2. Selected References — Northeastern Caribbean

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Presents pertinent data and conclusions on the crustal structure and evolution of the eastern Caribbean, as derived from seismic reflection, refraction, magnetic, and gravity data. The data support underthrusting, with resorption of crust and formation of basaltic magmas which rise beneath the island arc, as being the major structural forces involved in formation of the Lesser Antilles Arc. Inferred similarity of shallow and deep crustal structure between the Aves Ridge and the Lesser Antilles Arc suggests that the Aves Ridge may have been an earlier line of plate convergence, which later shifted to the Lesser Antilles.

Case, J.E. and T.L. Holcombe (1975). Preliminary Geologic-Tectonic Map of the Caribbean Region. USGS Open-file Map No. 75-146.

Geologic mapping of surficial geology and tectonics on the land surrounding the Caribbean has been integrated with mapping of tectonic fabric and sediment thickness in the deep-sea Caribbean to produce a land-sea geologic map which, for completeness and detail, is new for the area.

Donnelly, T.W. (1964). Evolution of Eastern Antillean Island Arc. Amer. Assoc. Petroleum Geol. Bull., v. 48, p. 680-696.

Discussion of the possible evolution of the eastern Greater Antilles, based on analysis of rock units, stratigraphic relationships and structural geology of Puerto Rico and the Virgin Islands, together with geophysical studies of adjacent marine areas. Mention is made of faulting and possible faulting on and in the vicinity of St. Croix.

Donnelly, T.W. (1966). The Geology of St. Thomas and St. John, Virgin Islands. Geol. Soc. Amer. Memoir 98, p. 85-176.

An extensive treatise on all aspects of the geology of the neighboring islands of St. Thomas and St. John, concluding with a summary of the geologic and tectonic history of the northern Virgin Islands. This work is the equivalent for these islands of the work done by Whetten (1966) on St. Croix.

Donnelly, T.W. (ed.) (1970). Guidebook to the Caribbean Island Arc System. International Field Institute, Amer. Geol. Inst., Washington, D.C.

General synopses of the geology and field trip guides complete with road logs for Puerto Rico and just about every island in the Lesser Antilles **except** St. Croix.

Edgar, N.T., J.I. Ewing, and J. Hennion (1971). Seismic Refraction and Reflection in the Caribbean Sea. Amer. Assoc. Petroleum Geol. Bull., v. 55, p. 833-870.

Synthesis of all available seismic refraction data with seismic reflection data from the Caribbean has produced an integrated view of thicknesses and velocities of crustal layers and plate-tectonic evolution.

Ewing, J.I., M. Talwani, M. Ewing, and N.T. Edgar (1967). Sediments of the Caribbean. Symposium on Tropical Oceanography. Univ. of Miami, v. 5, p. 88-102.

Describes the sediment section beneath the Venezuelan and Colombian Basin which is characterized by a pelagic section (delineated by horizons A" and B") and overlying turbidites. These showed the structural stability of the interior of the Caribbean plate for the interval of time represented by the sediment section, which was later determined to be late Cretaceous and younger.

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Revision of the interpretation of the history of the double island arcs in the Lesser Antilles north of Dominica through studies of the geology of the islands, particularly that of Guadeloupe and nearby submarine physiographic regions. The finding of Late Jurassic rocks on Desirade in the eastern or older arc suggests that the Lesser and Greater Antilles may have been a continuous feature during Late Mesozoic-Early Tertiary time.

Garrison, L.E. and others (1972a). Acoustic Reflection Profiles, Eastern Greater Antilles. Int'l Decade of Ocean Exploration and USGS Report No. USGS-GS-72-0004.

A short summary of the geology and publication of the seismic reflection traverses of the USGS-IDOE expedition in the northeast Caribbean between Puerto Rico and Antigua.

Garrison, L.E. and others (1972b). Preliminary Tectonic Map of the Eastern Greater Antilles Region. USGS Misc. Geol. Investigations Map I-732.

A colored tectonic/geologic map of the Puerto Rico/Virgin Islands area. Includes bathymetry and major structural trends. Also included is a residual intensity magnetic field map. Geology of St. Croix after Whetten, magnetics of St. Croix after Bracey.

Matthews, J.E. and T.L. Holcombe (1976). Regional Geological/Geophysical Study of the Caribbean Sea (Navy Ocean Area NA-9), 1. Geophysical maps of the eastern Caribbean, U.S. Naval Oceanographic Office reference publ. RP-3, 43 p.

Presentation of bathymetry, tectonic fabric, total-field magnetic intensity and sediment thickness maps of the eastern Caribbean which are currently the most accurate and detailed available. Accompanied by a synopsis of those features of the geology which are emphasized by the maps and illustrated with representative seismic reflection sections.

Nairn, A.E.M. and F.G. Stehli (eds.) (1975). Ocean Basins and Margins, v. 3. The Caribbean and Gulf of Mexico. New York, Plenum Publ. Co., 706 p.

A collection of general articles on the marine geology of the Gulf of Mexico and the Caribbean written by scientists who are familiar with the region.

Sykes, L.R. and M. Ewing (1965). The Seismicity of the Caribbean Region. Jour Geophys. Res., v. 70, p. 5069-5074.

A recomputation of earthquake epicenters in the Caribbean region which produced location accuracies on the order of ± 10 km. The pattern of earthquakes beneath the Lesser Antilles defines a westward-sloping seismic zone. Both shallow- and intermediate-focus earthquakes are present in the Puerto Rico area, but a sloping seismic zone is not clearly defined. Only shallow-focus earthquakes occur in the immediate St. Croix area.

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Contains a brief description of the physiography and rocks of St. Croix. Cleve correctly guessed that the older deformed volcanic and volcanic-derived strata are of Cretaceous age, and he estimated that the Kingshill Marl is Miocene in age based on fossil assemblages.

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4. Data

U.S. Naval Oceanographic Office — Bathymetry Collected by USS SHELDRAKE, 14-15 November 1962.

Navigation and sounding sheets. No echograms. Lack of echograms and ± 5 fm (uncorr.) relative accuracy of soundings suggests that soundings were collected prior to installation of a precision depth recorder. Raydist Navigation. Lines run on a N/S and E/W grid at 0.9 km line spacing. Area of coverage is west of St. Croix to 65°W and between 17°40′N and 17°46′N.

U.S. Naval Oceanographic Office — Bathymetry Collected by USS SHELDRAKE, 7 August 1965.

Navigation, sounding sheets, echograms, and bathymetric chart. Relative accuracy of soundings ± 1 fm (uncorr.). Raydist Navigation. Lines run on a N/S and E/W grid at 0.45 km line spacing. Area of coverage is west of St. Croix to 65°W, and between 17°42′N and 17°48′N. Bathymetry contour interval is 10 fm (uncorr.).

__________ — Bathymetry Collected by R/V OCEANIC, 1-5 October 1965.

Navigation, sounding sheets, echograms and bathymetry chart. Relative accuracy of soundings ± 1 fm (uncorr.). Raydist navigation. Lines run along lines of equal range from Raydist stations at 0.2-0.4 km line spacing. Relative sounding accuracy is ± 1 fm (uncorr.), but only plotted to ± 5 fm (uncorr.) on sounding sheets. Area of coverage is west of St. Croix to 65°W and between 17°41′N and 17°43′N. Bathymetry contour interval is 10 fm (uncorr.).

__________ — Bathymetry Collected by USNS LYNCH, 2-6 January 1976.

Navigation, sounding sheets, echograms, and bathymetry chart. Relative accuracy of soundings ± 1 fm (uncorr.). Navigation by range coordinates. Lines run on a N/S and E/W grid at 300m spacing. Area of coverage is west of St. Croix to 65°05′W and between 17°40′N and 17°48′N. Bathymetry contour interval is 10 fm (uncorr.).

__________ — Continuous Seismic Reflection Data Collected by USNS LYNCH, 2-6 January 1976.

Seismic reflection records made with a 3.5 kHz echo-sounder and a 30-kilojoule sparker were collected on the USNS LYNCH survey referred to above. Recorder sweeps were 1 second for the 3.5 kHz seismic records, and 4 seconds for the sparker records.

U.S. Geological Survey — Continuous Seismic Reflection Data Collected by UNITEDGEO I, 17 July - 5 August 1971.

Seismic reflection records were made with a 220 kilojoule sparker system on leg 3 of the USGS/IDOE Caribbean cruise. On N/S transits of the Virgin Islands Trough, they produced two seismic sections, the ends of which were obtained from the area of interest.

U.S. Naval Oceanographic Office — Bottom Photography Collected by R/V OCEANIC in 1965.

Runs of bottom photographs were collected at 5 localities in the area of interest immediately west of St. Croix. Photographs were taken continuously for ½ to 1 hour while the ship drifted or was propelled slowly over the bottom. Unpublished analyses of these photographs reveal that at two of the localities (vicinity of 17°45.5′N, 64°58.1′W and 17°41.7′N, 64°57′W) smooth, sediment-covered bottom was encountered. At three of the localities (vicinity of 17°45′N, and 64°57.7′W; 17°44′N, 64°57.6′W; and 17°44.8′N, 64°56.6′W), outcrops of stratified rock and steep slopes were encountered in addition to areas of smooth sediment-covered bottom.

Chesapeake Division, Naval Facilities Engineering Command — Bottom Photography Collected by Research Submersible ALVIN and Tender LULU in March 1976.

Runs of bottom photographs for several hours were made at 10 localities in the area of interest west of St. Croix. Photographs were taken continuously while the ALVIN was transiting for several hours on the bottom. Photos are clear and illustrate a variety of rock types and bottom character. Dive narratives and several CRT videotapes were recorded.

U.S. Naval Oceanographic Office — Gravity Cores Collected by USS SAN PABLO in 1962.

Fourteen gravity cores from the area immediately west of St. Croix were obtained. Descriptions of these cores and an analysis of engineering properties are presented in NOO IMR 0-34-63, Ridley et al., 1963.

Woods Hole Oceanographic Institution — Dredge Haul Collected by R/V CHAIN.

One dredge haul was obtained 3 km west of Sandy Point, St. Croix. A description of the sediments obtained is presented in Whetten's 1966 report on the geology of St. Croix.

Chesapeake Division, Naval Facilities Engineering Command, and Fairleigh-Dickinson University St. Croix Laboratory — Rock Samples and Sediment Sample from ALVIN Dives in March 1966.

Rock samples and one sediment sample were obtained by ALVIN. Locations and photographs were obtained for the rock samples, but not for the sediment sample.

U.S. Geological Survey/NASA — Aerial Photography Collected by High Altitude (U-2) Aircraft.

Color and color-infrared photographs taken from 18800-18900m elevation were obtained on one west-to-east pass over the island of St. Croix. Total coverage with 60% overlap is included within 8 frames. Reefs, shallow terraces, and water turbidity are visible in the waters encircling the island.

National Ocean Survey/NOAA — Aerial Photography

Coverage of the island of St. Croix is contained in black and white frames at a scale of 1:24000 and 1:30000, and color frames at a scale of 1:30000.

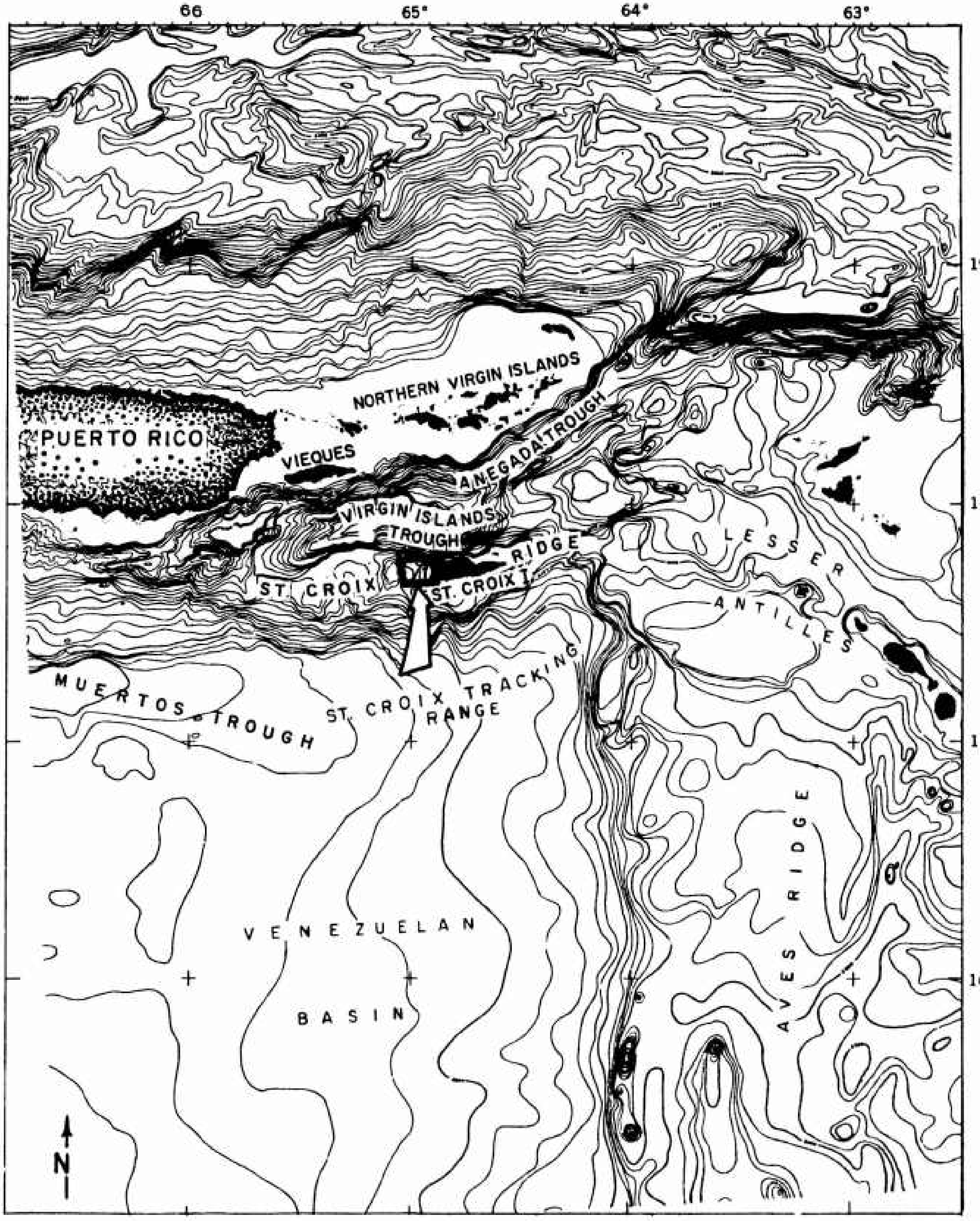


Figure 1. Bathymetry of the St. Croix Area

a. Bathymetry of the St. Croix vicinity, northeastern Caribbean. Contour interval 200 meters uncorrected (Matthews and Holcombe, 1976).

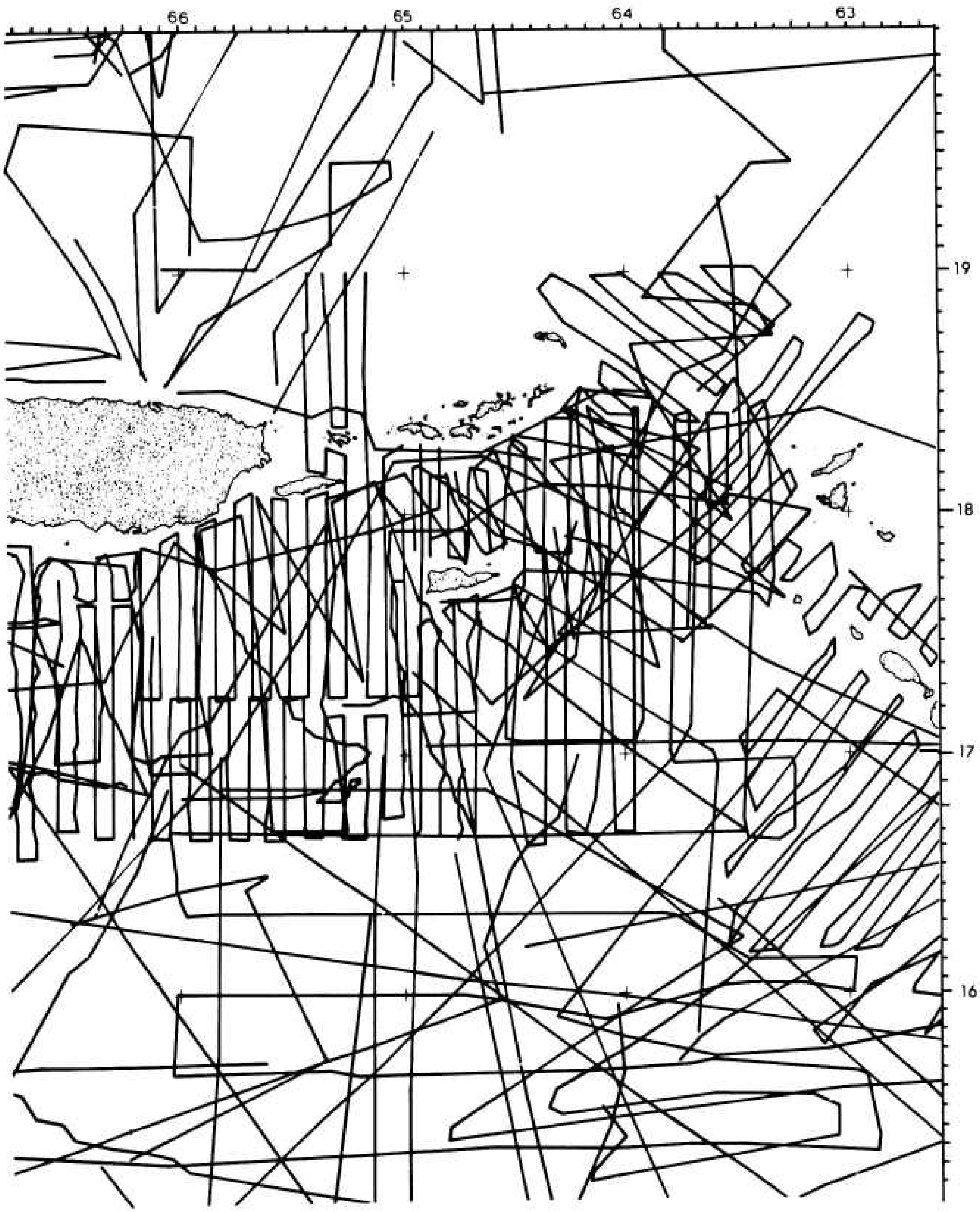


Figure 1. Bathymetry of the St. Croix Area
b. Track control for the bathymetrv.

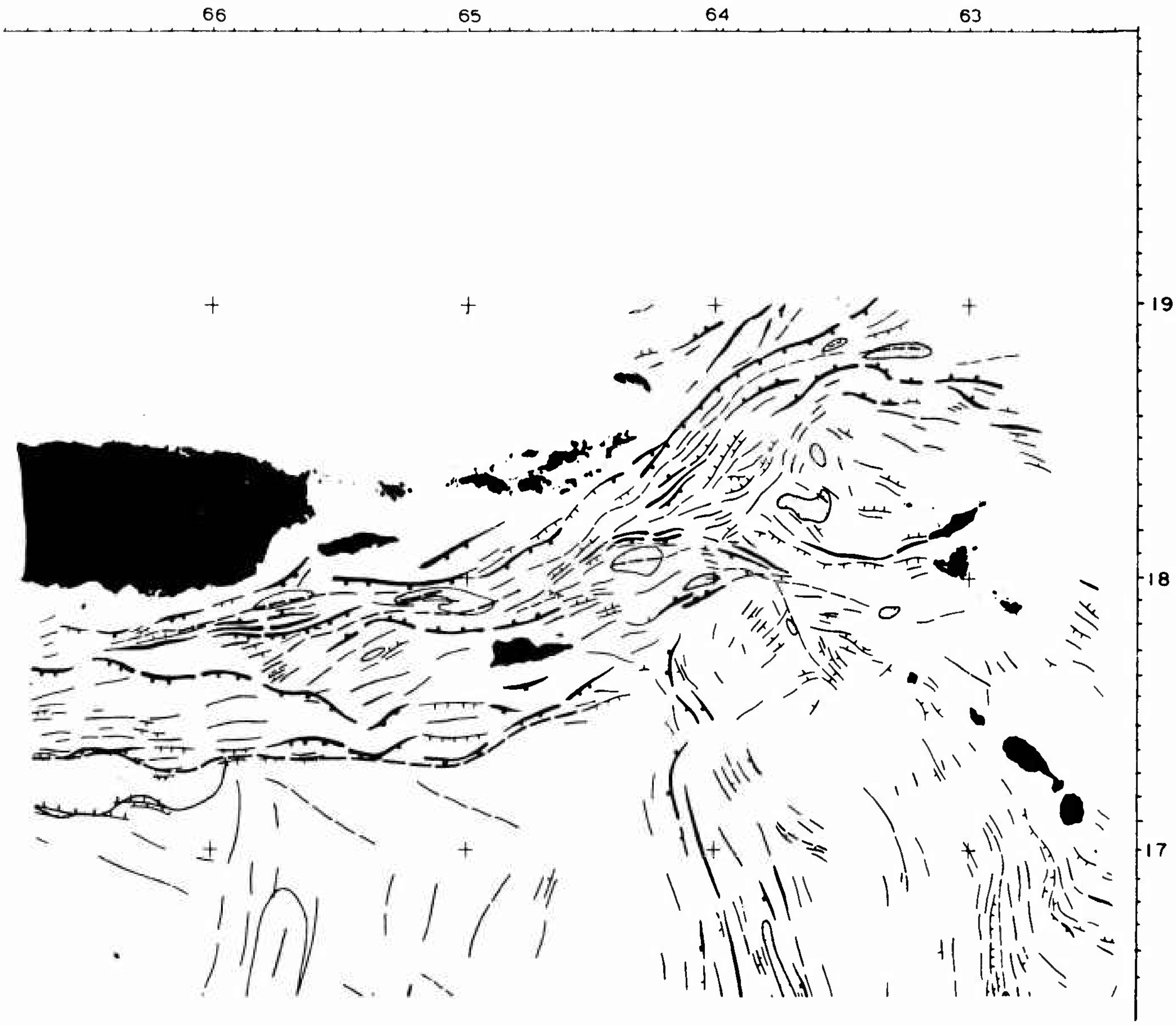


Figure 2. Regional Tectonic Fabric of the St. Croix Area (after Matthews and Holcombe, 1976).

Solid or long-dashed lines denote structural highs. Solid or long-dashed lines with hatching denote faults, with hatches on downthrown side. Short-dashed lines denote structural lows. Shaded areas are plains Heavy lines designate structural relief greater than 1 second, two-way travel time. This is a sketch map, using all available seismic reflection data.

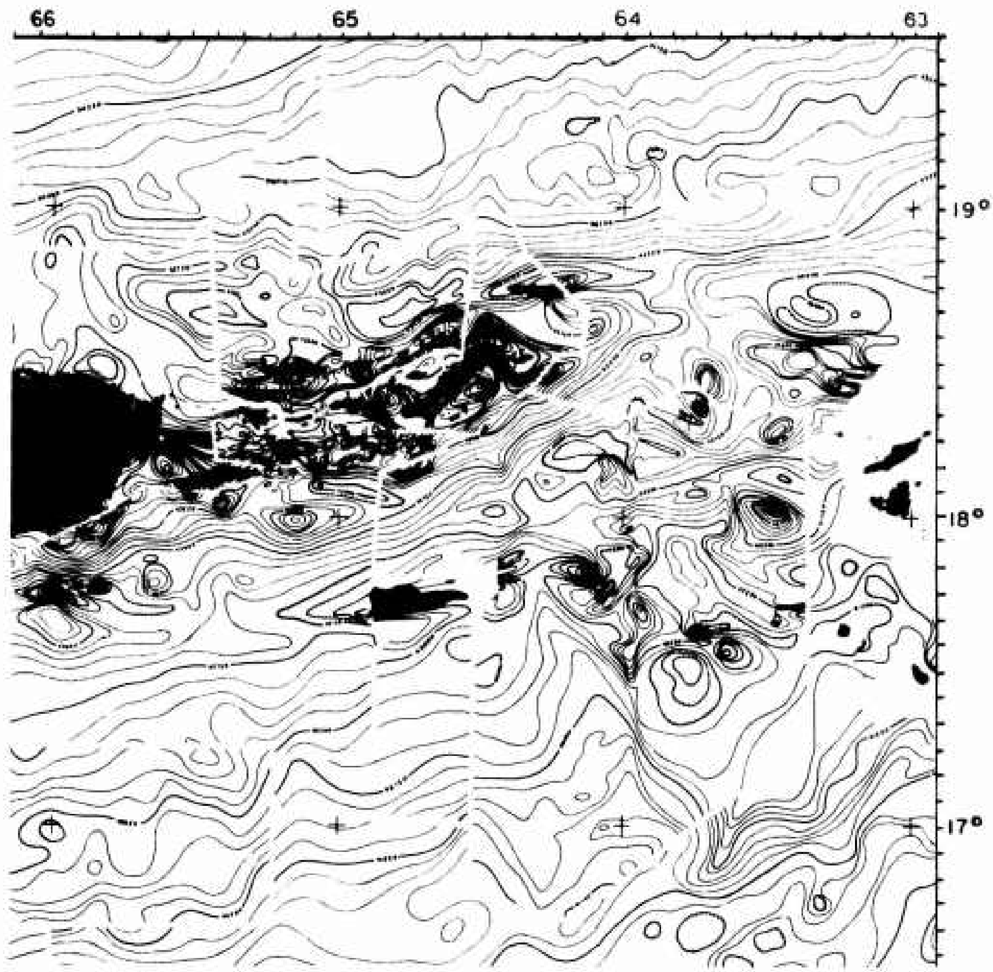


Figure 3. *Geomagnetic Field of the St. Croix Area*

a. Total field intensity magnetic map of the St. Croix area (after Matthews and Holcombe, 1976). Contour interval is 50 is 50 gammas. Breaks in contours separate distinct surveys or blocks of data. Across breaks, contour values do not agree, but patterns are continuous.

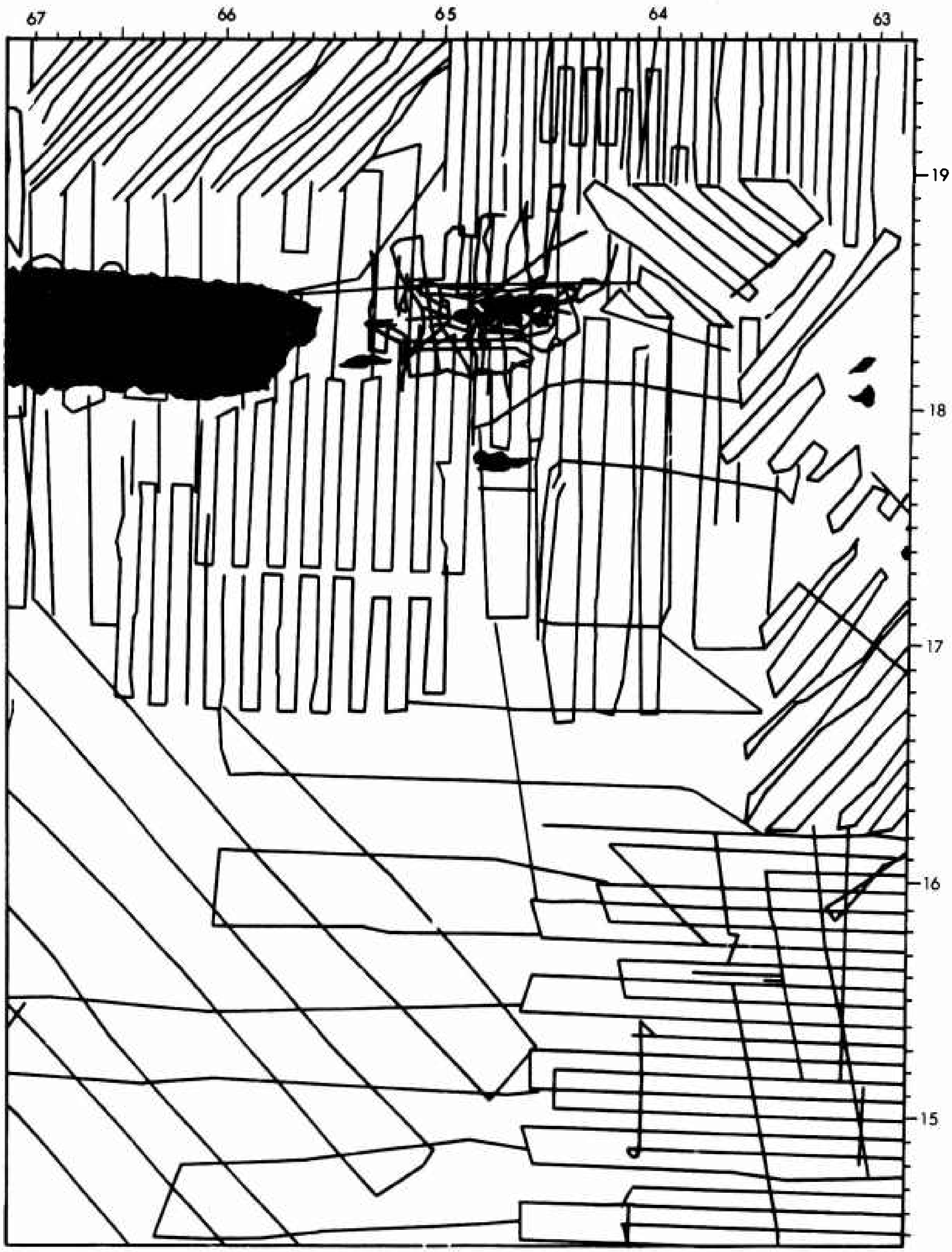


Figure 3. Geomagnetic Field of the St. Croix Area
b. Track control for the magnetic map.

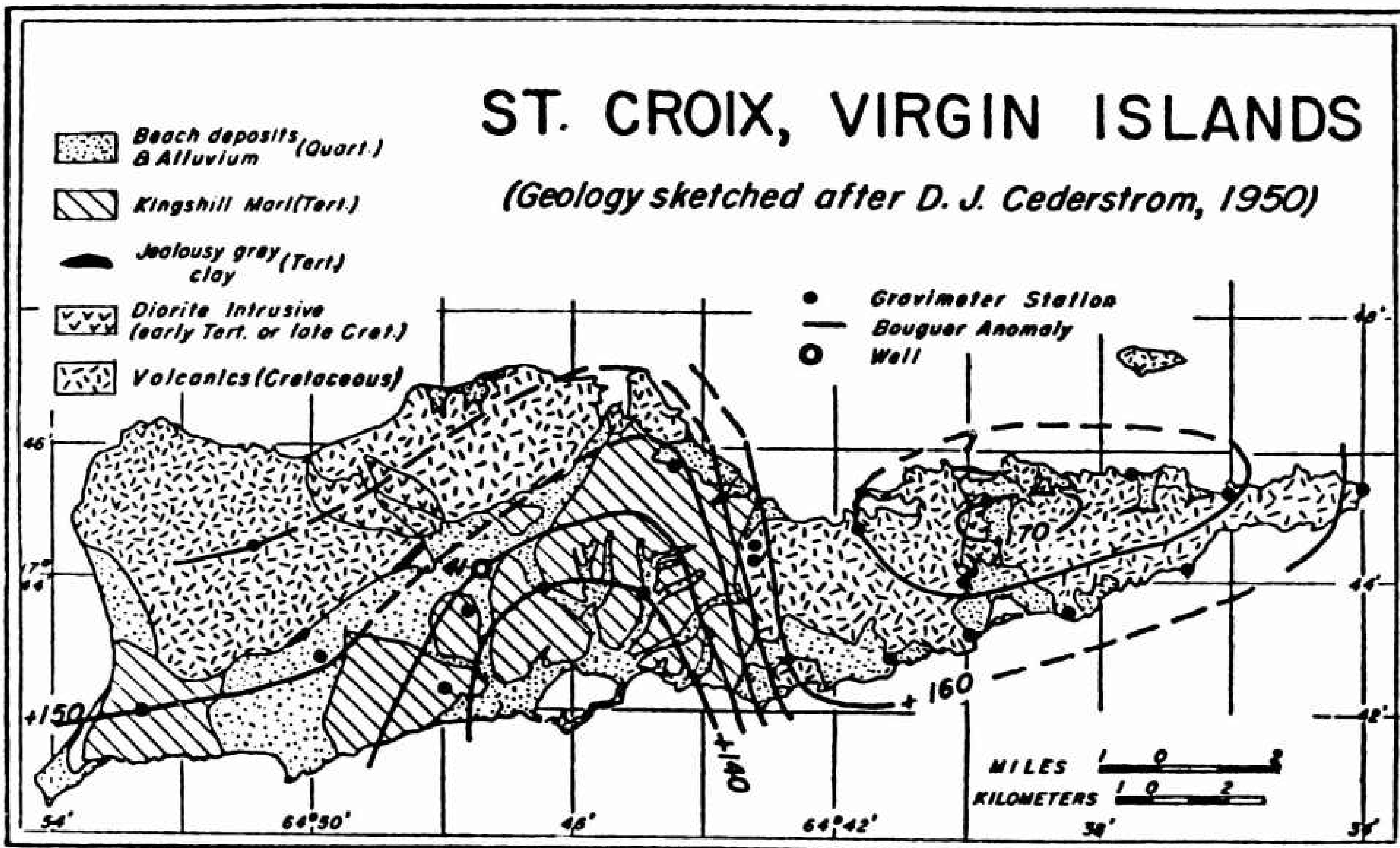


Figure 4. Gravity Field of the St. Croix Area
Simple bouguer anomaly map of St. Croix (after Shurbet et al. 1956) Reprinted by permission. Contour interval is 5 milligals.

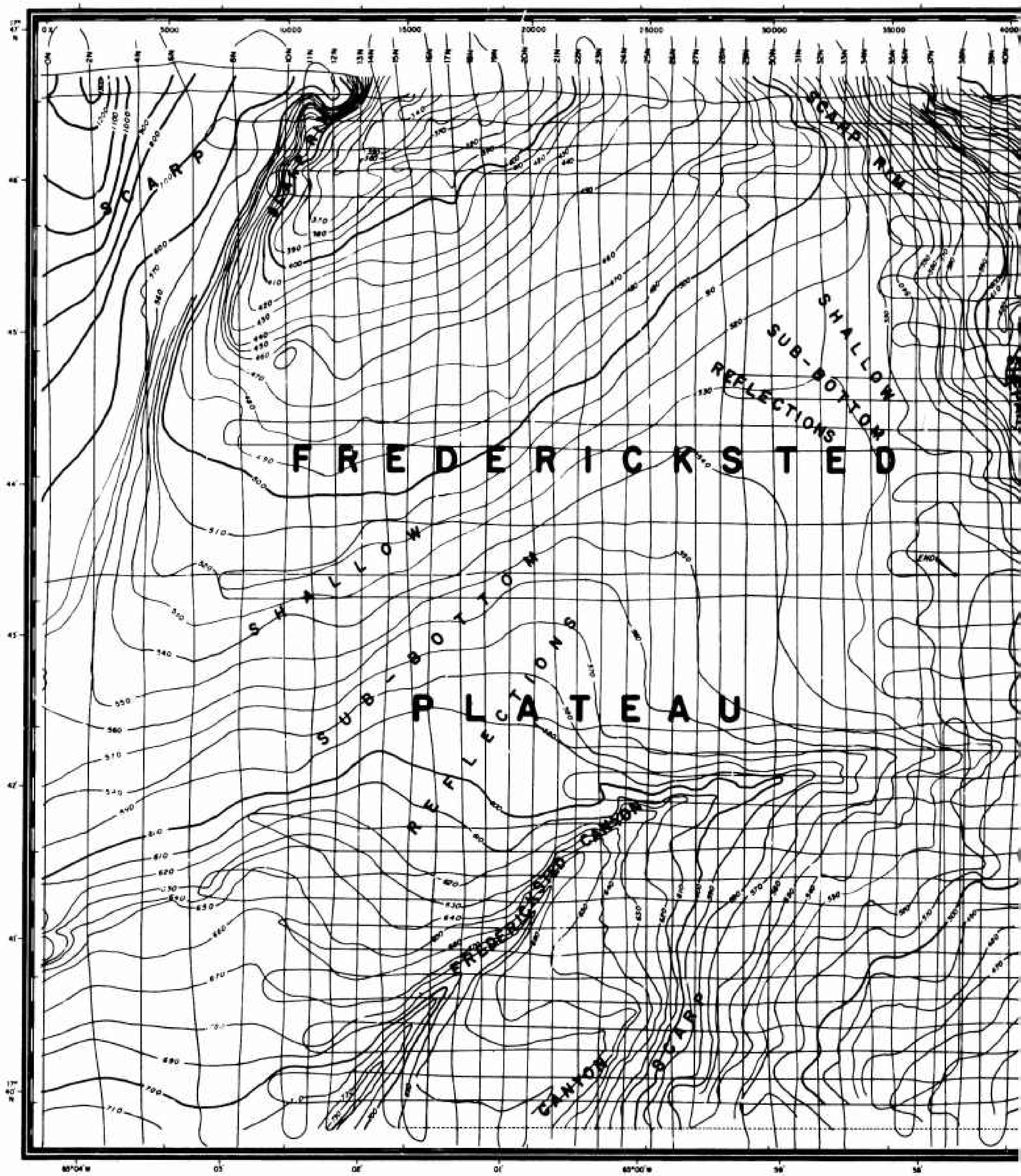
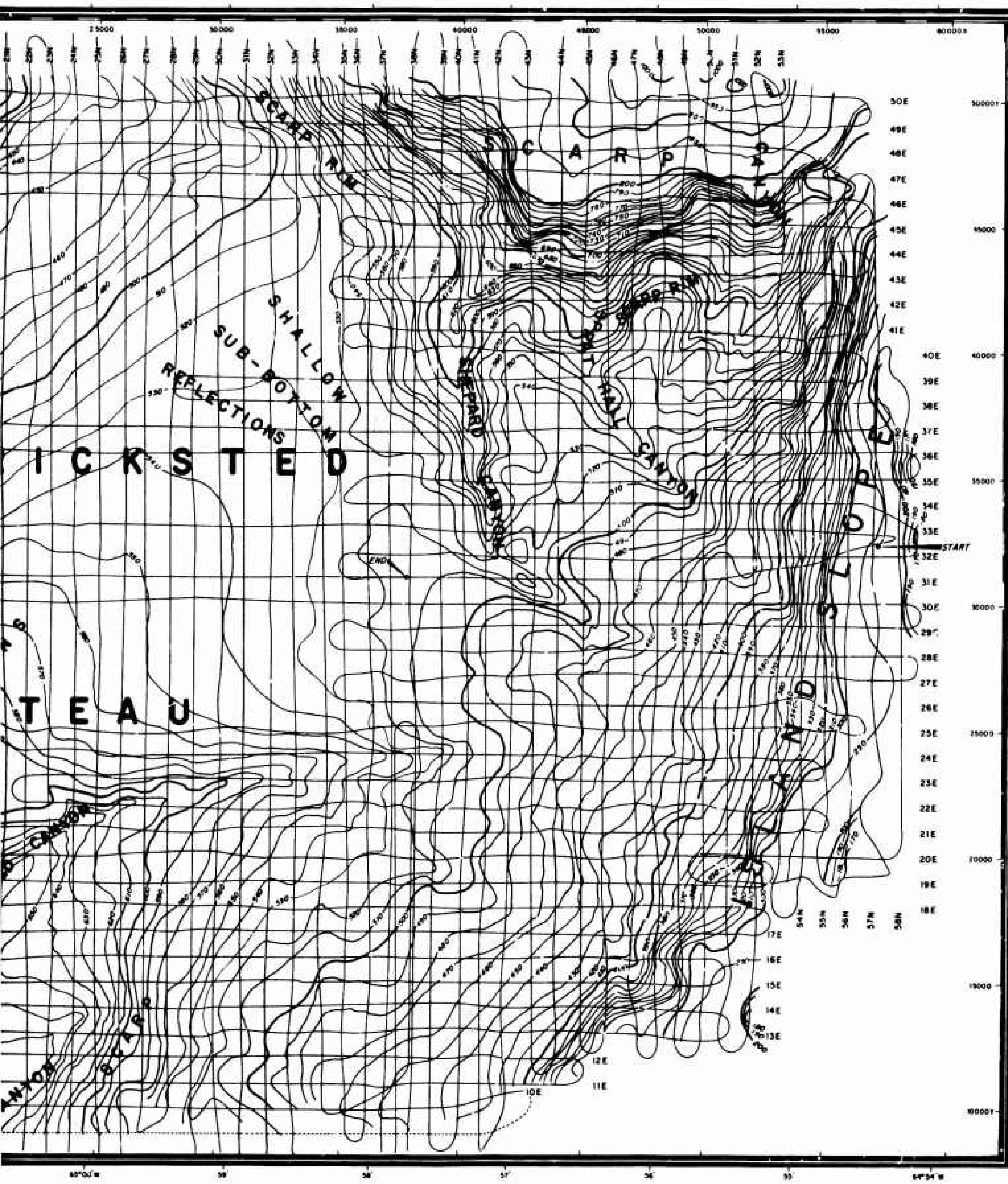


Figure 5. *Bathymetry West of St. Croix*

Depths are in units of 1/400 second, two-way travel time (1 second = 750 nominal meters, based on a sound velocity of 1500 meters/second, or 400 nominal fathoms, based on a sound velocity of 800 fms/sec). Contour interval is 10/400 second. Inaccuracies of positioning may occur, particularly on the steep slopes (see text). NS survey lines have been used as optimum control. Tracklines are numbered as a means of locating section lines. Two location grids are presented, one in range coordinates and one in latitude and longitude.



ominal meters, based on a sound velocity of of 800 fms/sec). Contour interval is 10/400 es (see text). NS survey lines have been used lines. Two location grids are presented, one in

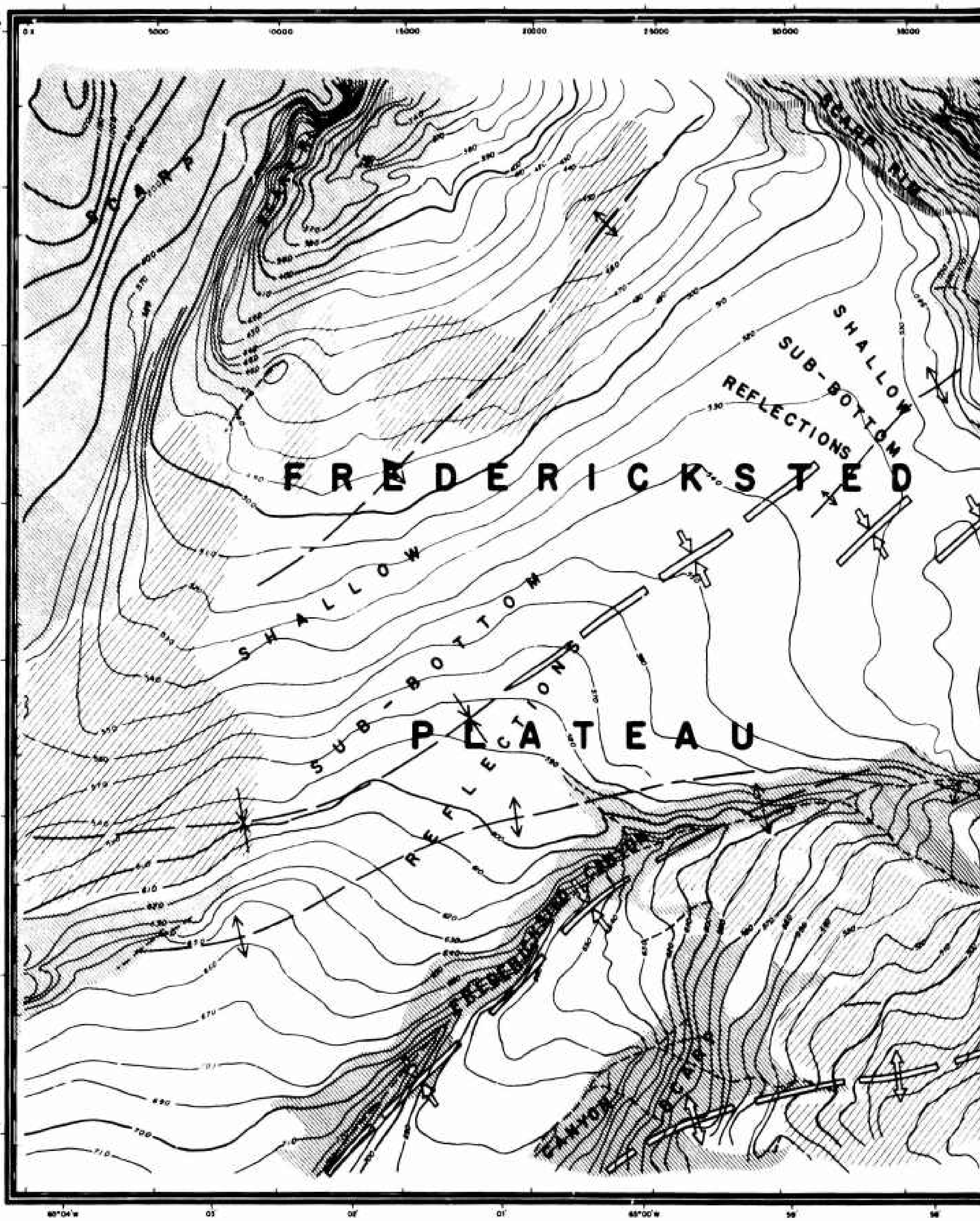
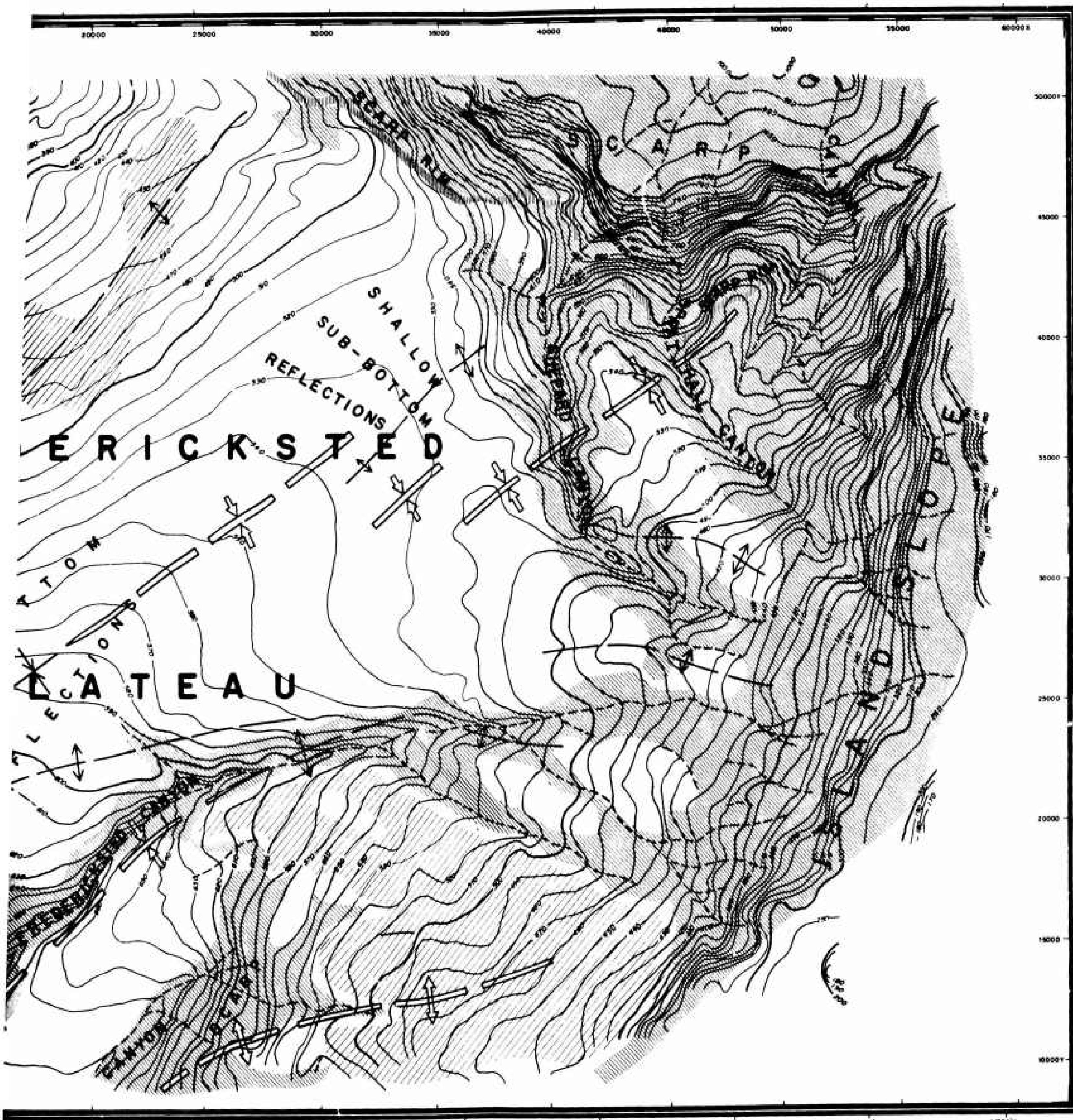


Figure 6. *Physiographic Features West of St. Croix.*

Areas with steeper slopes are shown by fine hatching. Areas regionally gentle-sloping, but locally hilly or undulating are shown by open hatching. Gently sloping, smooth areas are left open. Canyon or channel axes are delineated by long-dashed lines. The main features of subsurface structure are also presented. Anticlines and synclines are shown by dashed lines having diverging and converging arrows, respectively.



Areas regionally gentle-sloping, but locally hilly or undulating are
are left open. Canyon or channel axes are delineated by long-
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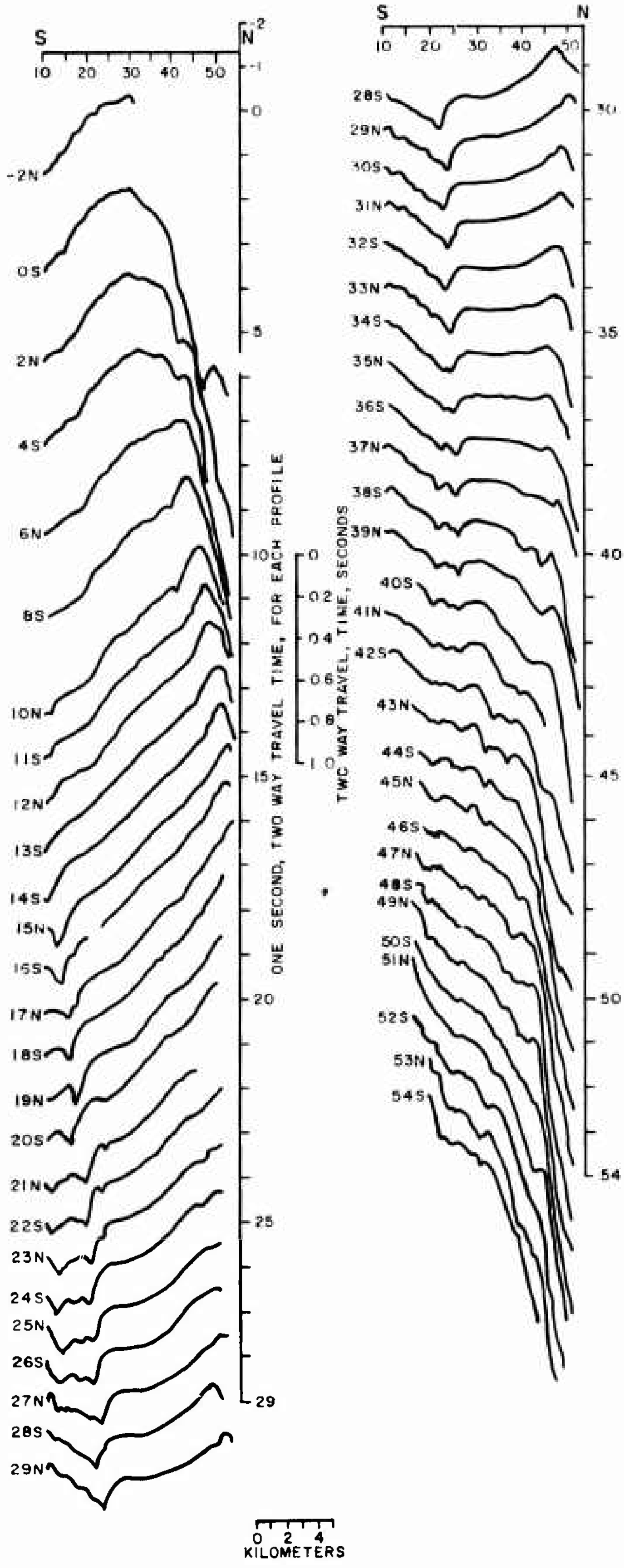

Figure 7. *North/South Topographic Sections*

Location of sections shown in Figure 5. Vertical exaggeration is approximately 20. Profiles are stacked proceeding from west to east, top left to bottom right. The north escarpment appears on profiles 0-10 and 36-54, and the Fredericksted Canyon appears on profiles 14-40.

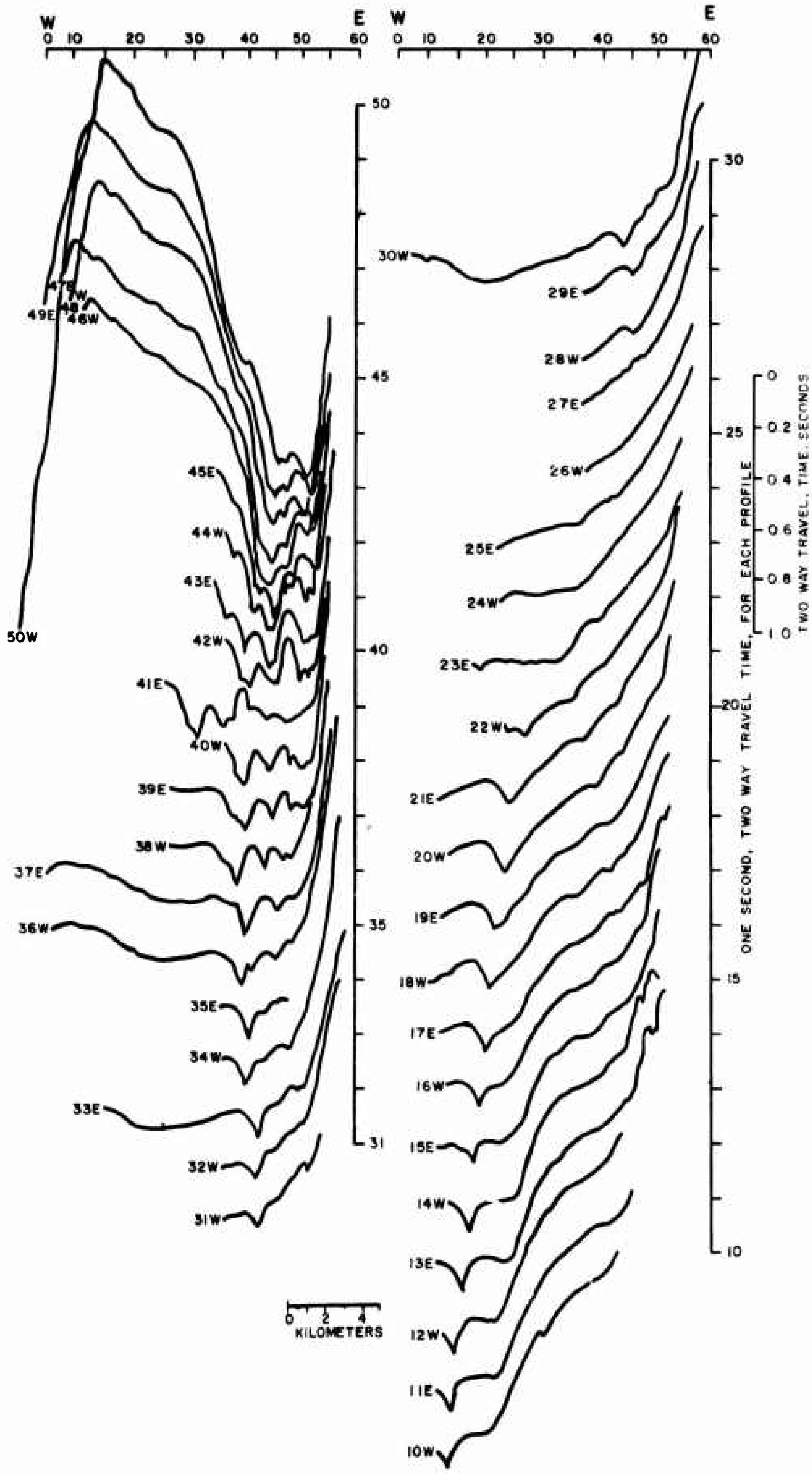

Figure 8 *East/West Topographic Sections.*

Location of sections shown in Figure 5. Vertical exaggeration is approximately 20. Profiles are stacked proceeding from north to south, top left to bottom right. Shepard Canyon appears in profiles 28-50, Sprat Hall Canyon in profiles 31-45, and Fredericksted Canyon in profiles 10-21. The island slope is on the extreme right in all sections.

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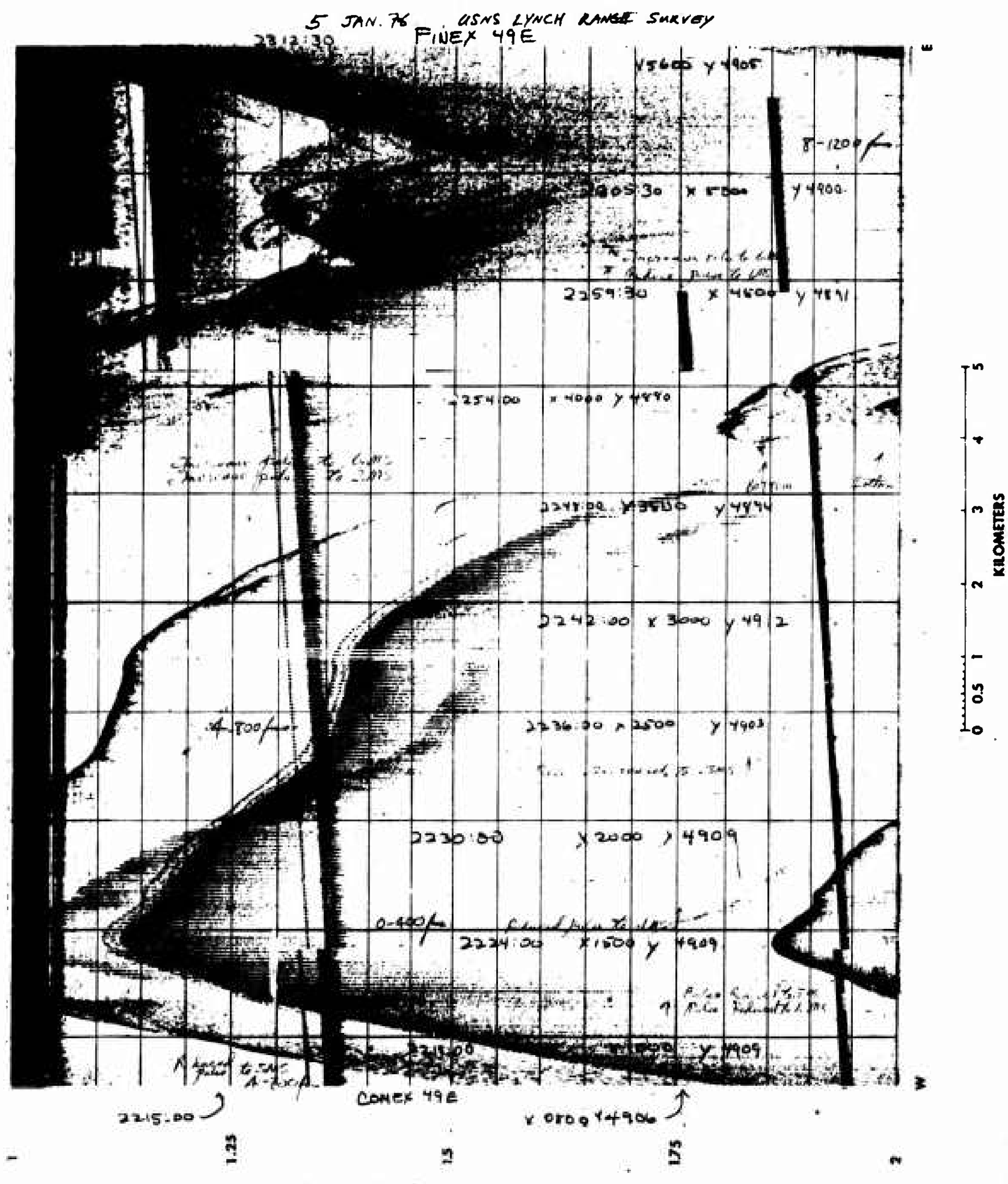

Figure 9. 3.5 kHz Echogram Along Section Line 49E (see Figure 5 for location of section). Travel time scale applies to left edge of section. Vertical exaggeration is approximately 20.

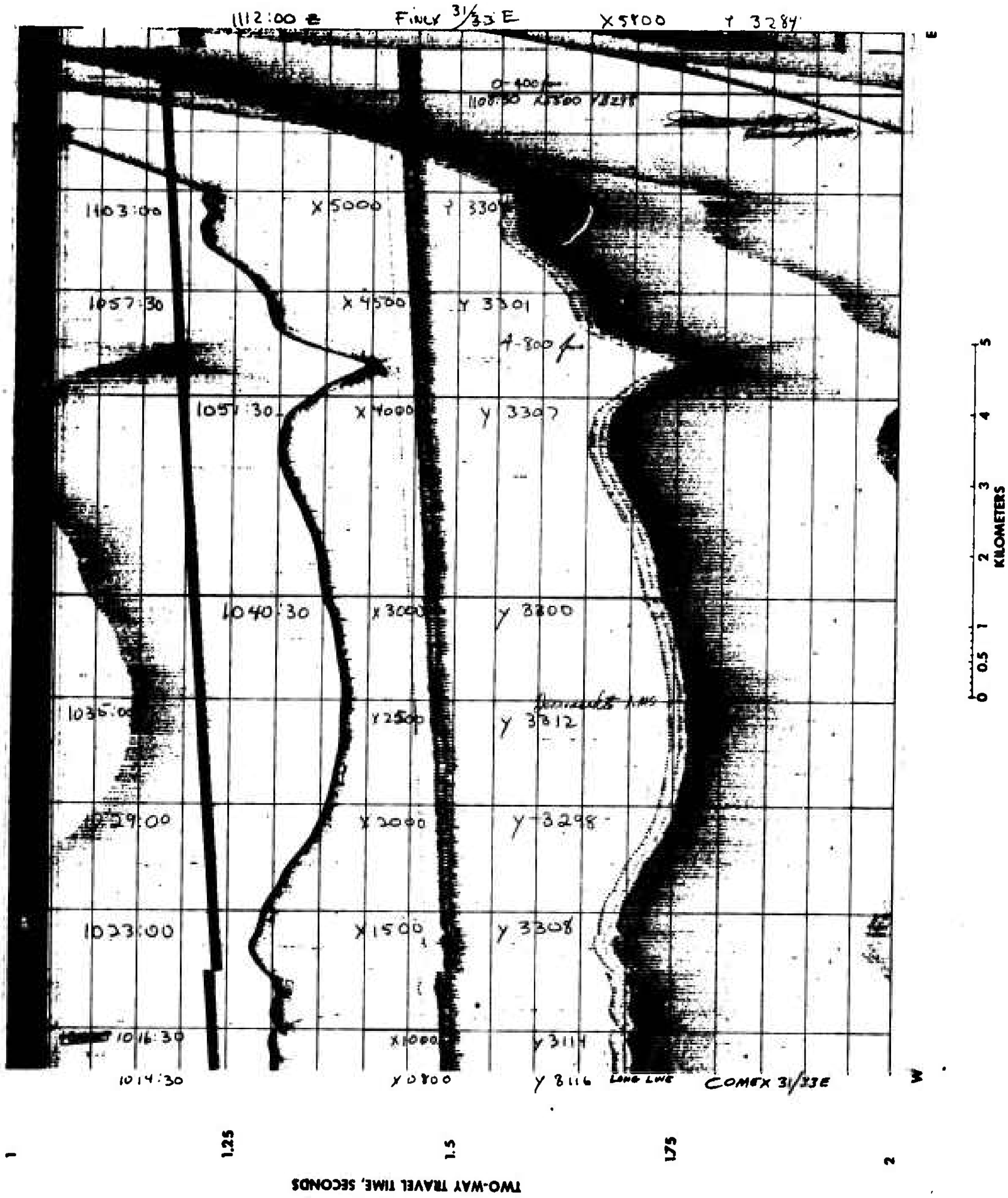

Figure 10. 3.5 kHz Echogram Along Section Line 31E (see Figure 5 for location of section.) Vertical Exaggeration is approximately 20

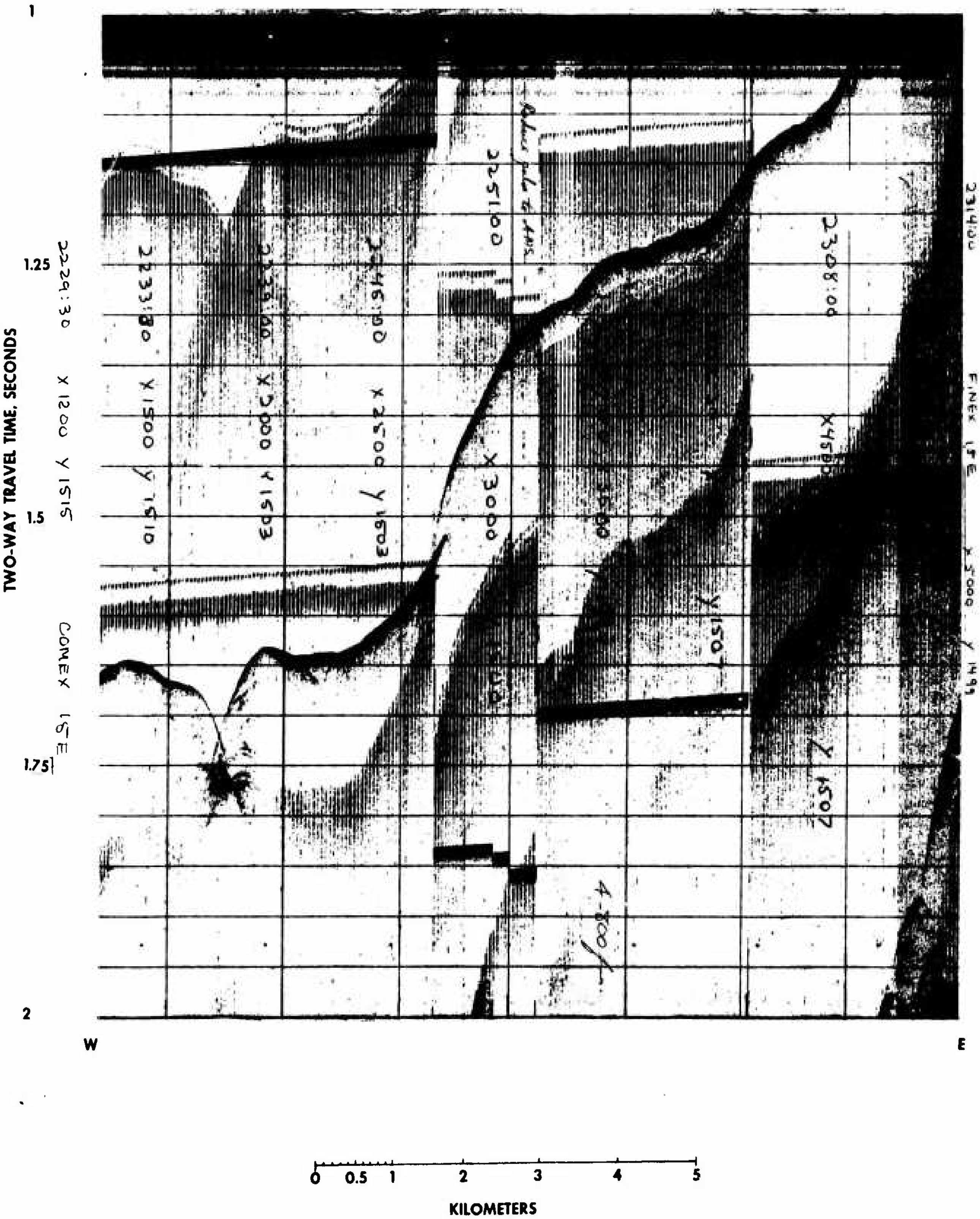

Figure 11. 3.5 kHz Echogram Along Section Line 15E (see Figure 5 for location of section.) Vertical exaggeration is approximately 20

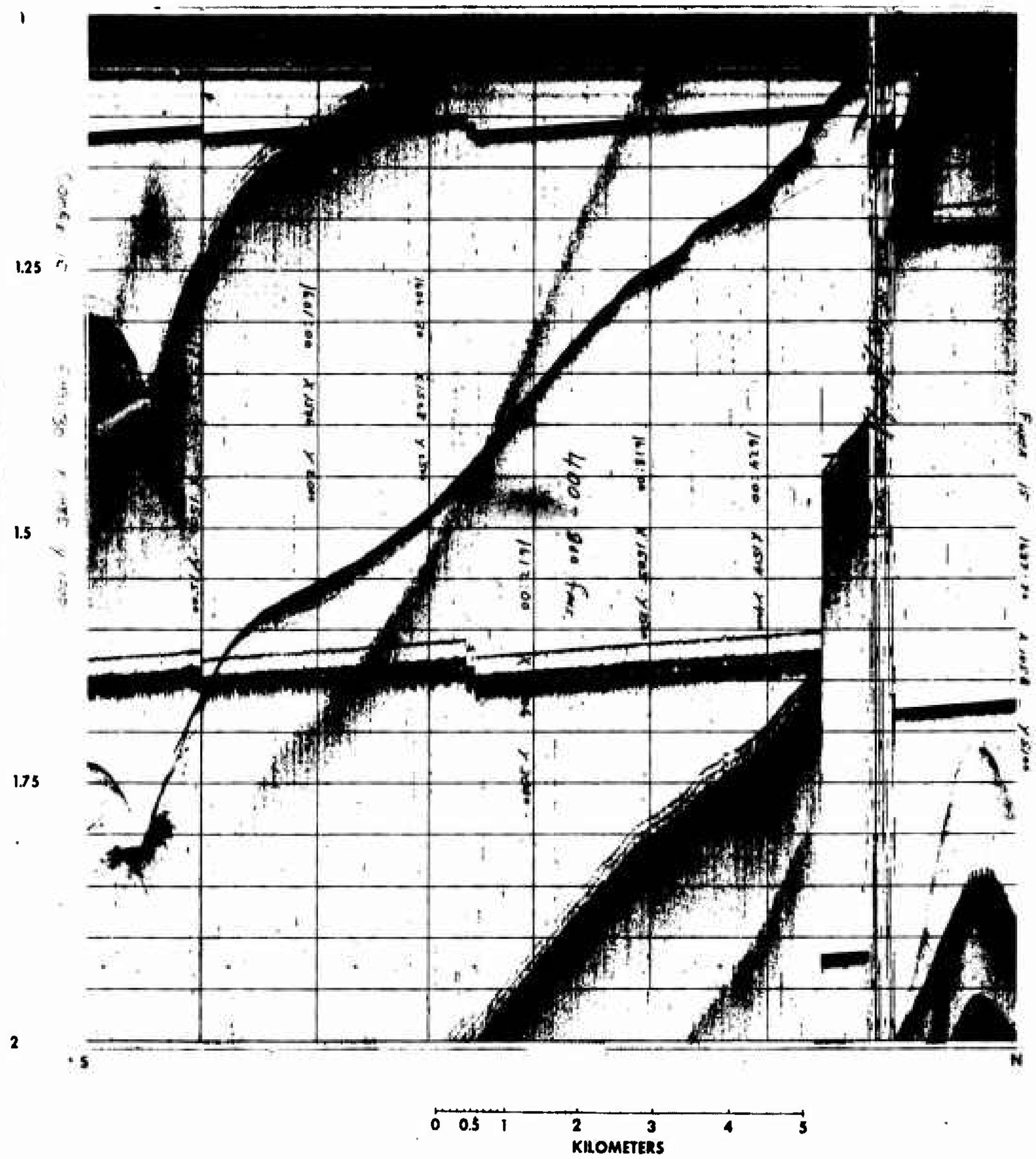

Figure 12. 3.5 kHz Echogram Along Section Line 15N (see Figure 5 for location of section.) Vertical exaggeration is approximately 20.

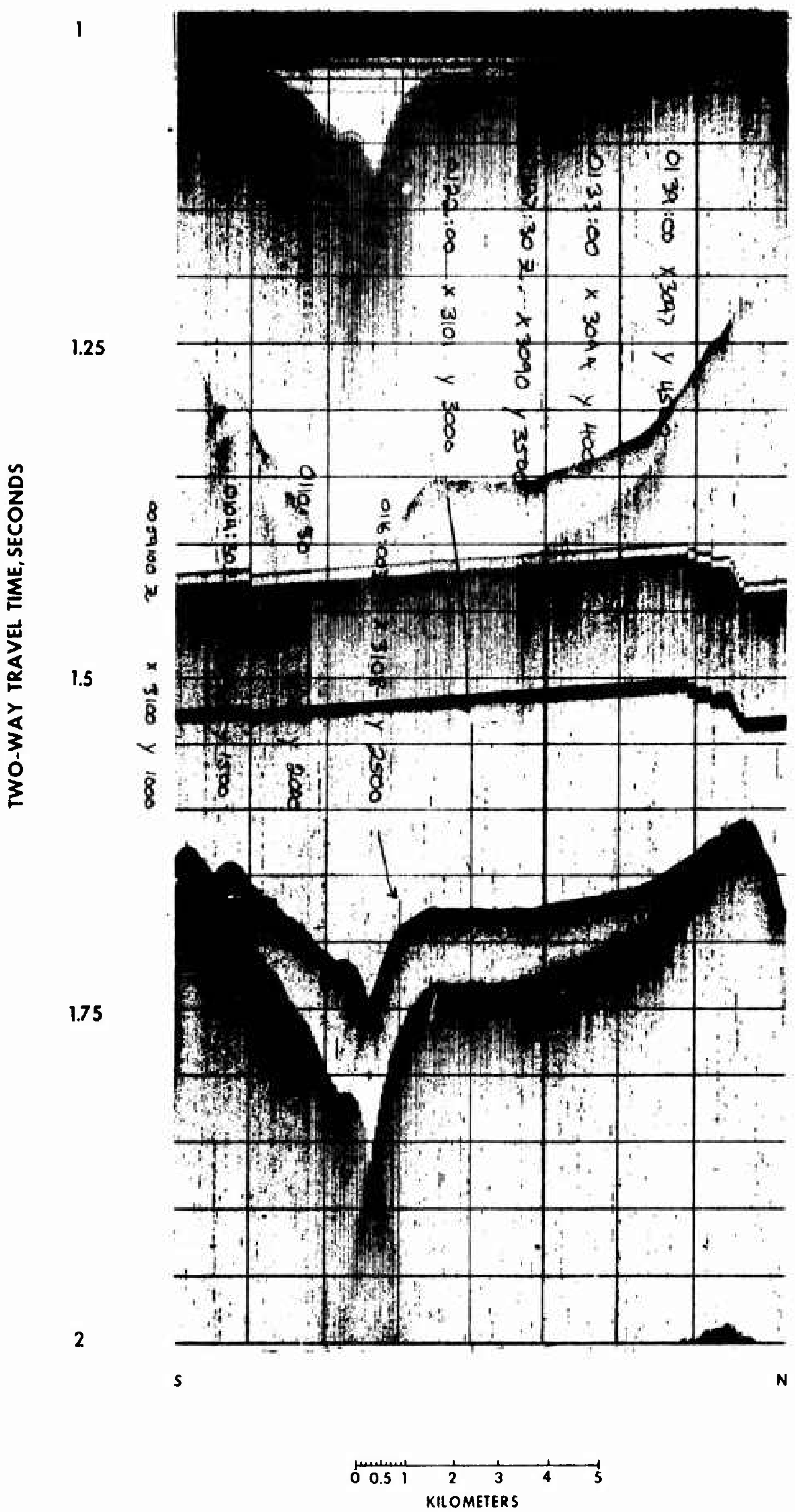

Figure 13. 3.5 kHz Echogram Along Section Line 31N (see Figure 5 for location of section). Vertical exaggeration is approximately 20.

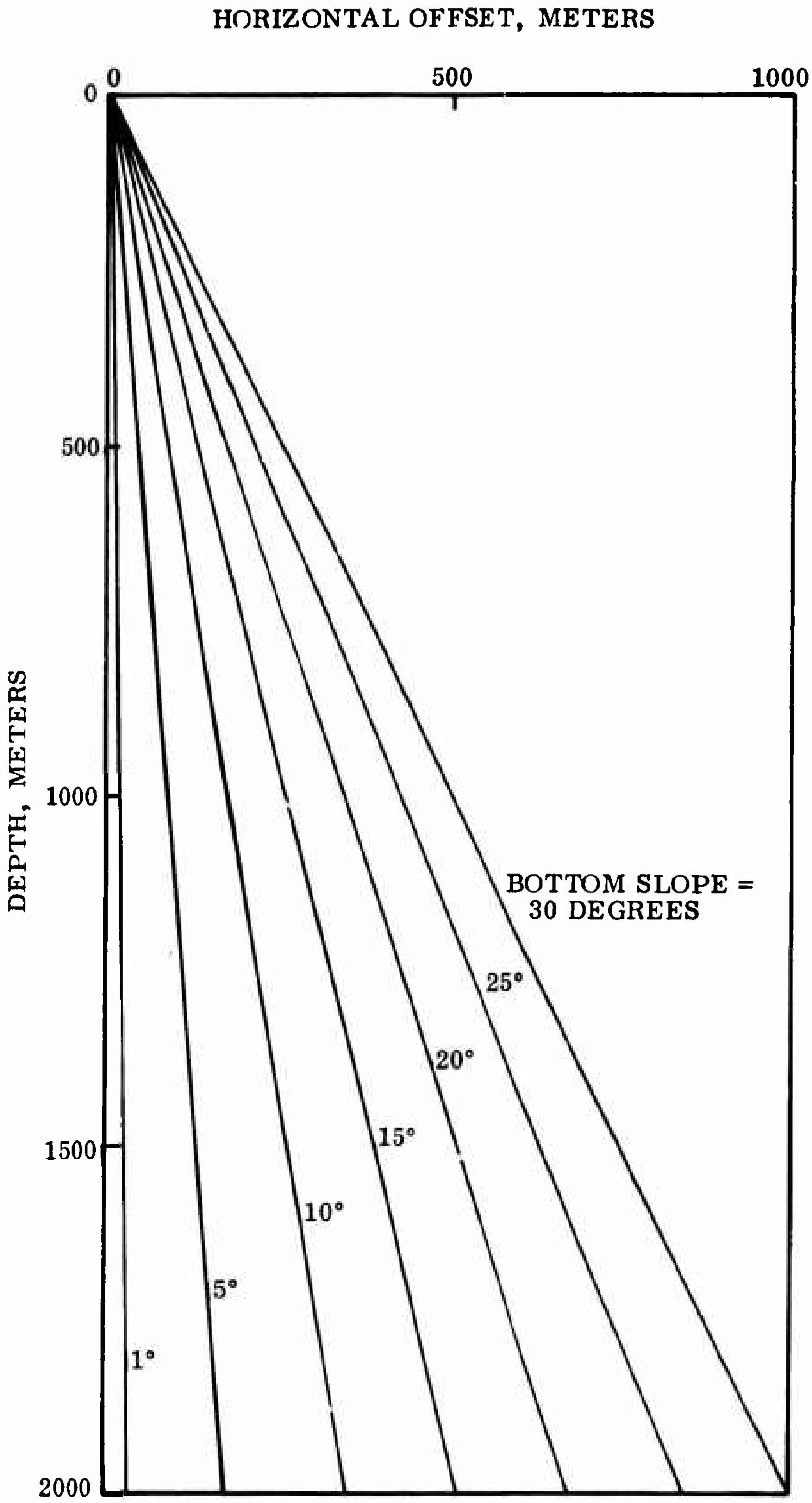

Figure 14 *Horizontal Offset of Sounded Bottom with Respect to Surface Ship, as a Function of Depth and Bottom Slope, for Wide-Beam Echo Sounder.*

Figure 15 Quiet Sediment-Covered Sea Floor Large holes frequently seen on the southern slopes of Fredericksted Plateau (OCEANIC, FREDERICKSTED CANYON SURVEY)

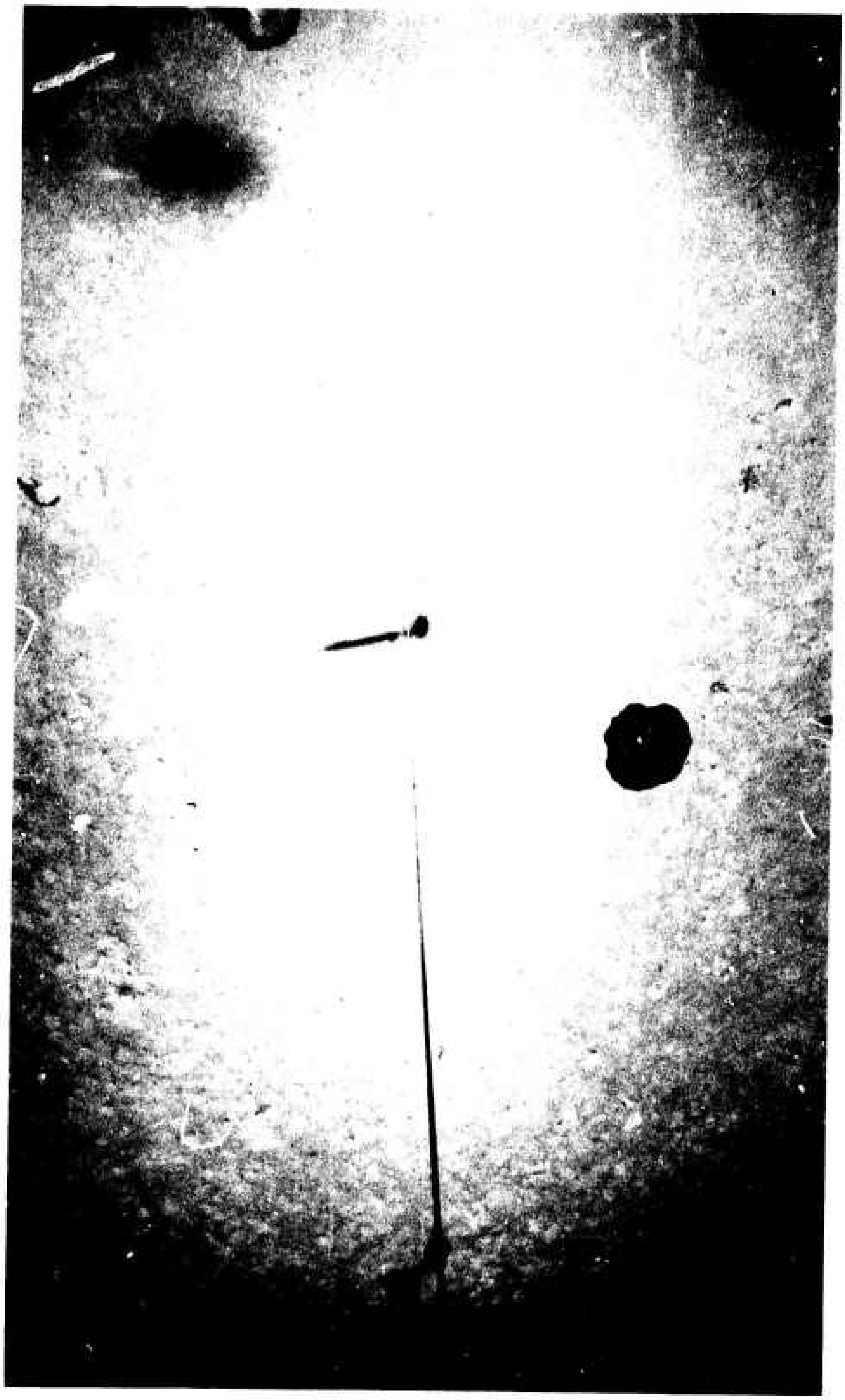

Figure 16 *Tranquil Sedimented Bottom. Imprints of starfish and evidence of other bottom activity have not been erased (OCEANIC ARRAY 5).*

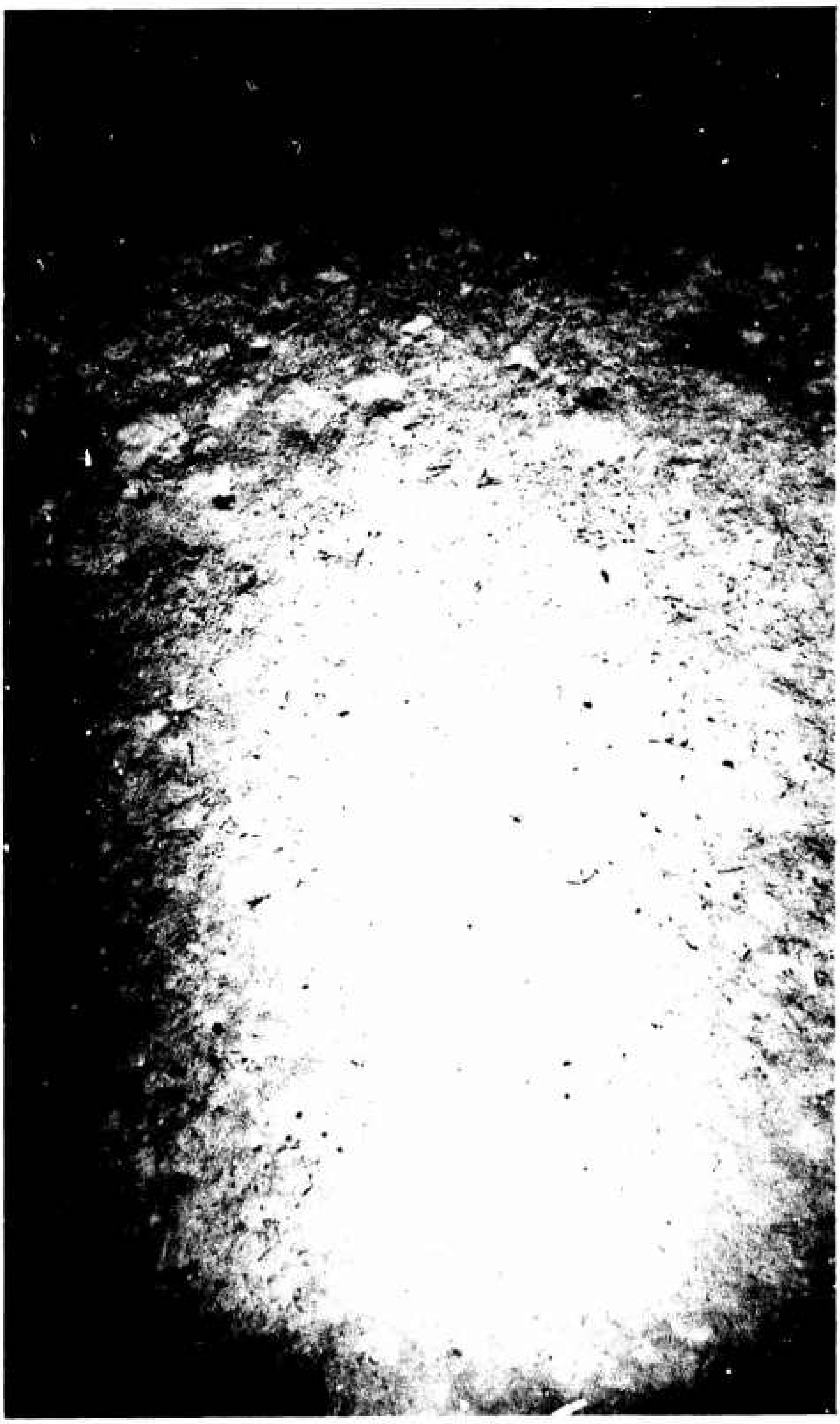

Figure 17   Quiet sedimented bottom with pits, holes, hummocks, and probable fecal pellets (OCEANIC, ARRAY 5).

Figure 18 Sedimented bottom with conical mounds, holes, and an undisturbed track (OCEANIC, ARRAY 5)

Figure 19. Mottled bottom, with tripod fish. Debris is randomly oriented (OCEANIC, ARRAY 5).

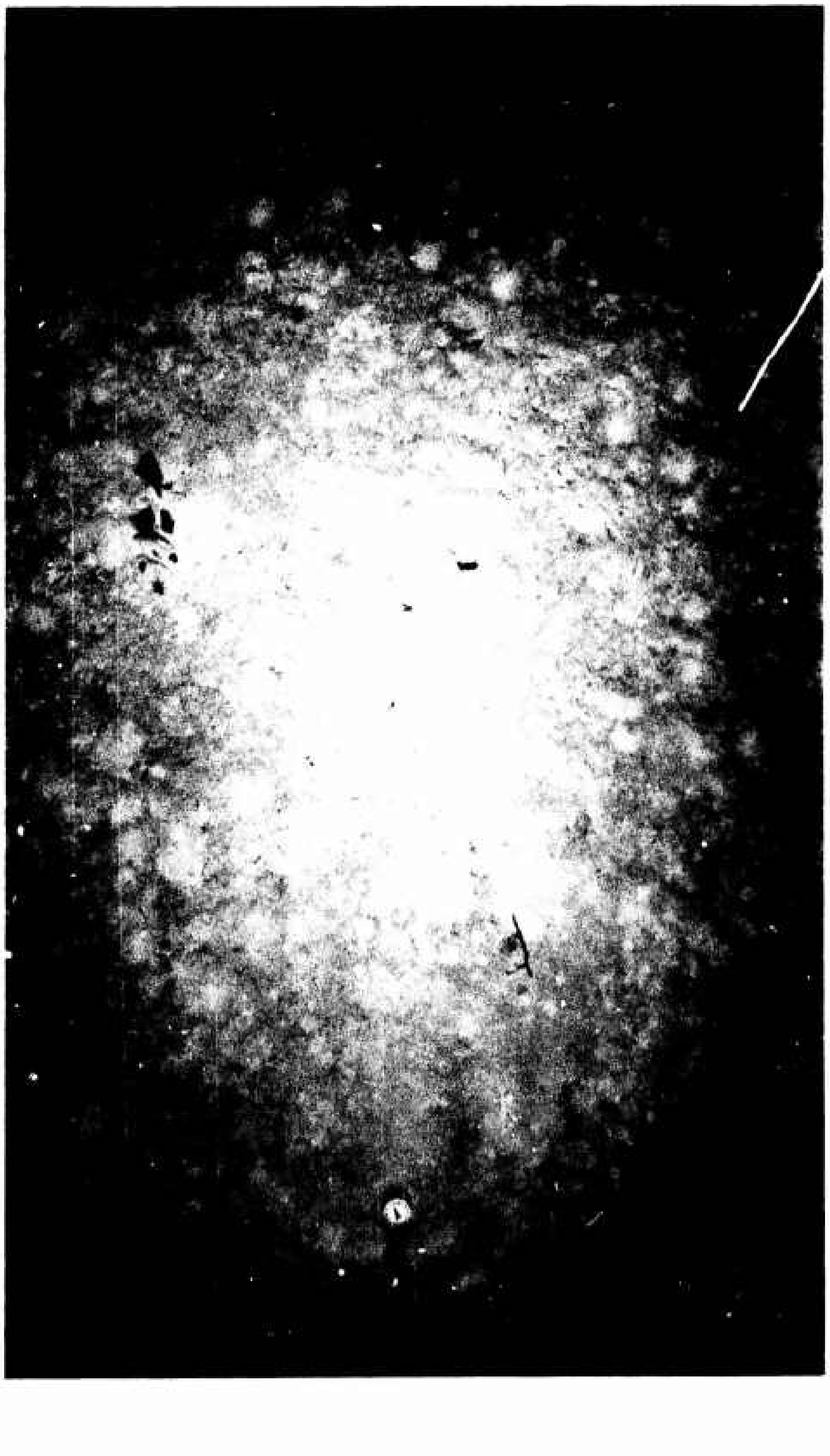

Figure 20 Mounds, holes, and a frequently seen, unidentified pattern of a mound surrounded by holes (OCEANIC, ARRAY 7)

Figure 21. Fan-shaped mark made in the sediments by a "feather" in variable currents (OCEANIC, ARRAY 8)

Figure 22 Moat scoured by currents around rock debris (OCEANIC, ARRAY 9)

Figure 23. Parallel orientation of feathers and tulips bending in a current (OCEANIC, ARRAY 9)

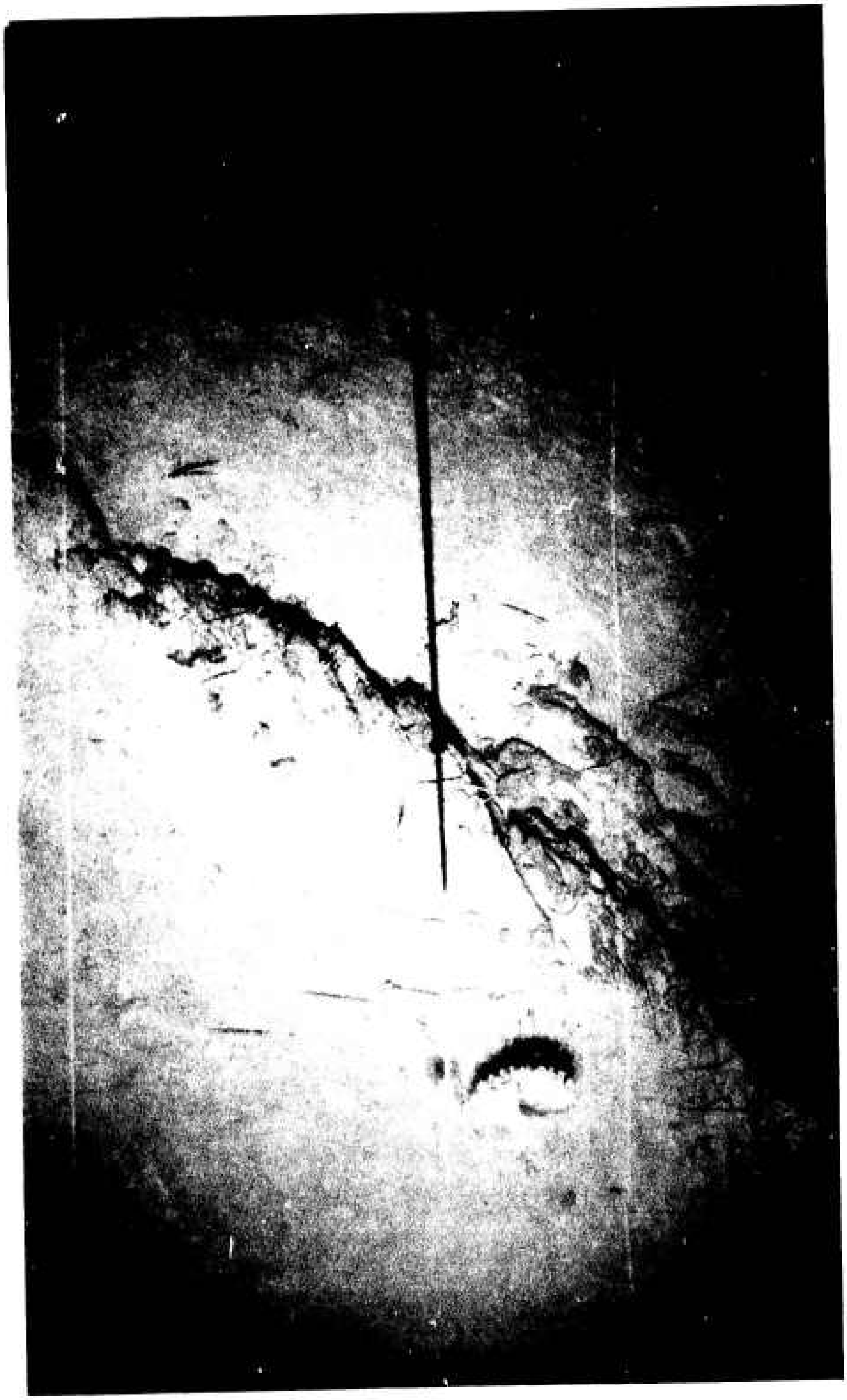

Figure 24 Partially buried rock ledge whose edges are swept clean by current which is also bending the bottom life (OCEANIC ARRAY 9)

Figure 25. Sediment ripple (ALVIN, ARRAY 6)

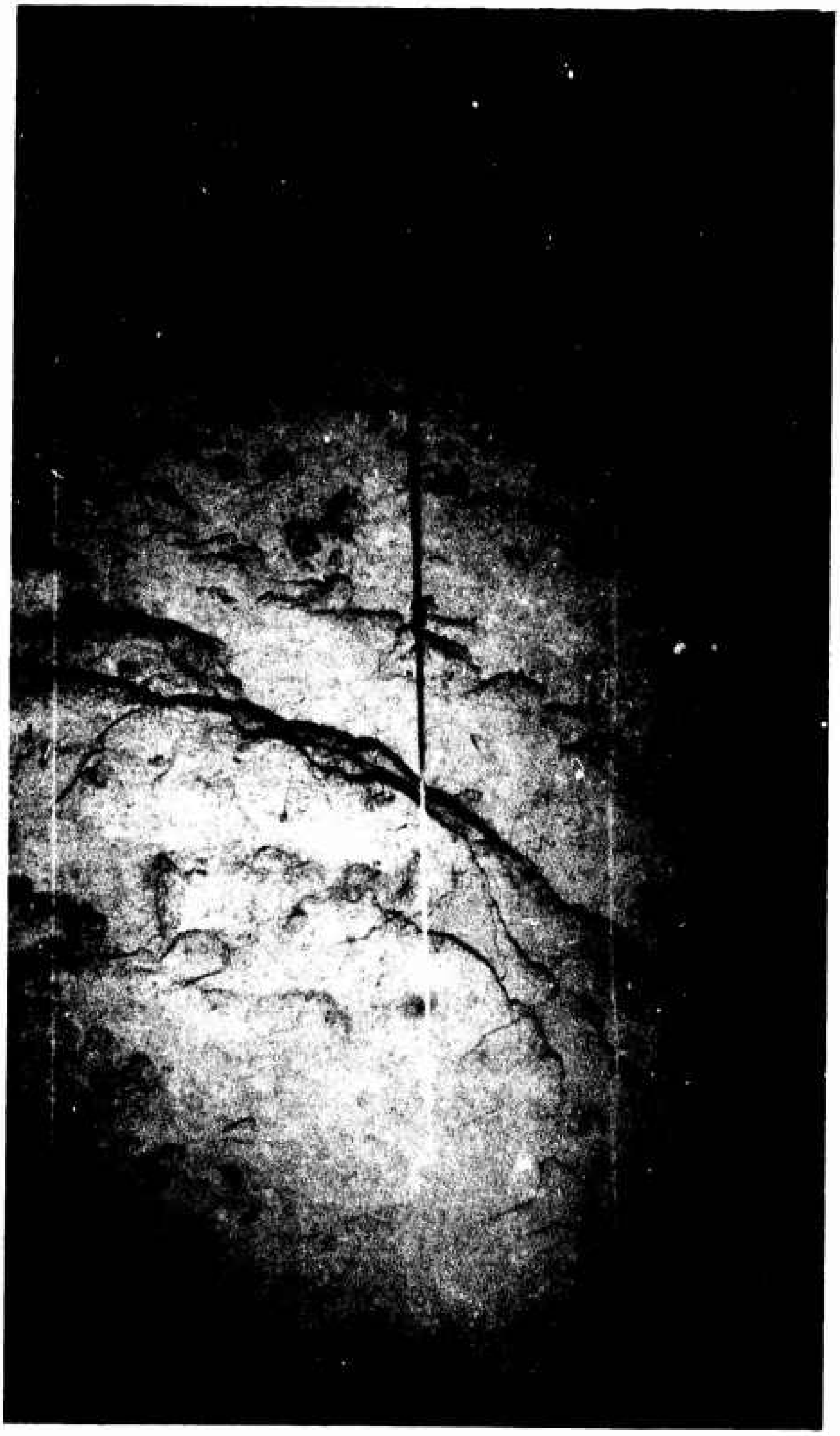

Figure 26   Partially sedimented rock outcrop with regular bedding (Rows) (OCEANIC. ARRAY 9)

Figure 27 Variety of rock bedding types (ALVIN, ARRAY 9)

Figure 28. Sedimentary "steps," covered with fine growth (ALVIN, ARRAY 7)

Figure 29. Massive bedding above thin beds (ALVIN, ARRAY 9)

Figure 30. *Sheer wall of massive rock, probably indicative of fracturing (ALVIN, ARRAY 9).*

Figure 31. Cap or crust (possibly manganese-coated) on top of the rounded, consolidated, bedded sediments (OCEANIC, ARRAY 9).

Figure 32. Sedimented bottom covered with rock debris or "float," both rounded and angular, in a great variety of sizes (OCEANIC ARRAY 9).

Figure 33. "Blocky" bedding, showing evidence of possible joint system (ALVIN ARRAY 9).

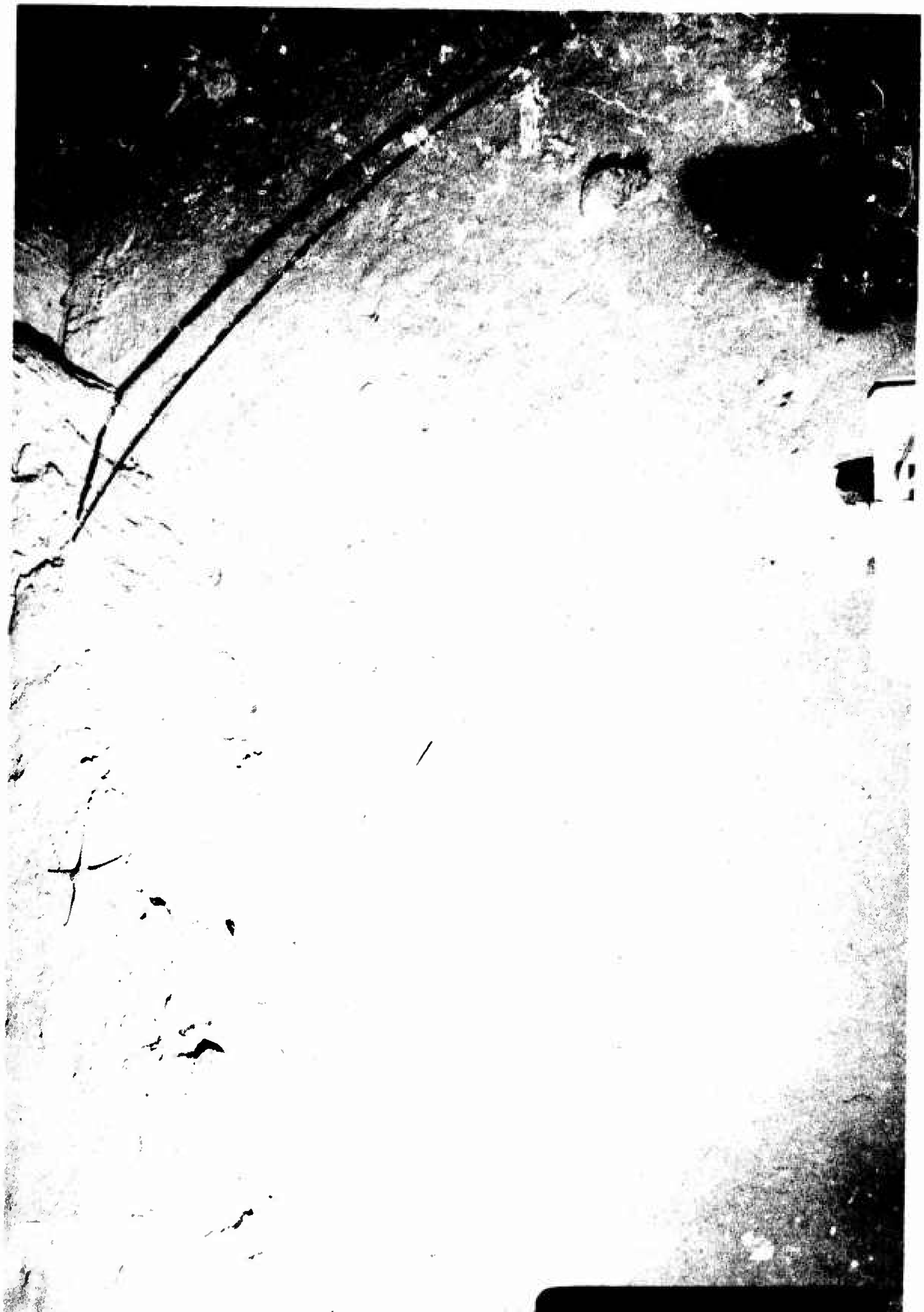

Figure 34. Small, undercut ledge of consolidated sediments. Groove made by cable shows quality of consolidation (ALVIN, ARRAY 5).

Figure 35. *Manganese encrusted, porous limestone formation from which rock sample was obtained; description is in the text for Array 8. Note smoothly rounded and lobate character of the sediment-topped bedding (ALVIN, ARRAY 8).*

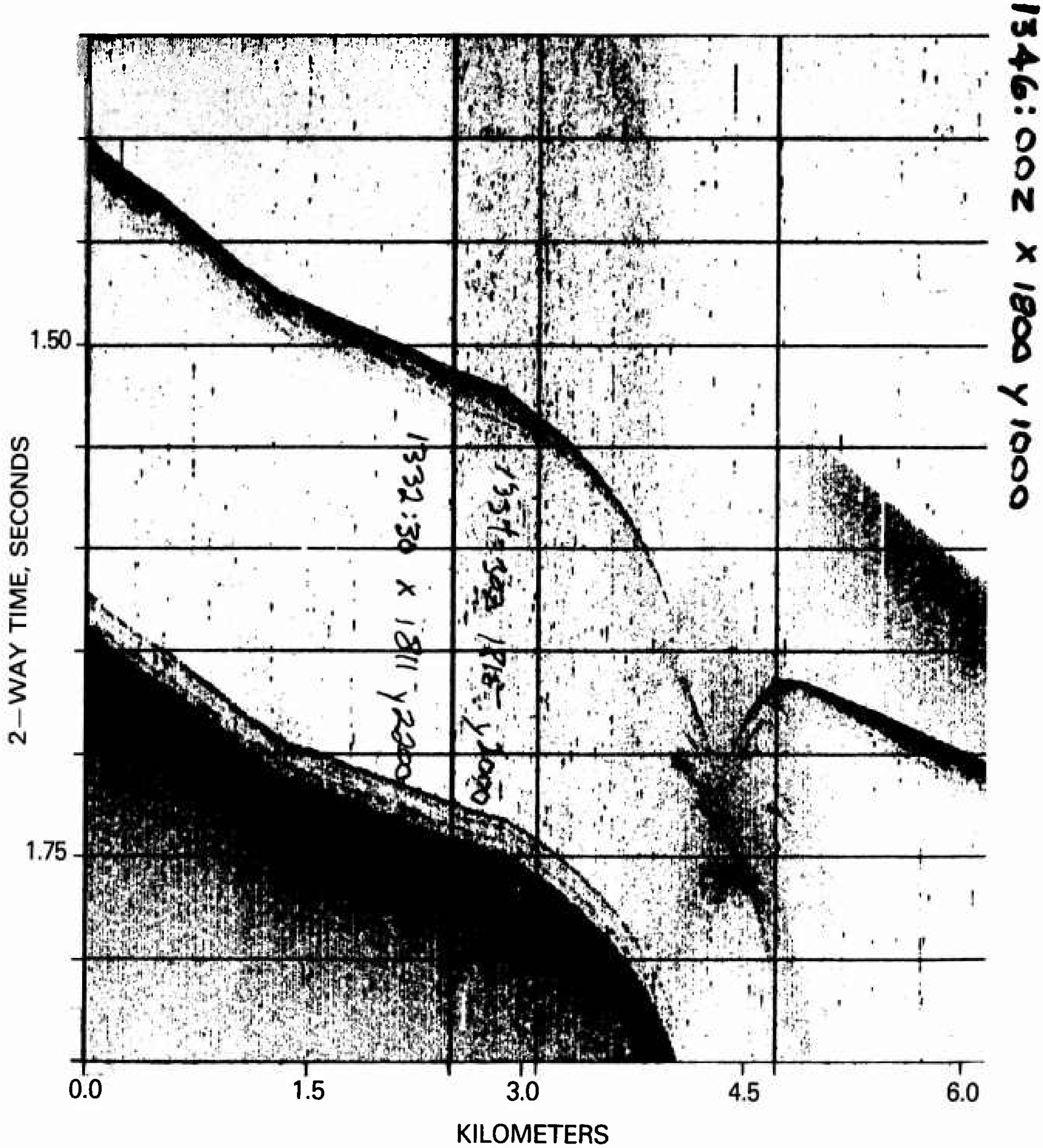

Figure 36 *3.5 kHz Seismic Section Illustrating Stratified Surficial Sediments. North is on the left. Section is from survey line 18N, see Figure 5 for location. Note that the walls of Fredericksted Canyon are higher on the north than on the south. Vertical exaggeration is approximately 20*

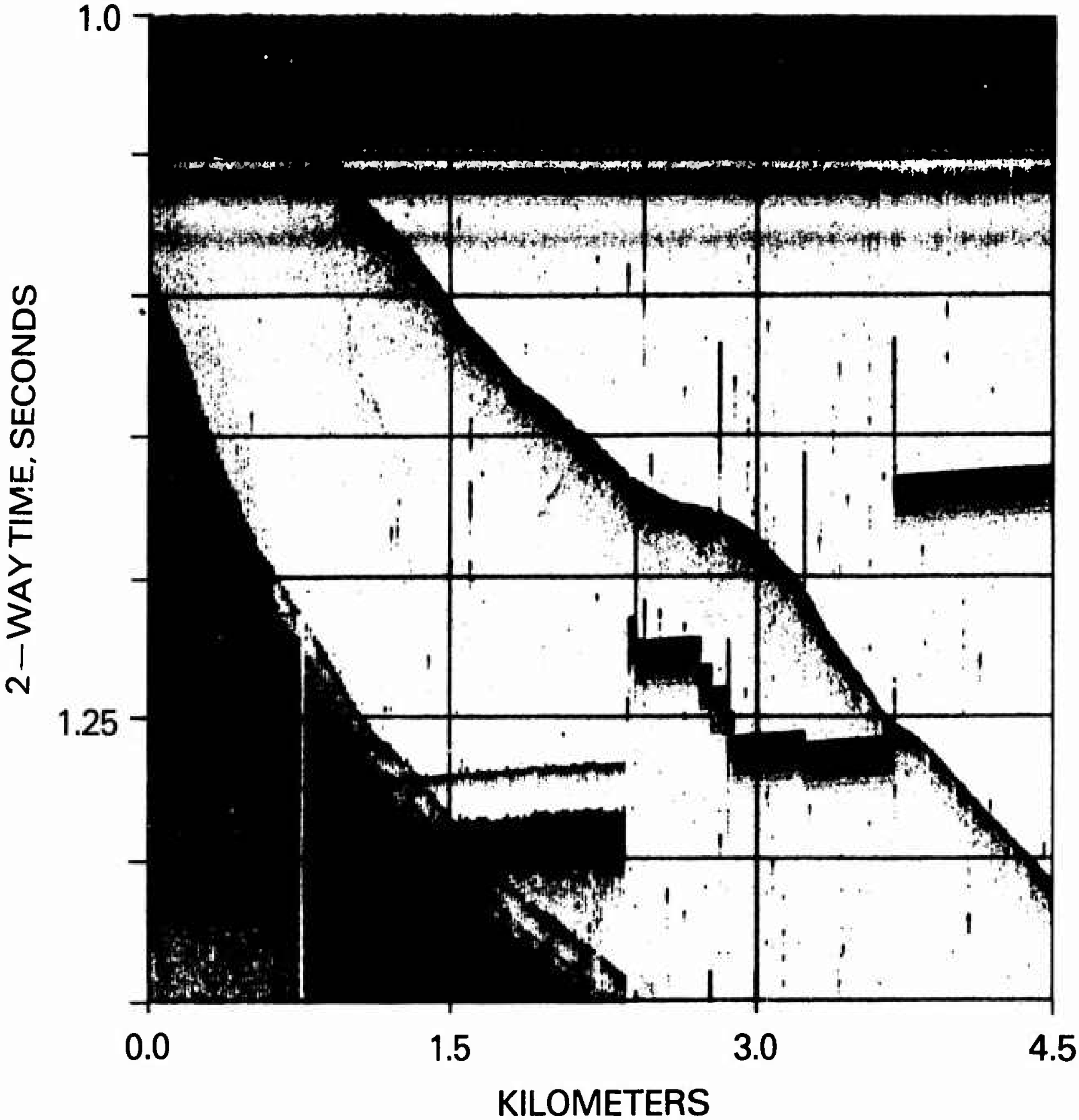

Figure 37. *3.5 kHz Seismic Section Illustrating Disturbed Surficial Sediments. North is on the left. Section is from survey line 20N; see Figure 5 for location. Bottom slope is steeper here than in previous section. Stratification is not distinct. Structural disturbance is evident at the base of the steepest portion of the bottom surface. Vertical exaggeration is approximately 20.*

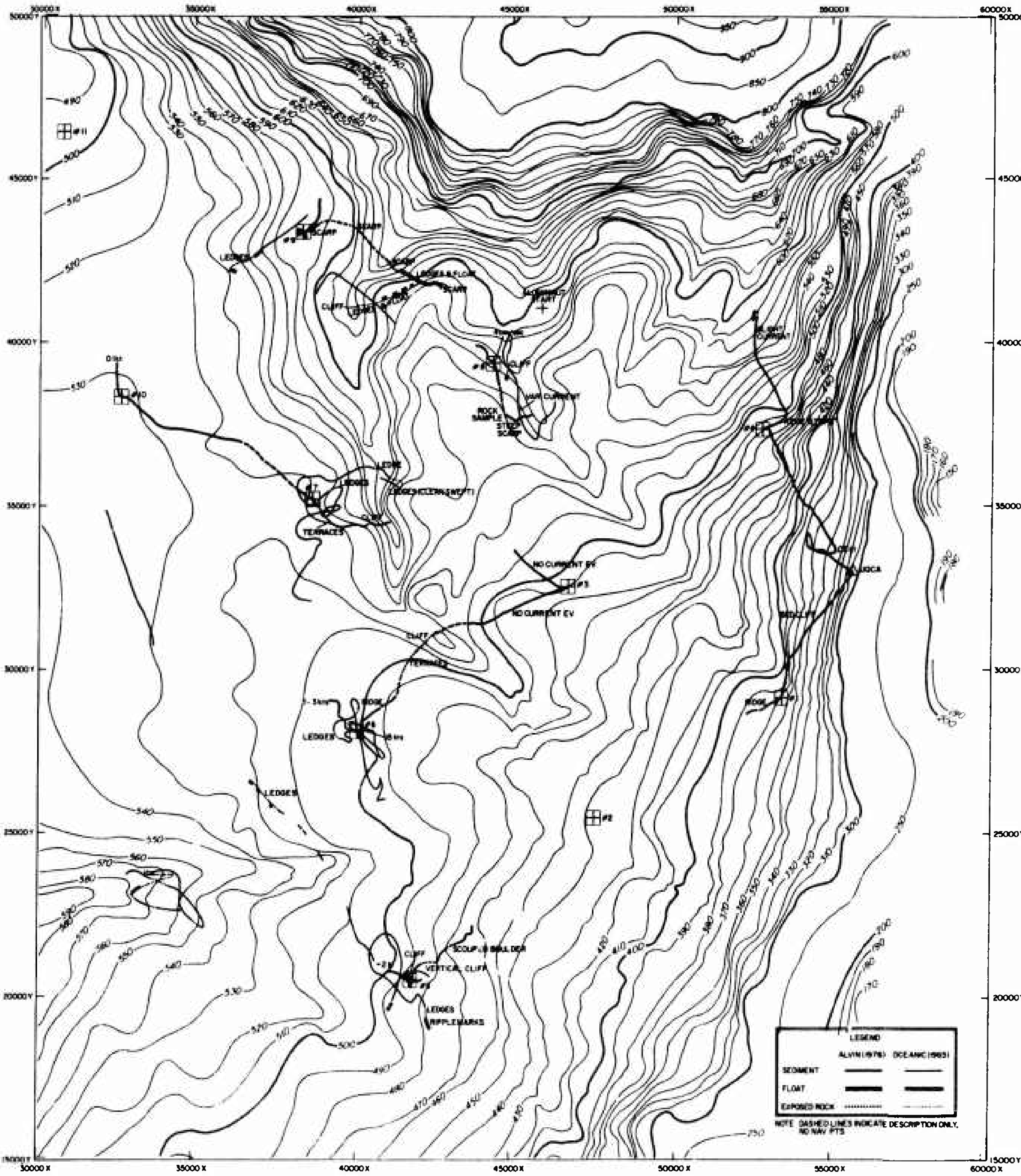

Figure 38. Character of Bottom as Seen in OCEANIC and ALVIN Photograph Surveys. Positioning of OCEANIC cameras is only approximate.

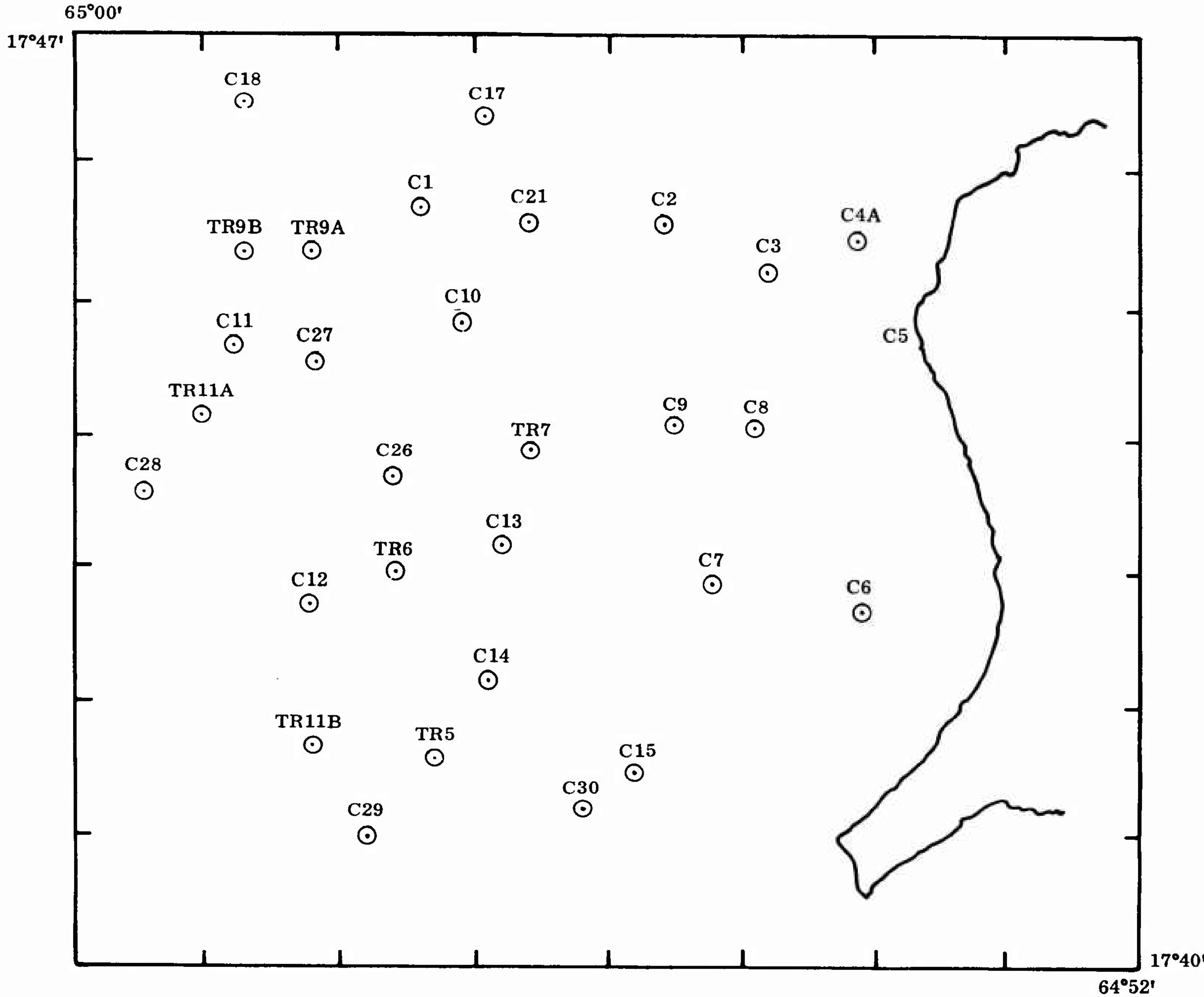

Figure 39. Location of Sediment Samples.

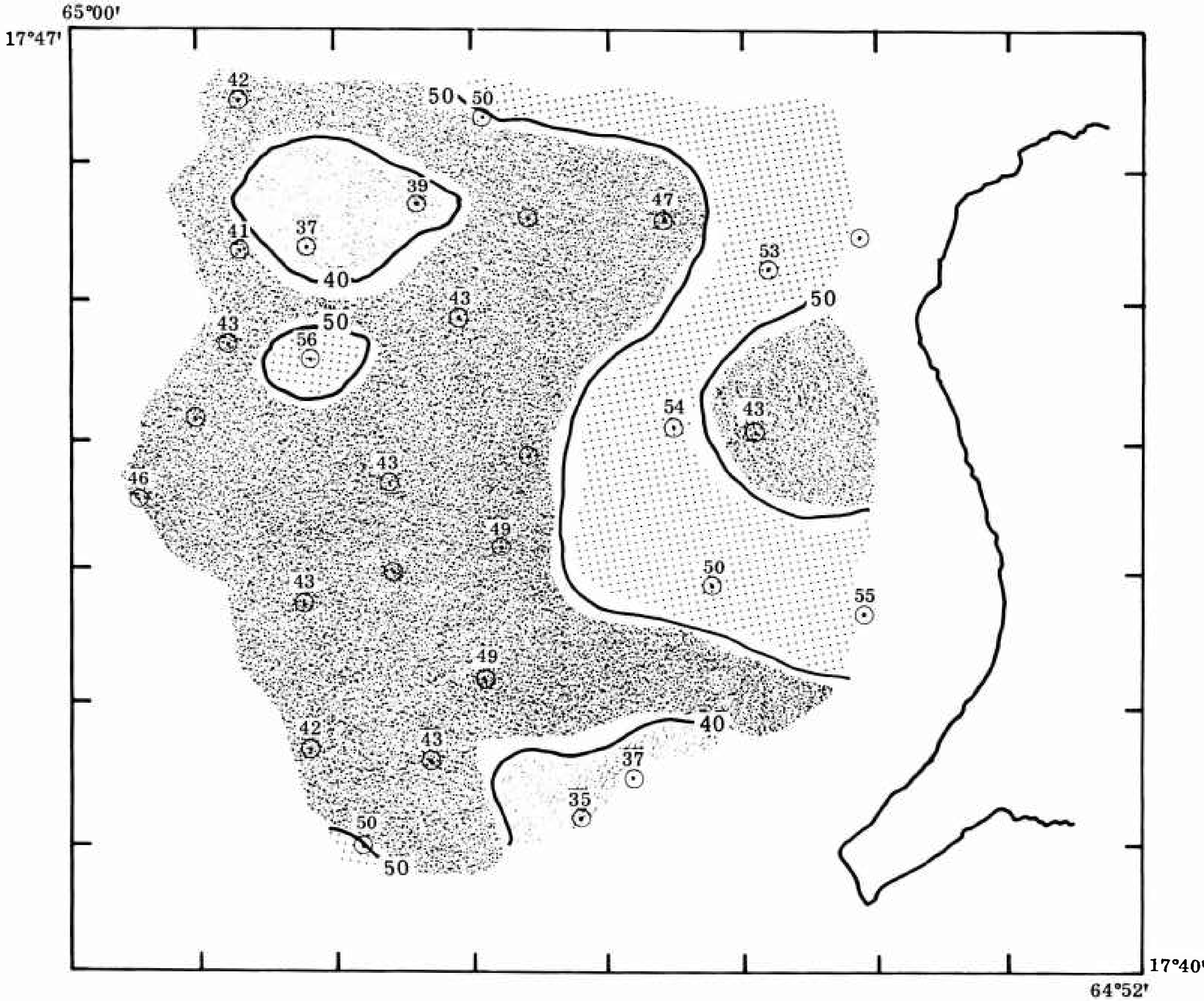

Figure 40. Percent Silt-size Particles in the Top 0-7 cm of Sediment.

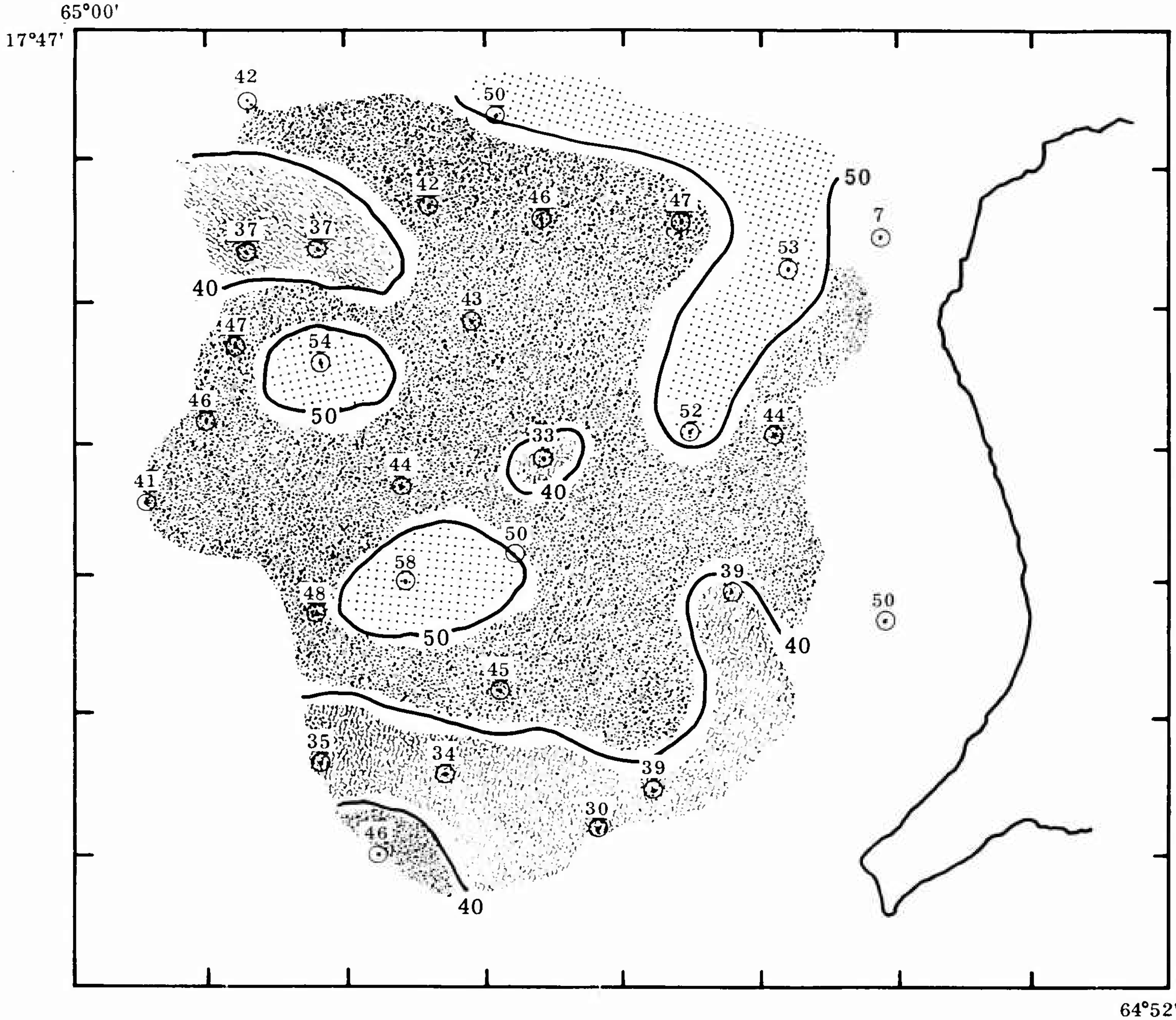

Figure 41. Average Percent Silt-Size Particles Based on All Samples from Each Core.

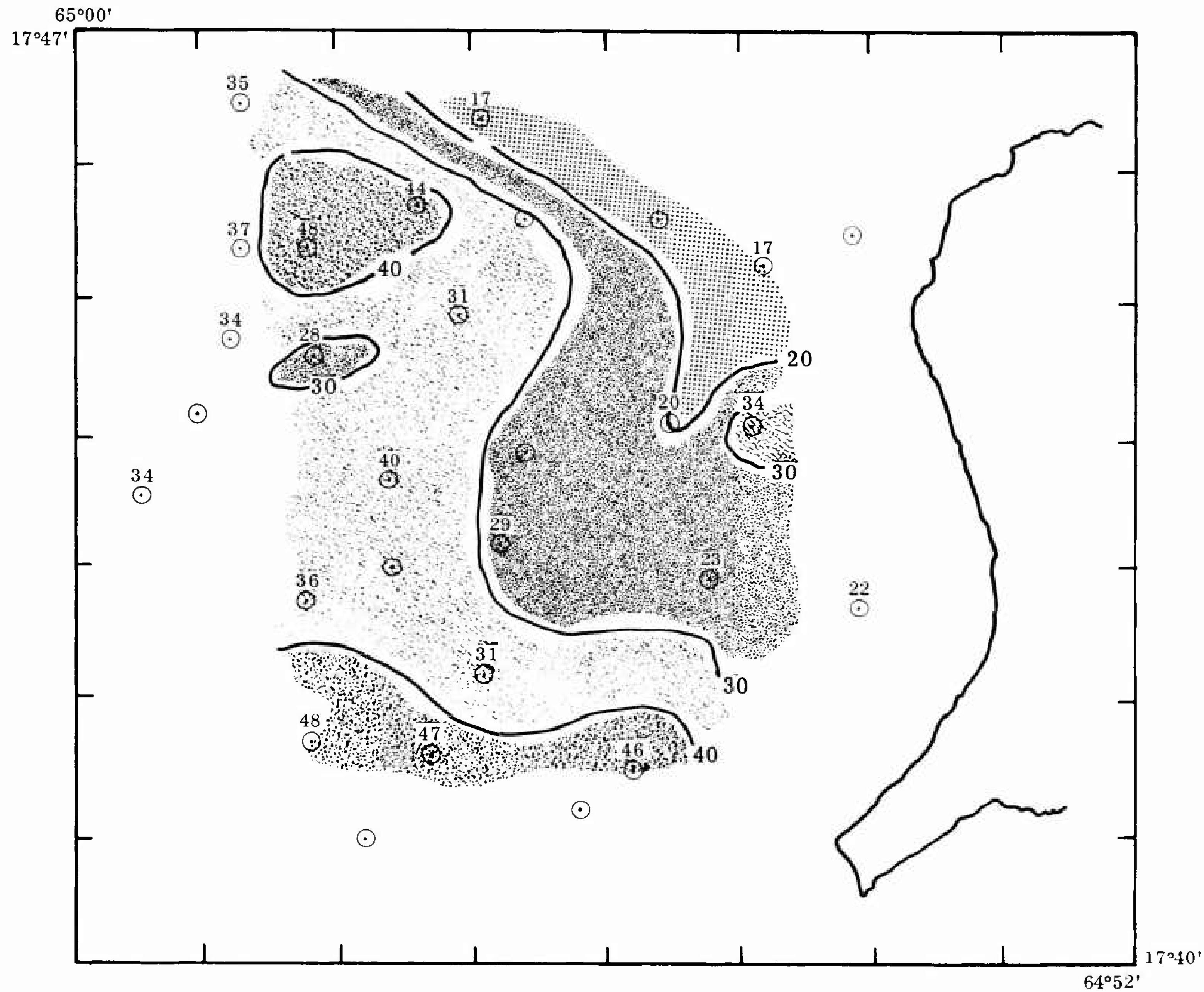

Figure 42. Percent Sand-Size Particles in the Top 0-7 cm of Sediment

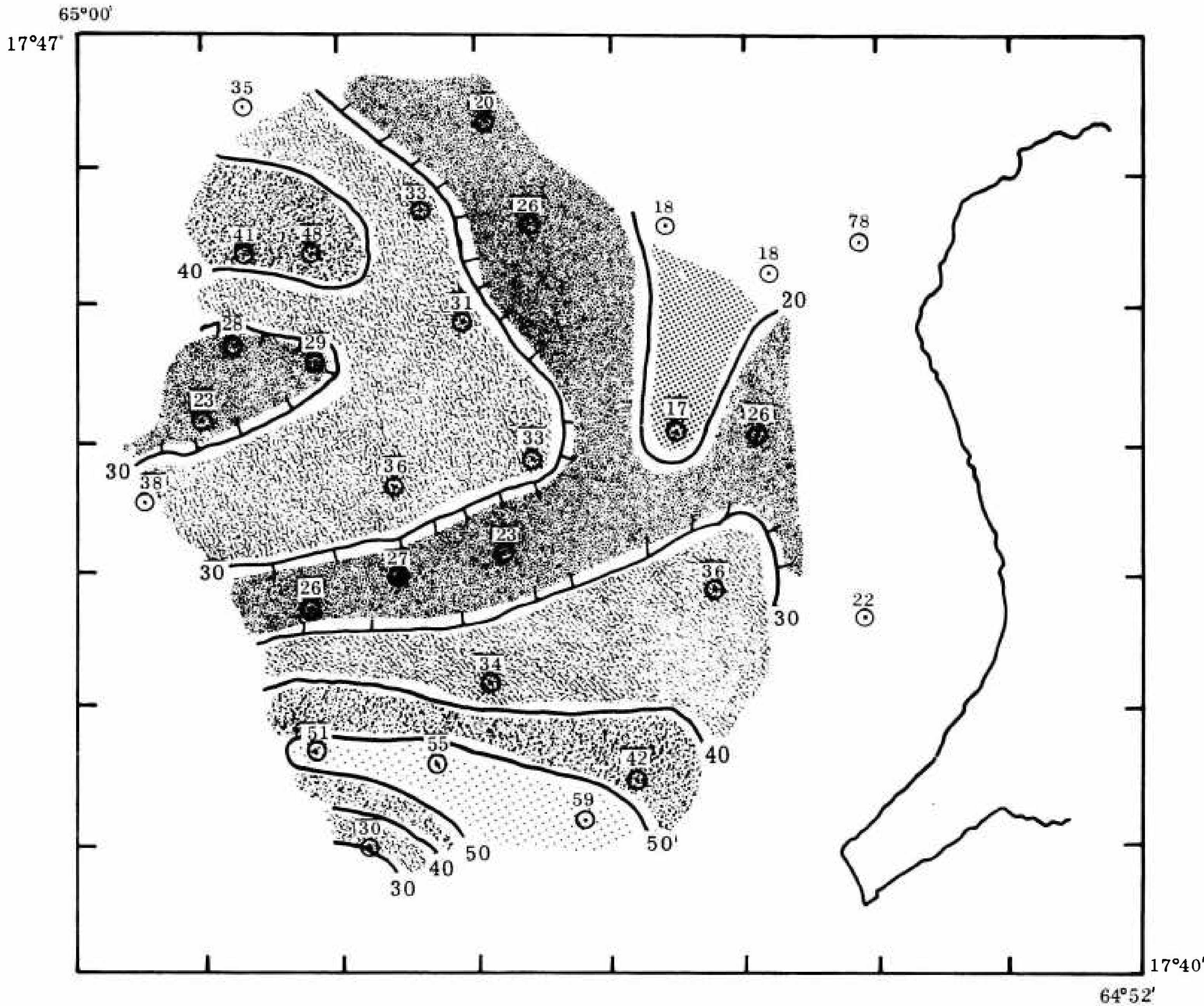

Figure 43. Average Percent Sand-Size Particles Based on All Samples from Each Core.

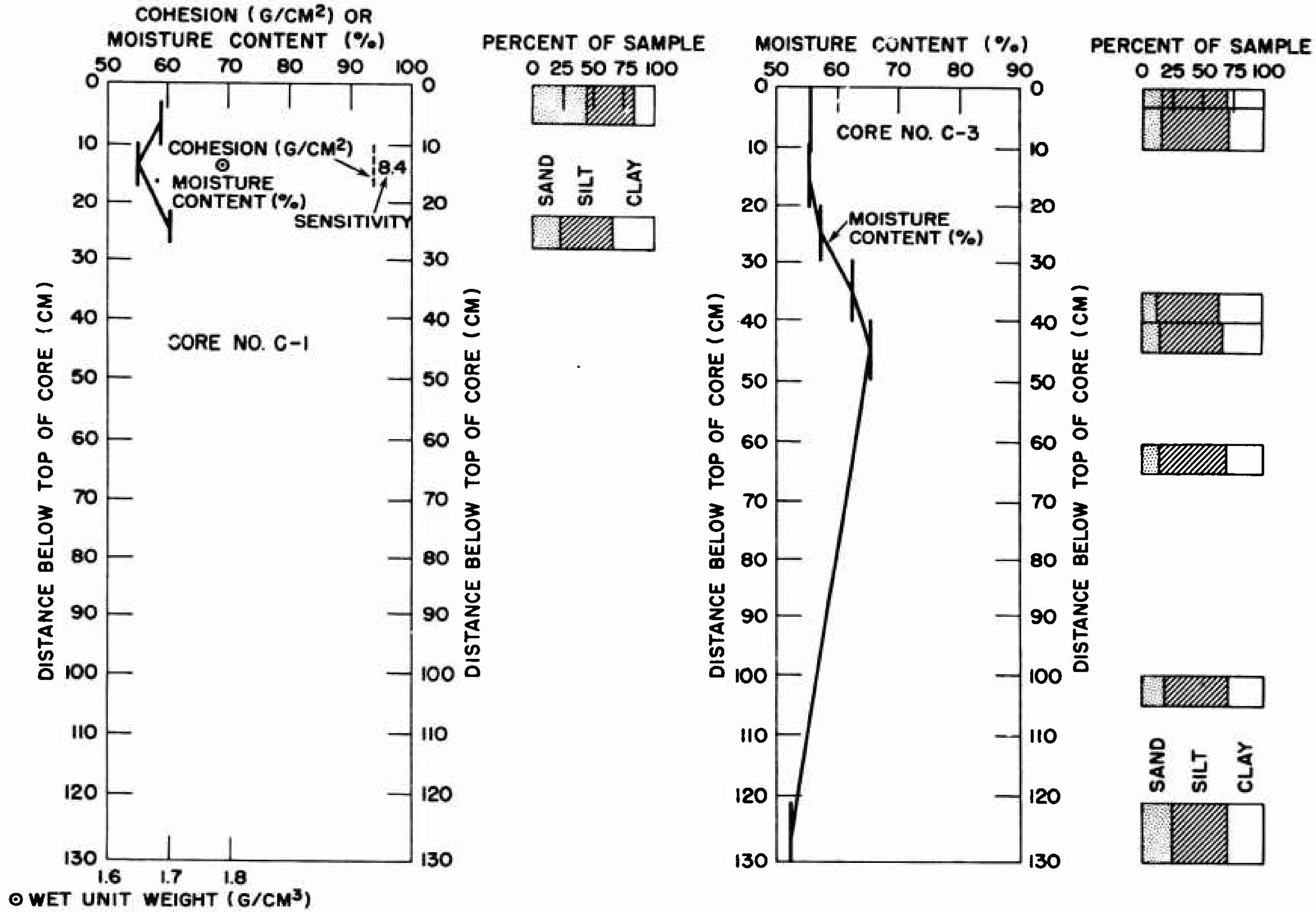

Figure 44. Engineering Properties of Selected Cores.

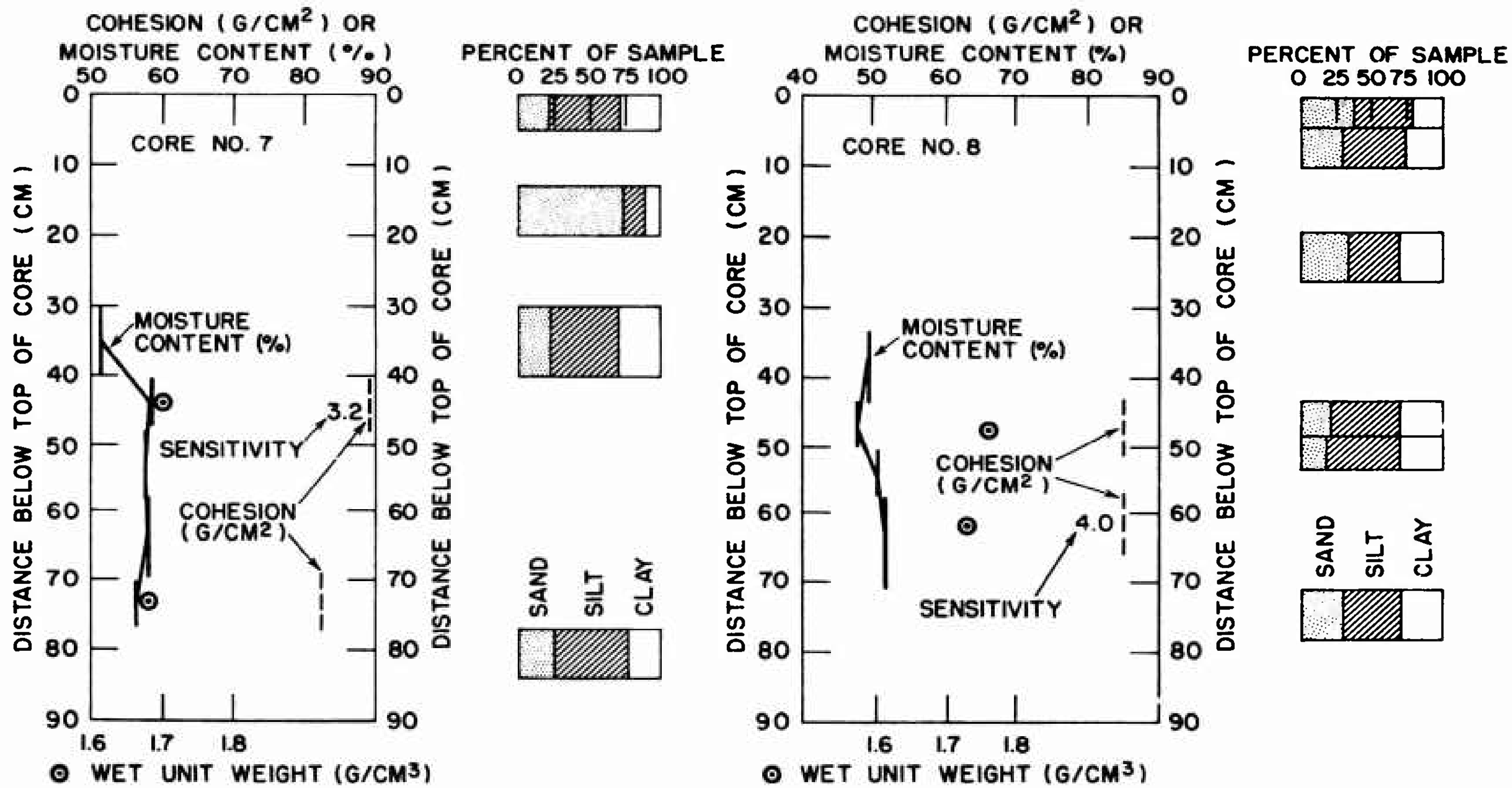

Figure 44b. Engineering Properties of Selected Cores (Cont'd)

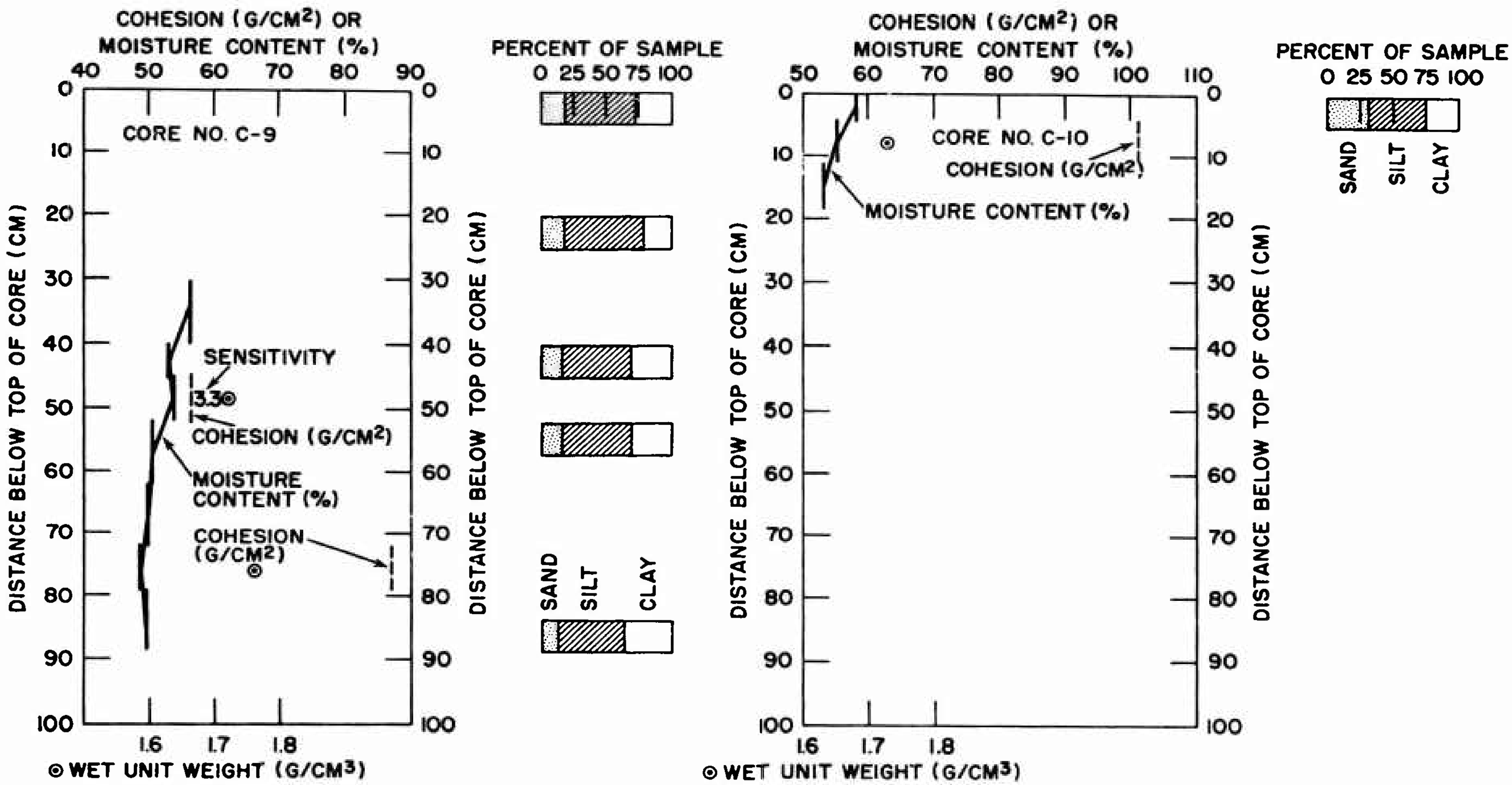

Figure 44c. Engineering Properties of Selected Cores (Cont'd)

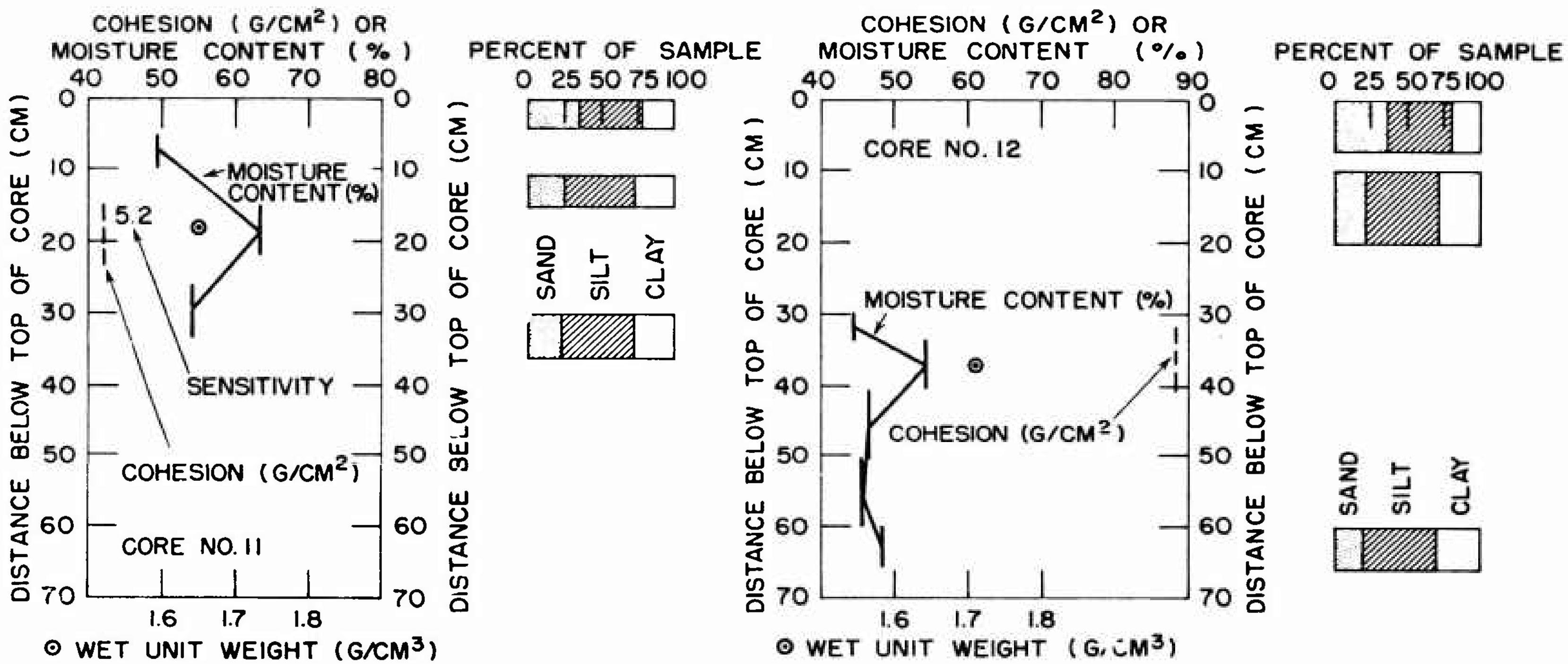

Figure 44d. Engineering Properties of Selected Cores (Cont'd)

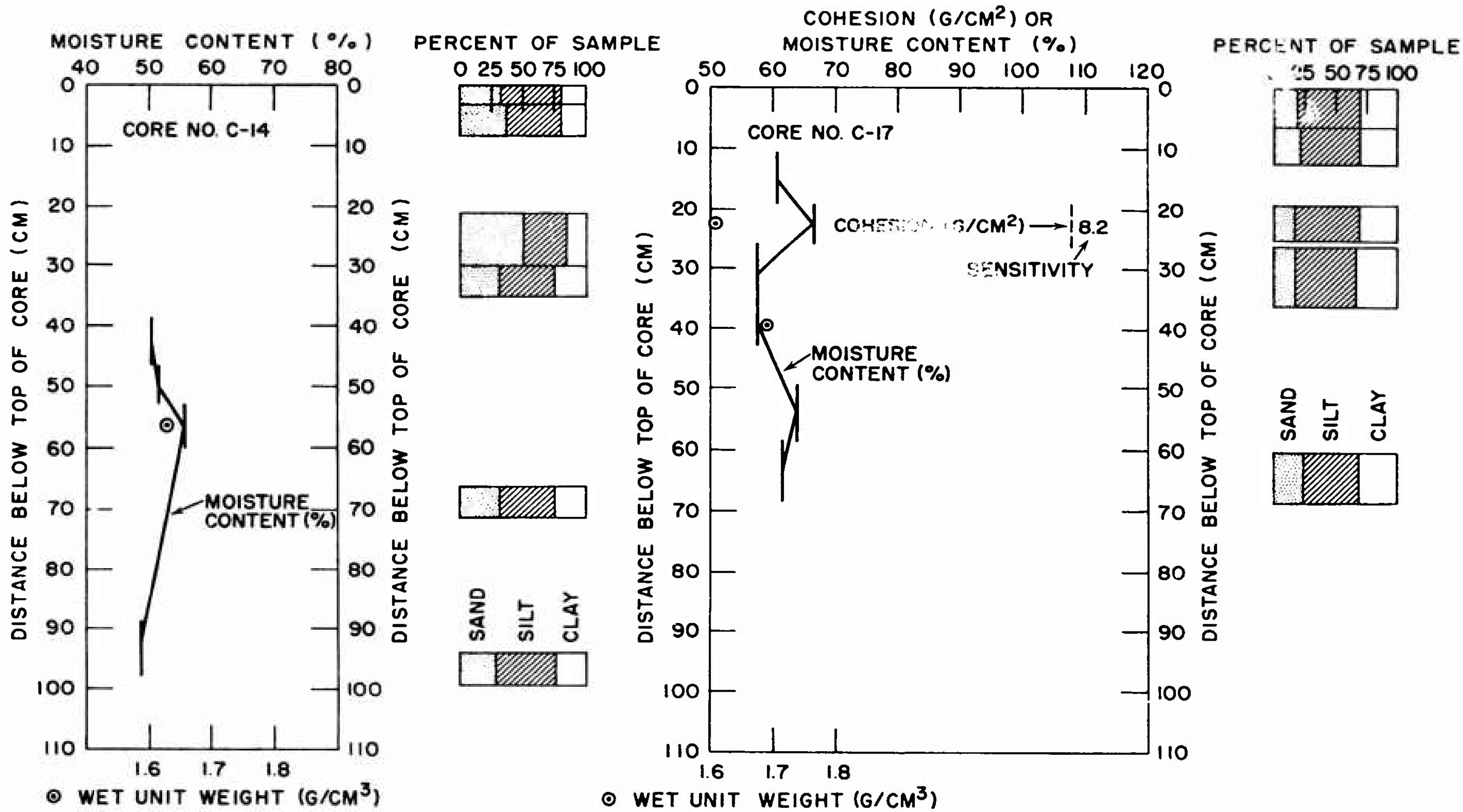

Figure 44e. Engineering Properties of Selected Cores (Cont'd)

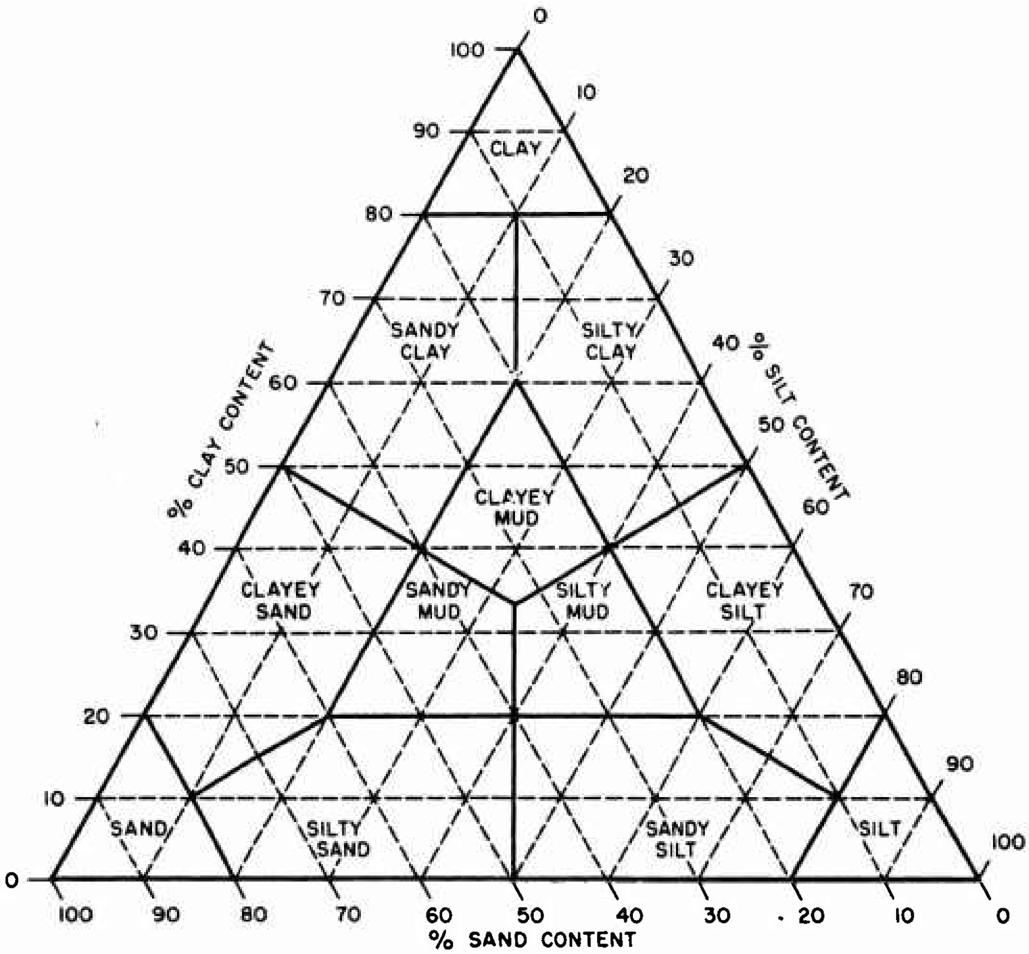

Figure 44f. Nomenclature Based on Sand, Silt, and Clay Ratios

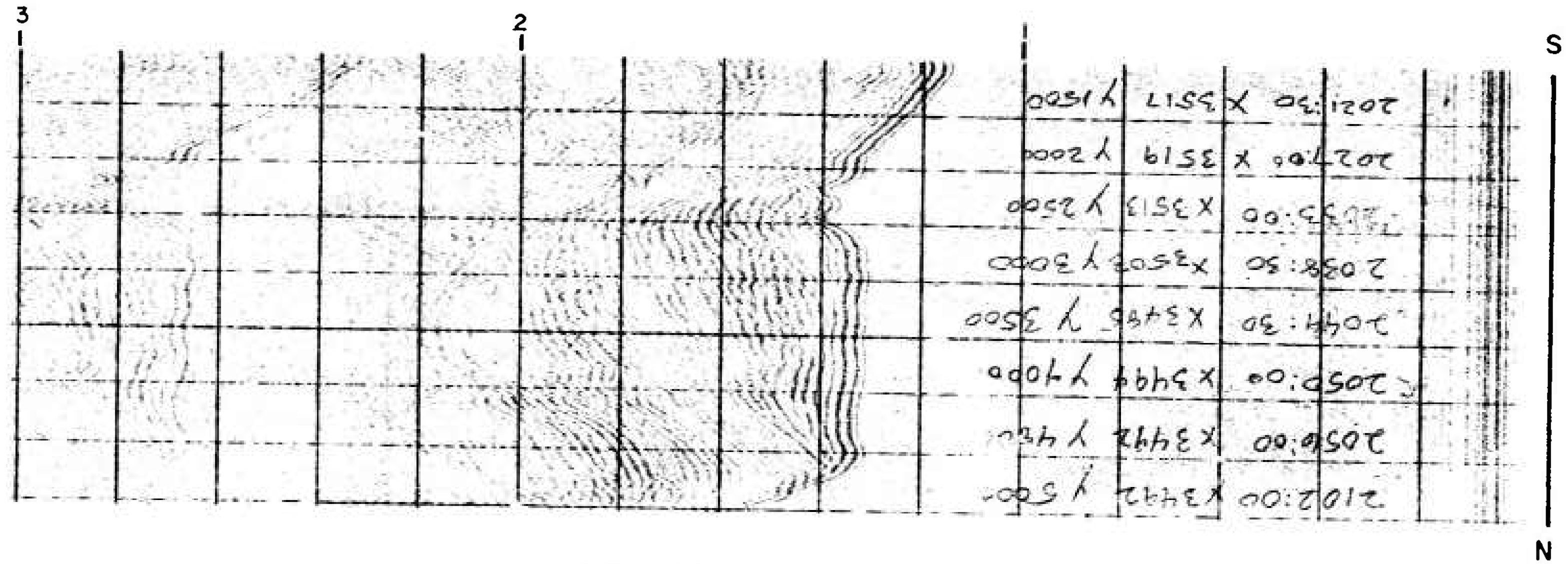

Figure 46. Seismic Section. Line 35N. Compare with geologic section in Figure 49

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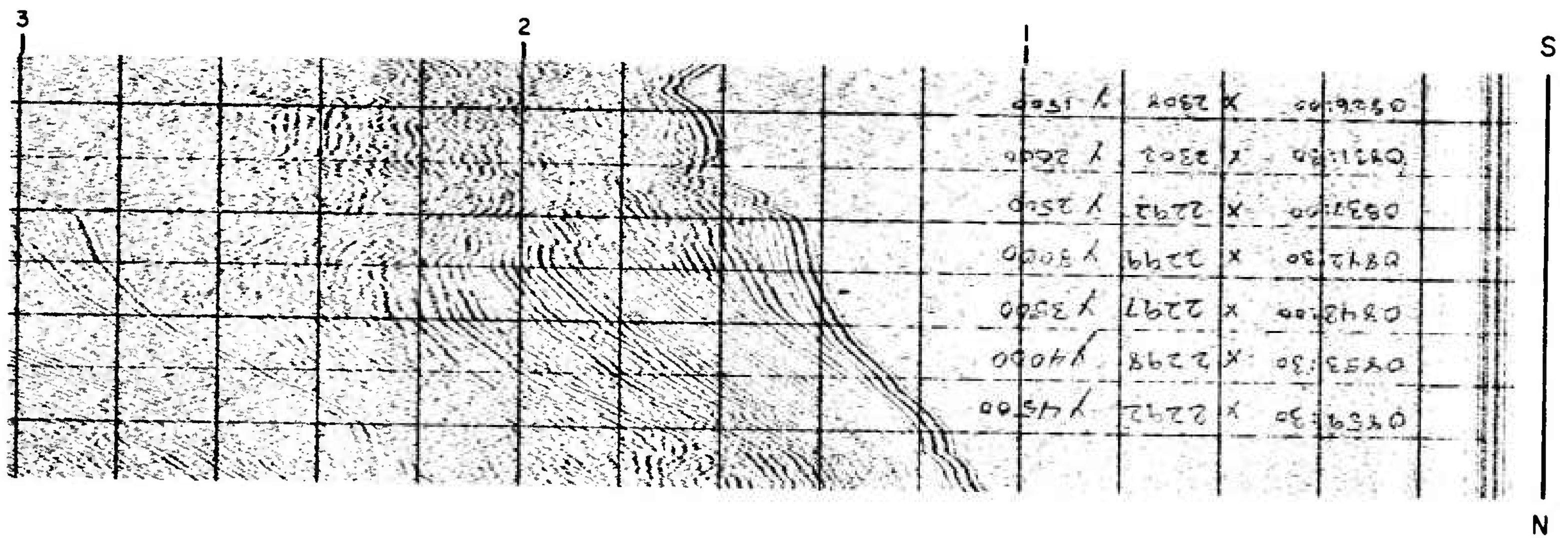

Figure 45 Seismic Section. Line 23N Compare with Figure 49 and note changes in reflective character between Units A. B. and C

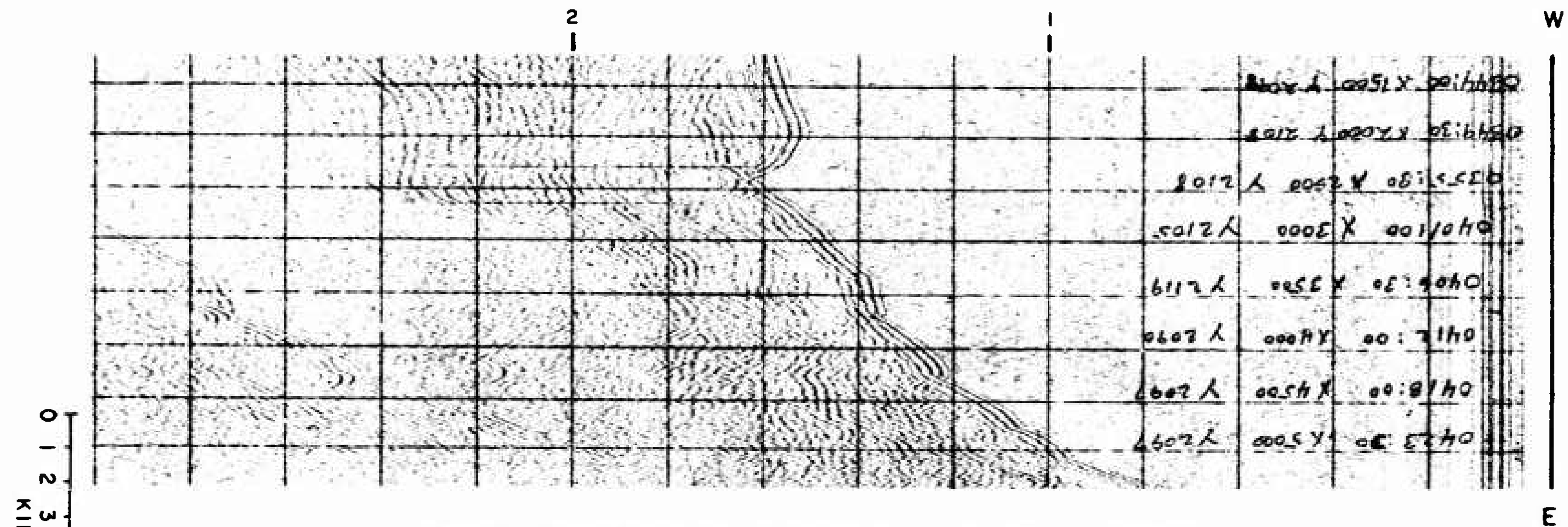

Figure 48. Seismic Section, Line 21E. Compare with geologic sections in Figure 50.

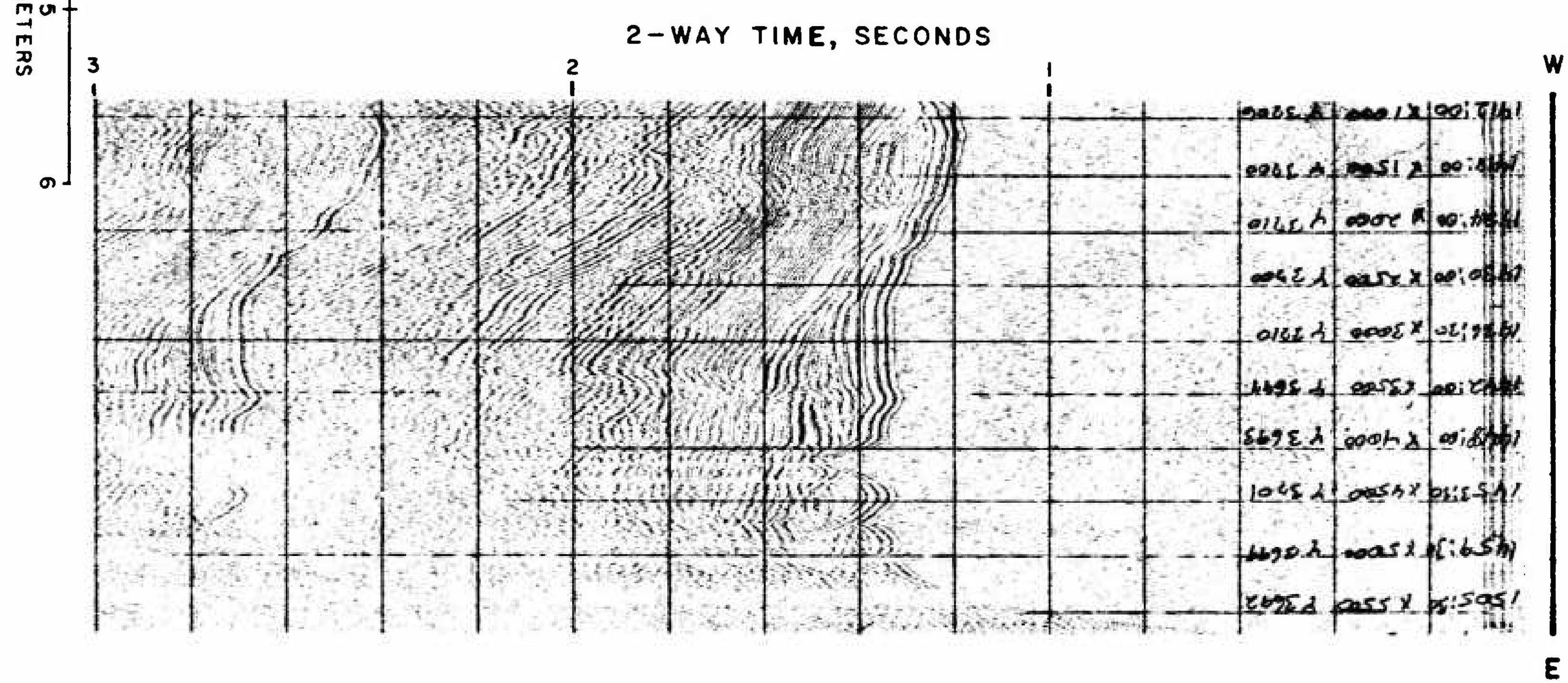

Figure 47. Seismic Section, Line 37E. Compare with geologic sections in Figure 50.

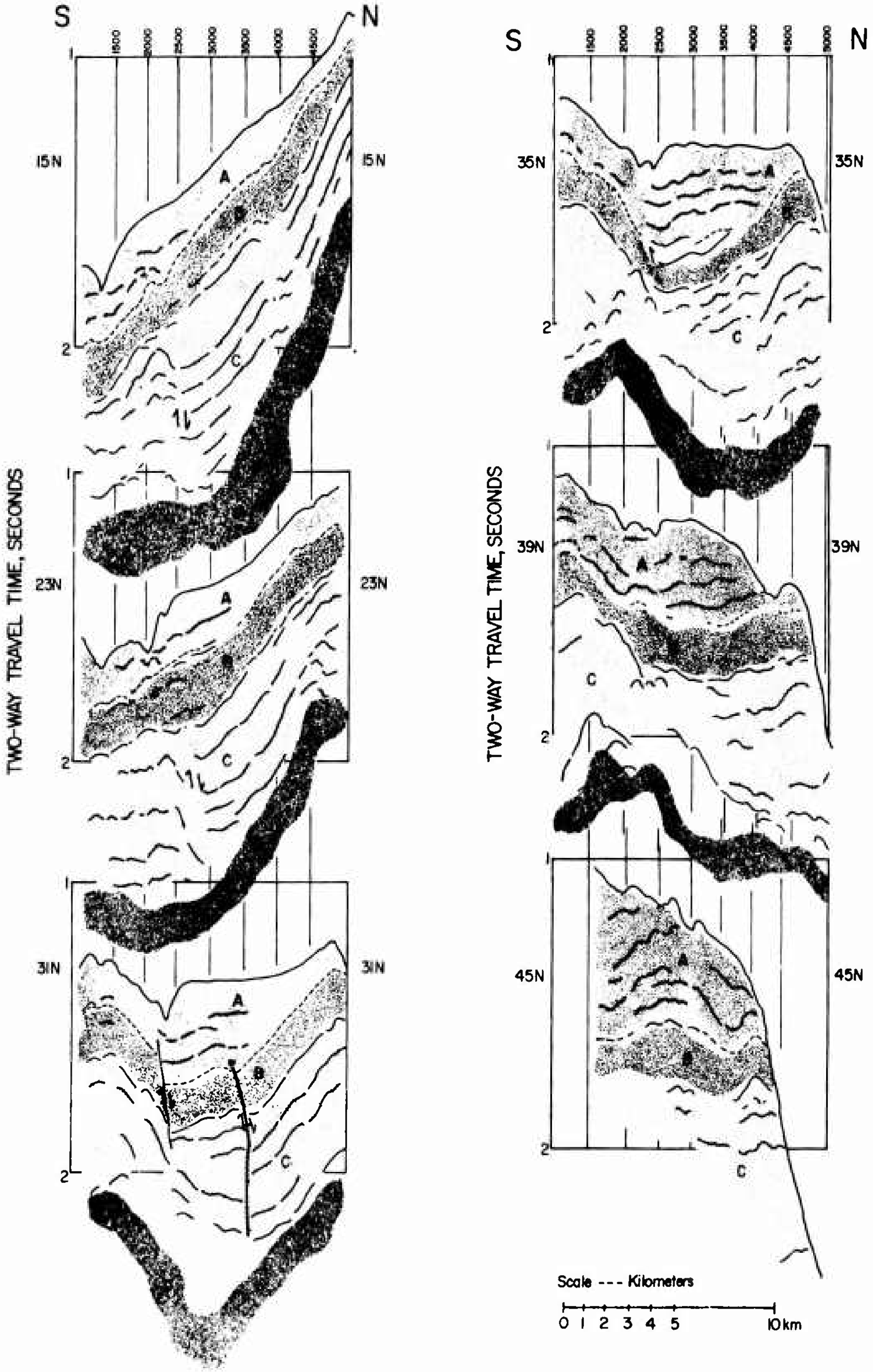

Figure 49 North/South Geologic Cross-sections Made from Seismic Sections. Tracking range coordinates of Y/10 are labeled at the top. Stratigraphic units A, B, C, and D are clearly shown. Note how unit A fills the syncline in sections 23, 31, and 35

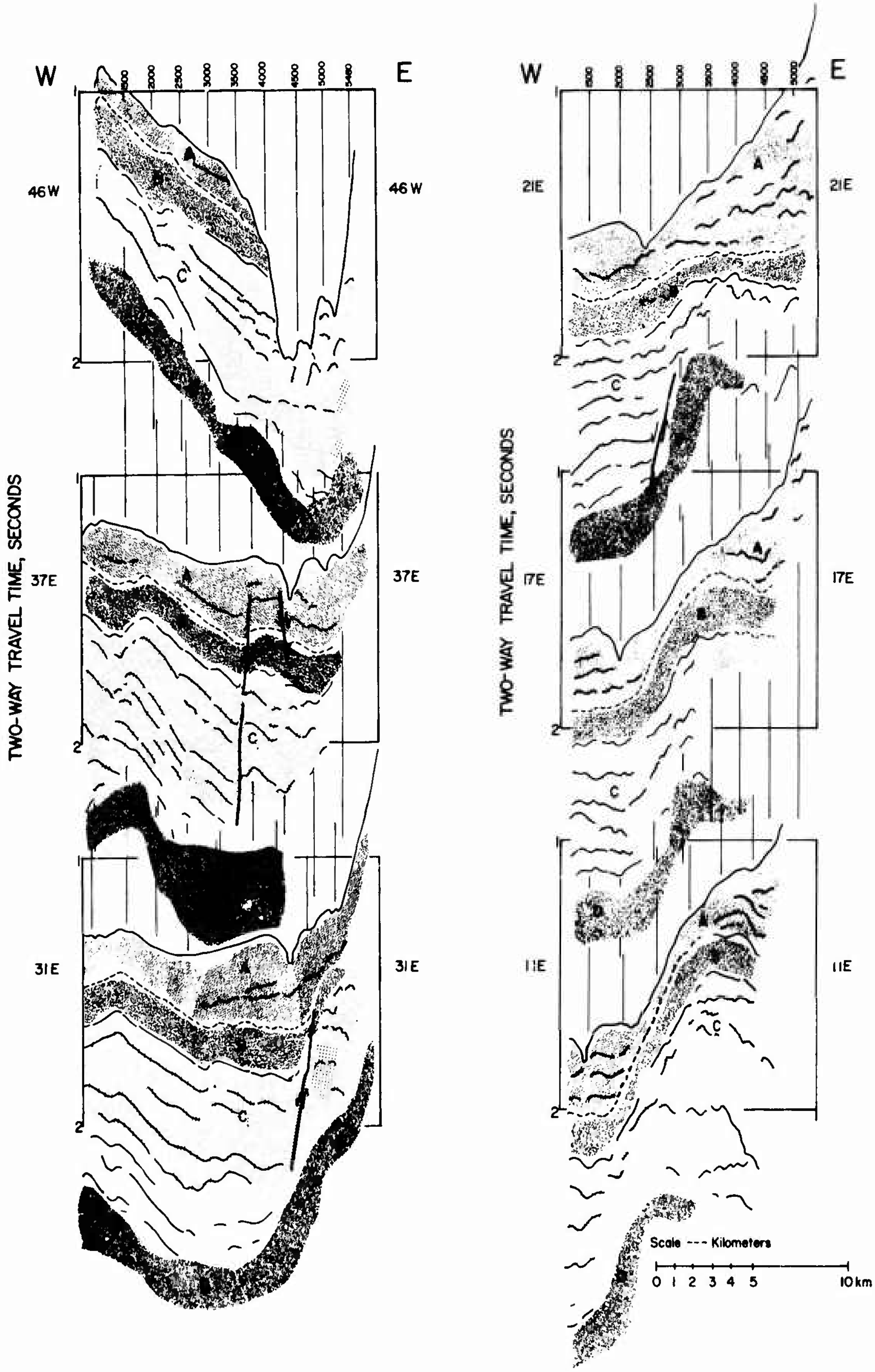

Figure 50. *East/West Geologic Cross-sections Made from Seismic Sections. Tracking range coordinates of X/10 are labeled at the top. Stratigraphic units A, B, C, and D are clearly shown. Note the increased structural disturbance in unit C, and also in unit A, approaching the island slope.*

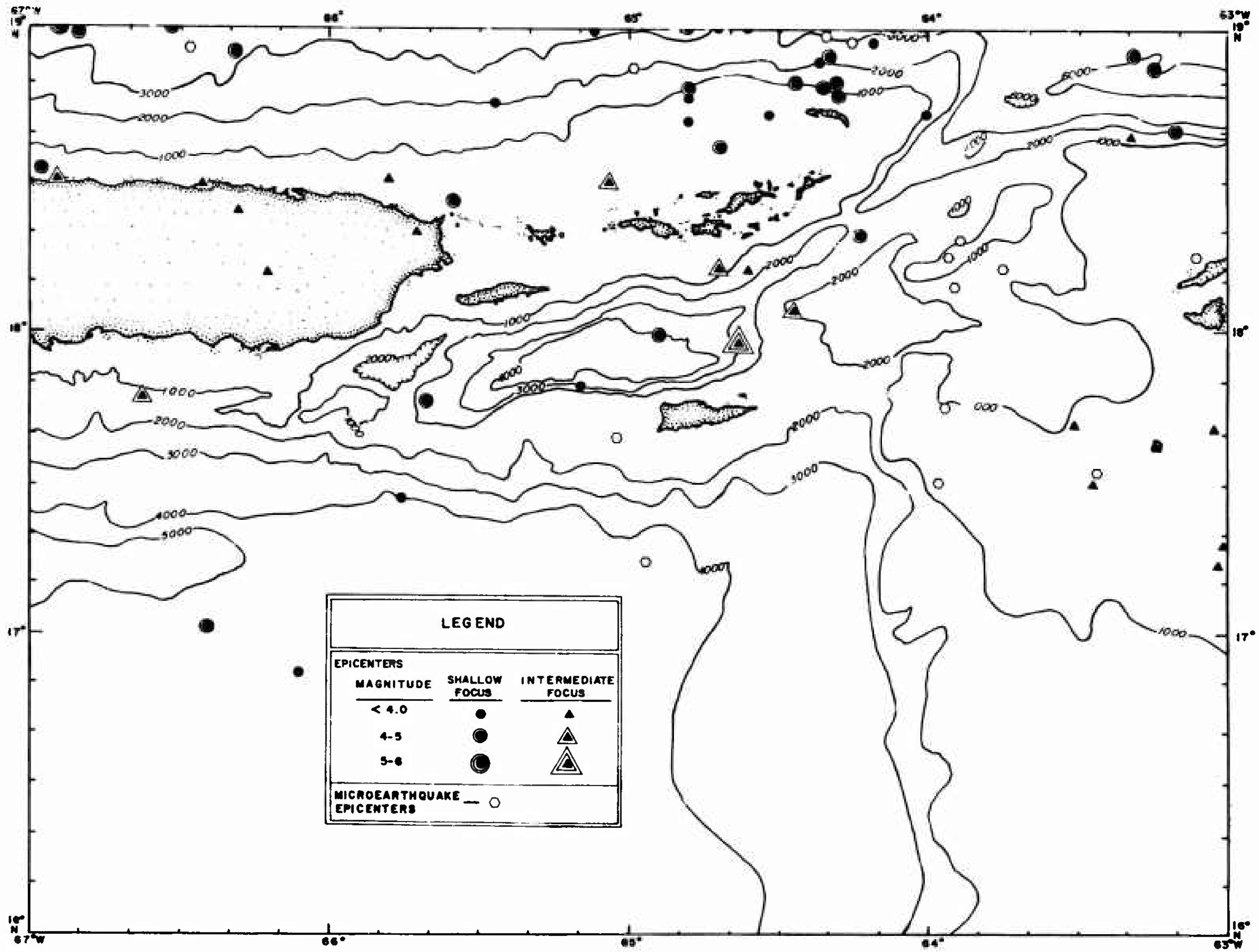

Figure 51. Seismicity of the St. Croix Area. Bathymetry contours are in uncorrected meters. Epicenters are from Sykes and Ewing (1965) for the years 1950-1964 and from the National Earthquake Information Service for the years 1964-1973. The microearthquake epicenters are from a microseismicity study conducted by Murphy et al. (1970).