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THE SEDIMENTARY PROCESSES AND GEOMORPHIC HISTORY OF WRECK SHOAL, AN OYSTER REEF OF THE JAMES RIVER, VIRGINIA

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THE SEDIMENTARY PROCESSES AND GEOMORPHIC HISTORY OF WRECK SHOAL, AN OYSTER REEF OF THE JAMES RIVER, VIRGINIA

A DISSERTATION

PRESENTED TO

The Faculty of the School of Marine Science

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In Partial Fulfillment

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Joseph T. DeAlteris

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APPROVAL SHEET

This dissertation is submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

Wreck Shoal is a subtidal oyster reef area located in the James River, Virginia. Two significantly different types of oyster reefs are found in adjacent areas on Wreck Shoal. Hard-rock reefs are characterized by a relatively thick oyster shell layer, higher densities of live oysters, a coarser interstitial sediment, and a negligible sediment cover. In contrast, mud-shell reefs are characterized by a very thin oyster shell layer, considerably lower densities of live oysters, a finer interstitial sediment, and a 1-2 cm layer of very fine sediments covering the reef.

The contemporary sedimentation processes operating on the hard-rock and mud-shell oyster reefs are distinctly different. The hard-rock oyster reefs are in shallower water, experience stronger bottom currents, and present a hydraulically rougher surface to the flow. The mud-shell oyster reefs are in deeper water, experience weaker bottom currents, and present a hydraulically smoother surface to the flow. These factors result in substantially different bottom shear stresses at the fluid-bed interface. The hard-rock oyster reef, with the high bottom shear stress is rarely depositional with respect to fine sediments. In contrast, the mud-shell oyster reef with the low bottom shear stresses is rarely erosional with respect to fine sediments.

The James River estuary has evolved, moving upstream and landward in response to a rising sea level. The Wreck Shoal oyster reefs have developed on the ridge and swale topography of a point-bar formed during the late Pliestocene Epoch. From the 155Ø's to the 185Ø's the oyster reef developed vertically almost 1.5 m. From the 185Ø's to present the oyster reefs have lost more than 1.Ø m of elevation due to intense harvesting activity. Conceptual models of subtidal oyster reef dynamics and development are proposed and verified based on field observations. The management implications of the results of the study are presented and recommendations are made for the rational exploitation and management of the resource.

THE SEDIMENTARY PROCESSES AND GEOMORPHIC HISTORY OF WRECK SHOAL, AN OYSTER REEF OF THE JAMES RIVER, VIRGINIA

INTRODUCTION

General Statements

An oyster reef is an aggregation of live oysters and empty shells occupying the bottom of an estuary (Galtsoff, 1964). The term is used interchangeably with oyster bottoms, oyster beds, oyster banks, oyster rocks, and oyster grounds. A more liberal definition of an oyster reef is a localized estuarine bottom area inhabited by oysters (Bahr, 1981). The American oyster or Eastern oyster, *Crassostrea virginica* (Gmelin), inhabits the bottoms of Atlantic and Gulf Coast estuaries over a range extending from 20° to 54° North Latitude. Oyster reefs of the American oyster are found in both intertidal and subtidal areas. In general, the oyster reefs in the southern latitudes are intertidal and subtidal in the northern latitudes. This study addresses the subtidal oyster reefs of the James River estuary in Virginia (37° North Latitude). The term oyster reef is used in this study to describe estuarine bottom areas with live oysters and shells in densities ranging from sparse and scattered (10/m^2) to very concentrated (1000/m^2).

On the East Coast of the United States the harvest of oysters has declined markedly during the last half century.

Oyster culturists and biologists have noted siltation as a natural estuarine process contributing to the decline in the production of the oyster reefs (Grave, 1905; Moore, 1910; Churchill, 1920; Gross and Smyth, 1946; Wilson, 1950 a, b; Lund, 1957 a, b, c; Galtsoff, 1964; Haven and Morales-Almo, 1968; and others). Other causes cited for the diminished harvest of oysters during this period include overfishing, disease, biofouling, and pollution. More recently however, MacKenzie (1983) has labeled siltation as the primary cause for the decline in oyster populations based on the in situ observations of SCUBA diving scientists. It is argued that previous investigators, not having the advantage of direct in situ observations, have underestimated the significance of siltation on oyster reefs.

Previous investigators have noted two negative effects of siltation on oyster reefs. The first and most important effect of siltation was that it covered an otherwise clean, hard bottom substrate, reducing the potential area for oyster larvae to strike (attach) thus reducing recruitment. The second effect was that siltation smothered the young spat (small oysters) or if severe, would bury older mature oysters.

The term siltation as used by oyster ecologists refers to the accumulation of fine sands, silts and clays on oyster reefs. Siltation is the result of complex estuarine processes that are not well understood. The overall purpose of this study was to investigate the sedimentary processes and geomorphic development of a subtidal oyster reef so as to provide an understanding of these phenomena. This knowledge is required for the successful management of the oyster resource.

Wreck Shoal is an oyster reef located in the James River estuary, Virginia (Figure 1). The James River is a major tributary of the southern portion of the Chesapeake Bay. The estuary is approximately 80 km long and varies in width from 3 to 10 km. Channel depths range from 6 to 28 m. The Wreck Shoal oyster reef is in the middle of the James River estuary with water depths ranging from 3 to 9 m, and encompasses an area of approximately 8 km^2. Wreck Shoal is a subtidal, drowned river valley estuarine oyster reef, in contrast to the intertidal, lagoonal, bar-built estuarine oyster reefs of the Southeast and Gulf Coasts, and the Eastern Shore of Virginia.

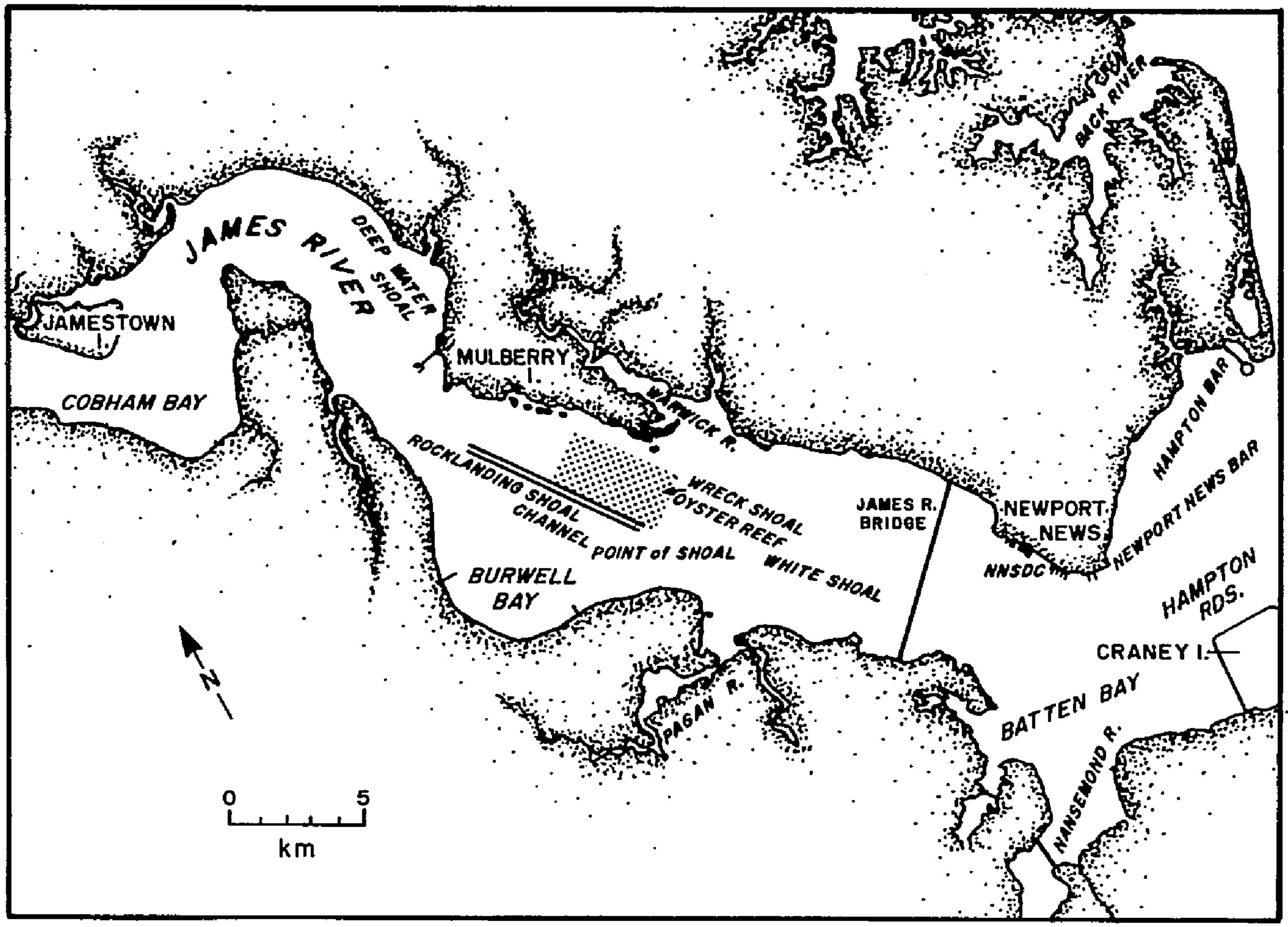
Wreck Shoal was selected for study for several reasons. There were numerous previous studies in the James River on associated subjects: Moore, 1910; Pritchard, 1953; Nichols, 1972 a, b; Larsen, 1974; Johnson, 1976; Haven, Whitcomb and Kendall, 1981; and Peebles, 1984.

Wreck Shoal is also very important to the Virginia oyster industry as a seed oyster reef. At present, 75 percent of the seed oysters used to produce market oysters on leased (private) bottom come from the James River. Leased bottom accounts for about 40 percent of the total Virginia production of market oysters, a decline from

Figure 1

Map of the James River Estuary,
Showing the Wreck Shoal Oyster Reef

JAMES RIVER ESTUARY



about 80 percent of the total Virginia production in the pre-1960's. Wreck Shoal is a major producer of seed oysters. The catch on the James River seed oyster reefs is about 300,000 to 400,000 bushels (1.6-2.1 x 10^{7} l) per year.

The oyster industry of the James River is summarized in detail as part of a review of the entire oyster industry of Virginia in Haven, Hargis and Kendall (1978). At present, the James River oyster reefs produce two classes of oysters for harvest: seed oysters and market oysters.

The seed oyster harvest from the public reefs of the James River consists of rough culled small oysters (1-8 cm) and shell. This product is taken by independent watermen working small boats using shaft tongs and is sold to buy-boats or truckers, who transport the seed oysters to private oyster reefs where it is spread over the bottom to grow to maturity. Seed oysters are primarily harvested in the fall and spring months.

The market oysters are taken from the public reefs in the fall, winter and spring; only oysters that are 7.6 cm or larger can be taken, and these must be clean culled.

To promote the oyster production in the waters of Virginia, the Commonwealth, through the Virginia Marine Resources Commission (VMRC) oyster repletion program, plants oyster shells on the bottom of the estuaries in the spring and early summer to provide a clean substrate for oyster larvae to strike on. This practice is followed in the James

River, and there are several large shell plants inshore and upstream of Wreck Shoal.

Hypothesis

Contemporary sedimentary processes on the Wreck Shoal oyster reef are influenced by supply and removal of sediments to the reef, the estuarine flow over the reef, and the interaction between the flow and the reef. Primary sources of sediments to the oyster reef include the fine suspended sediments transported to the reef by the estuarine flow, and sediments generated by the living organisms of the reef. The strength of the flow over the oyster reef is controlled by tide range, freshwater discharge and the regional and local bathymetry of the estuary. The interaction between the flow and the bottom depends on the stength of the flow and the bottom roughness. The balance between these factors determines the resultant sedimentary character of the reef. Superimposed on these processes is the effect of man's harvesting activity, removing oysters and shells and resuspending fine sediments.

In the geologic time scale, the Wreck Shoal oyster reef is an ephemeral feature. The lower James River is a drowned river valley estuary. It is moving upstream and spreading laterally in response to a rising sea level during the Holocene period. Within the confines of the James River estuary, oysters survive and flourish in a narrow zone that is limited at its extremities by salinity, predation and disease. The oyster reefs of the James river have evolved laterally, along with the estuary, moving upstream and landward in response to a rising sea level. The oyster reefs have also developed vertically due to the deposition of skeletal shells and feces.

Goal and Specific Objectives

The overall goal of this study was to develop a model that accounts for the contemporary sedimentary processes operating on the Wreck Shoal oyster reef, and the geomorphic development of the Wreck Shoal oyster reef and the adjacent areas of the James River estuary. To accomplish this general goal, the following specific objectives were identified:

1. To describe the surficial geomorphic character of the Wreck Shoal oyster reef, in particular to investigate spatial and temporal variability in the geomorphic character of the reef, and to determine if there are significant spatial differences in the character of the reef.
2. To investigate the contemporary hydraulic and sedimentary processes operating on Wreck Shoal, in order to explain the spatial and temporal variability in the geomorphic character of the oyster reef.
3. To study the recent geomorphic history of Wreck Shoal in order to understand the relationship between the contemporary oyster reef morphology and the

development of the oyster reef within the mid-estuary region of the James River.

4. To investigate the Holocene evolution of the James River estuary, particularly in the region of Wreck Shoal, so as to understand the relationship between the long-term development of the river, the estuary, and the contemporary oyster reef morphology.

LITERATURE REVIEW

Oyster Biology and Reef Geomorphology

The American oyster, *Crassostrea virginica*, a bivalve mollusc, is probably the most widely studied species in the estuarine environment. This is primarily due to the relatively high economic value of the animal and secondarily due to the relative convenience of studying a large sessile organism. Unfortunately, because most of the scientific effort in the past has been devoted to the biology of individual animals studied in the laboratory, relatively little is known about oyster ecology, that is, the relationship between individual oysters, the oyster habitat, and the estuarine environment.

Galtsoff (1964), Loosanoff (1965) and Yonge (1960) have published detailed accounts of the biology of the American oyster and are briefly summarized in the sequel. With respect to the environment, the American oyster is very adaptable. It has the ability to survive in water where the salinity and temperature tend to vary greatly. The optimal salinity range is 10 to 28 parts per thousand. The animal can survive temperatures from 0 °C (freezing) to 30 °C. The oyster is a filter feeder, ingesting flagellates, unicellular algae, detritus, silts and clays. Oysters filter the estuarine waters in search of food particles, and absorb calcium carbonate for building a shell that is their means of protection from predators. Food particles are passed along ciliated gills to the mouth and passed to the stomach for digestion. Feces are expelled from the intestine through the anus. When actively feeding, an average 7.6 cm oyster will filter up to 380 liters of water and consume 10 to 20 thousand cells of phytoplankton a day. In the Mid-Atlantic region, oysters begin feeding in early spring and cease in late fall, and generally feed only when the water temperatures are greater than 10 °C.

The reproduction of the American oyster is accomplished by the release of eggs and sperm directly into the water column by the mature adults. Oysters will spawn when the water temperature reaches a favorable temperature, usually about 18°C. Spawning occurs in the Mid-Atlantic region from June to September. Immediately after release, the sperm and eggs mix in the water column and fertilization occurs. The fertilized eggs develop to larvae, and the larvae drift for one to three weeks before "setting" or attaching itself to a suitable substrate where it will develop. The recently attached oysters are referred to as "spat". The substrate material to which the oyster attaches is referred to as "cultch". Traditionally, old oyster shells are planted to collect "spat" in the commercial cultivation of oysters. The juvenile oysters are referred to as "seed". Seed oysters are often collected from the bottom at one to two years of age and are transplanted to grow-out areas where environmental conditions are more favorable for rapid growth and diminished mortality due to disease, predation and overcrowding. Typically, a productive natural or planted oyster reef supports 5ØØ bushels (26,25Ø l) of oysters per acre (Ø.4 h), (McHugh, 1968 and Haven and Morales-Almo, 1966). Oysters survive on the average from four to five years. Mortality on oyster reefs is customarily measured and reported based on the percentage of oyster boxes observed to the sum of live oysters and boxes. An oyster box is an oyster shell pair, with the hinge intact. Mackin (1961) notes that comparisons between the box count method for estimating of mortality and other more efficient methods such as the tray method, year class analysis, and productivity studies indicate a wide disparity in the results. Typically "box counts" indicate mortalities of five to 15 percent on productive oyster reefs. Simple year class analysis of a population that survives only four to five years, with five percent of the original population remaining, requires a mean annual mortality of 5Ø percent. Mackin cites examples from the tray method and productivity studies that confirm substantially higher annual mortalities, on the order of 4Ø to 6Ø percent as compared to the box count method.

The oyster larvae are gregarious in the setting activity; that is, they tend to settle in colonies, forming reefs. Several factors have been identified as causative agents for this activity. Hindu and Haskins (1971) suggest that the oyster larvae positively respond to a water borne pheromone or to metabolites released by oysters that have already metamorphosed. Crisp and Meadows (1963) report that larvae respond positively to a protein on the surface of oyster shells. The formation of reefs or colonies is most important to the survival of the oyster species, in that proximity of the mature adults is required for successful fertilization at spawning.

The oyster reefs of the American oyster have been investigated, classified, and reclassified since the early 1900's. Graves (1905), investigating the oyster reefs of the North Carolina sounds, proposed a method for the origin and growth of oyster reefs. The scheme was based on the observation that the river bottom was soft mud unsuitable for oyster settlement, but along the shore there were always some clean hard surfaces to which oyster larvae could strike. Thus, the oyster reef began along the shoreline, and generation after generation built its way into the river, only to eventually be cut off or isolated from land as a patch on the bottom of the river.

Norris (1953) studied the buried oyster reefs in some Texas bays using probes made of poles and pipes. The results of his investigation suggest that modern reefs retain their narrow surface width at depth. With respect to the depth of the reefs, it was noted that shell dredging operations have shown the reefs to be at least 4 m thick.

Norris concluded his paper by speculating that the cause for the burial of the reefs was mortality of the oysters due to change in the salinity of the bays, thus upsetting the balance between granular sedimentation and oyster reef growth.

Price (1954) noted that not all oyster beds correspond to Graves' description. He proposed that longitudinal reefs are formed with their long axes parallel to channels, and that these are associated with river valleys cut during the late Pliestocene low sea level stage. The reefs developed on the stable and slightly elevated natural levees, as the valleys were flooded.

Price (1968), summarizing the existing information at that time on the geomorphology of oyster reefs stated that the oyster communities consist of scattered clusters, densely populated beds, elevated patch reefs ("tow heads"), tabular bodies ("bottoms"), and oval to linear reefs ("bars", "banks"). While Price noted that oyster reefs range from the intertidal zone to 15 m in depths, no correlation was made between reef type and water depth.

Stenzel (1971) described oyster reefs as natural accumulations of oyster shells, dead or alive, that rise above the general level of the substratum. The oyster reefs are then classified on the basis of their configuration and the independence of the configuration from the nearest shoreline. Fringe reefs are parallel to the shore, and are common in drowned river estuaries, on the flank of the main channel axis. Stenzel noted the oyster reefs of Tangier Sound in Chesapeake Bay as an example of fringe reefs. String reefs are described as having narrow crests, which may be exposed at low water. Most string reefs are at right angles to the nearest shore as noted by Grave (1905). They are normal to the direction of the tidal currents. The intertidal oyster reefs of the Gulf Coast region are typical examples of string reefs. Patch reefs grown far from shore and have irregular but compact outlines. Patch reefs are exclusively subtidal, and are exemplified by the Helogoland oyster reef in the North Sea.

Bouma (1976) investigated the structure of the oyster reefs of San Antonio Bay, Texas, using electronic sub-bottom profiling techniques and borings. Based on the results of their detailed data collection effort, both the live surface reefs and the fossil subsurface reefs were identified. Bouma concluded that the oyster reefs started to develop in the deepest portions when sea level was low, and that most of the present reefs are located in areas where fossil reefs originally formed, in that, these dead reefs provided the most favorable stratum for new growth. In one case, the roots of an oyster reef were found to extend to a depth of 20 m below present sea level. In Hynes Bay, the growth of the oyster reefs had ceased, and it was proposed that this was due to changes in the salinity and granular sedimentation rates.

Recent interdisciplinary investigations of the ecology of the oyster reefs, in contrast to the focused studies of biologists and geomorphologists, have shed new light on the dynamics, structure and evolution of oyster reefs. Based on gross ecological considerations, there appear to be two distinctly different types of reefs formed by the American oyster. There are the shallow, intertidal oyster reefs, ranging from the Mid-Atlantic to the Gulf Coast regions. These reefs are usually located in bar-built, relatively higher salinity estuaries. In contrast, there are the subtidal oyster reefs associated with drowned river valley estuaries of the Mid-Atlantic to New England regions. Typically, these oyster reefs are located in the lower to middle salinity range of the estuary. The factors influencing the distribution of the principal types of oyster reefs are probably tidal range, salinity, predators, disease, and temperature.

Grinnell (1971), Bahr (1974) and Bahr and Lanier (1981) report on the results of detailed investigations of the ecology of intertidal oyster reefs in the South Atlantic region. Models of reef development and community energetics are presented, and the role of the oyster reef in the estuarine ecosystem is discussed. Because of the relative difficulty of investigating subtidal oyster reefs, this type of analysis has yet to be accomplished for subtidal oyster reefs. The results of the study described herein will address certain aspects of subtidal oyster reef development and dynamics from a biological, physical and geological sense.

Estuarine Circulation and Sedimentation Processes

An estuary is defined as a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage (Pritchard, 1967). Estuaries have been classified according to the mode of the basin formation, the dominant driving mechanism (wind, tide, or fluvial discharge), and the characteristic circulation pattern (Schubel, 1963). Based on the modes of formation, Pritchard (1967) distinguished between estuaries formed in drowned river valleys, and fjords, bar-built estuaries, and estuaries produced by tectonic processes. Drowned river valley estuaries are generally relatively shallow with gently sloping bottoms. The cross section is commonly V-shaped, and the water depth increases uniformly toward the mouth of the estuary. The balance between the magnitude of the tidal forces and amount of fresh water input determines the degree of mixing between the fresh and salt waters. Based on these dynamic considerations, coastal plain estuaries were classified into four types (Pritchard, 1955 and Cameron and Pritchard, 1963).

The circulation patterns for the class of drowned river valley estuaries were described by Pritchard and Carter (1971), based on river flow, tidal velocities, and the physical geography of the basin. This classification scheme identified the following types of estuaries:

1. Type A Estuary - Salt Wedge. This estuary is characterized by high river discharge, negligible tide, little or no wind. The estuary is highly stratified. In the upper layer, fresh river water discharges seaward, progressively increasing in salinity due to the upward mixing of salt water from the sea in the lower layer. The lower layer penetrating upstream under the upper layer, retains its original salinity because at the interface, mixing is only upward.
2. Type B Estuary - Partially Mixed. In this estuary, the tide becomes an effective mixing mechanism, erasing the salt-wedge. Not only is salt water mixed upward, but fresh water is mixed downward. The resultant circulation pattern is that the net outward flow in the upper layer is at least an order of magnitude greater than the river discharge. Likewise, the inward flow in the bottom layer must balance this.
3. Type C Estuary - Vertically Homogeneous. This is a well mixed estuary. Tidal velocities are further increased, and if the estuary is wide enough, the interface between the fresh and salt water is entirely erased so that the water becomes vertically homogeneous. The longitudinal gradient

in the salinity remains with salinity increasing seaward.

4. Type D Estuary - Sectionally Homogeneous. In this estuary, the salinity is homogeneous both laterally and vertically. Tidal flow is so large that it overwhelms the effect of river flow.

Pritchard (1967) proposed that drowned river valley estuaries follow a developmental sequence from Type A to Type C or D. The factors controlling this development include the initial basin geometry, the rate of sea level rise, the tidal input and the sediment input from the fluvial drainage basin. The time scale for the development of the estuary is thousands of years.

In the short-term, the physical limits of an estuary include the landward boundaries in the lateral direction, and the upstream limit of salt water penetration and the open sea in the longitudinal direction. As the estuary develops according to the sequence described by Pritchard, the geographic limits of the estuary move upstream predominantly in response to the rising sea level.

The sedimentary processes of estuaries have been the subject of intense investigation during the last twenty-five years, based on the description of estuarine circulation developed by Pritchard. Comprehensive reviews of the investigations are found in McDonnell and O'Conner (1977) and Nichols and Biggs (1984). Selected aspects of estuarine sedimentation and circulation processes, as applicable to this study, are presented in the sequel.

The sources of sediments to estuaries include the sea or estuary mouth, the fluvial discharge, the erosion of the estuarine shoreline, the reworking of existing sediments in the estuarine system, and the sediments produced by the biological activity in the estuary (Schubel, 1971b). The longitudinal distribution of sediments from the estuary mouth and river discharge is controlled by the estuarine gravitational circulation (Meade, 1969 and 1972). A result of the dynamic circulation is the turbidity maximum that occurs in the middle to upper portion of partially mixed estuaries. In this area of the estuary, concentrations of suspended sediments are 1Ø to 1ØØ times greater than those either in the river or further seaward in the estuary (Nichols and Poor, 1967). The processes controlling a turbidity maximum are primarily the gravitational circulation, in which suspended particles moving seaward in the upper portion of the water column in the mid to lower reaches of an estuary, sink and are carried upstream in the lower portion of the water column. Another process cited as also contributing to the turbidity maximum, is the resuspension of bottom sediments by tidal currents in the vicinity of the null zone for bottom sediment deposition and bottom water circulation (Officer and Nichols, 1983).

The reworking of existing estuarine granular sediments and the transport of non-cohesive sediments eroded from the estuary shoreline is a classical sediment transport problem for erosion of the bed, transportation and deposition on the bed. The details of these processes are different for non-cohesive and cohesive sediments. The investigations and analyses of non-cohesive sediment transport processes in fluvial and coastal areas are summarized by Graf (1971), Bagnold (1963 and 1966) and Sternberg (1967, 1968 and 1972).

Cohesive sediments or estuarine muds are more complex in their structure and therefore more difficult to investigate and understand. These sediments are platy and very small with a large surface area to mass ratio. The cohesion results from interparticle attractions between the constituent clay minerals, and makes the bed sediment more resistant to erosion than a fine non-cohesive sediment. The mechanics of cohesive sediment erosion, transport, and deposition has been investigated and reported on by Krone (1962 and 1978), Partheniades (1962 and 1971) and more recently by Mehta (1973 and in preparation).

On a localized basis, the estuarine sedimentation processes are a function of the interaction between the near bed fluid and the estuary bottom. The movement of the fluid over the bottom produces on a drag force on the bed surface, referred to as the shear stress. Because the fluid at the bed surface has no motion, and the fluid overhead is moving, a vertical velocity profile develops. The amount of the shearing force is related to roughness of the bed and the free stream velocity.

The erosion of cohesive bottom sediments can occur only after the interparticle bonds are broken. The hydraulic shear stress at the bed must therefore exceed a critical shear stress of erosion for the cohesive bed before erosion takes place. The resistance of a cohesive bed to erosion by flowing water depends on many factors: the types of clay minerals that constitute the bed, the chemical compositon of the pore and eroding fluids, and the stress history of the bed. At bed shear stresses above critical, erosion begins particle by particle and this process is referred to as surface erosion. At higher levels of stress, the bulk shear stress of the bed may be exceeded, and mass erosion occurs. The critical shear stress for erosion of many different types of estuarine cohesive sediments have been determined in laboratory studies, and these vary from 0.3-0.6 N/m^2 (Parchure and Mehta, 1983).

The deposition of cohesive sediment particles occurs when the bottom shear stress is not sufficient to resuspend particles that contact and bond with the bed. The shear stress at which there is an incipient net rate of deposition is referred to as the critical shear stress for deposition. This value is less than the critical shear stress for erosion, and ranges between 0.04 and 0.15 N/m^2 (Mehta, in preparation).

The bottom boundary shear stress for steady, uniform, turbulent open channel flow can be determined from the velocity profile. The von Karman-Prandtl velocity profile equation relates the mean velocity at a given distance from the boundary to the boundary shear stress. By measuring the near-bed velocity profile, the bottom shear stress can be calculated. For steady-turbulent flows, the Quadratic Shear Stress Law relates the boundary shear stress to the fluid density and the square of the mean free stream velocity or the velocity at other levels with a constant of proportionality, the drag coefficient. Investigations in laboratory (Nikuradse, 1933) and field studies in estuaries (Sternberg, 1968), have shown that for hydrodynamically rough flows, the drag coefficient assumes a constant value related to the bed configuration. Under these conditions, the bottom boundary shear stress can be determined from the free stream velocity or the velocity at other levels and the characteristic drag coefficient.

Tidal flow in an estuary of complex basin geometry such as the James River, presents many problems that must be addressed when considering the application of the "Law of the Wall", or the logarithmic velocity profile to the interaction between the near bed flow and the bottom. Soulsby and Dyer (1981) note that the most significant of these problems is that tidal flow is not steady, and therefore the near bed velocity profile departs from the usual logarithmic form. The amount of the departure may not necessarily be large, but is important when the profiles are used to calculate the bed roughness length and shear stress. An acceleration parameter is proposed, that can be used as a measure of the steadiness of the flow. A limiting value is proposed for this parameter to define near steady flow.

Soulsby (1983) further notes that the flow in an estuary is stratified, and probably non-uniform, both of which will also result in departures from the logarithmic velocity profile. When estuarine tidal current velocities are near maximum, the accelerations are near minimum. Likewise, the velocity profile has had the greatest amount of time to develop, and the effects of density stratification should be minimal due to increased mixing.

Biodeposition is the process whereby feces or pseudofeces are deposited on the bottom by filter feeding benthic organisms as they remove particulate matter from suspension in the water column. The sedimentation caused by this biodeposition in the estuarine environment has been well documented in the literature. Lynch and Harrison (1970) made direct measurement of changes in bottom elevation in the York River, caused by the tube-building amphipods, Ampelisca abdita. The total increase in bottom elevation was 108 mm, and the maximum rate of increase was 39 mm per week. With respect to oysters, Ito and Imal (1955) determined that in Japanese waters, a single raft of oysters 60 m^2 will deposit 0.6 to 1.0 metric tons (by weight) of fecal material per year. For Texas waters, Lund (1957) calculated that if oysters were densely grown in a one acre plot (0.4 h), 7.6 metric tons of material would be removed from the water in 11 days. Haven and Morales-Almo (1966), using fluorescent particles fed to oysters to label their feces and pseudofeces, were able to trace the incorporation of the biodeposits into the estuarine sediments. In a detailed laboratory study on aspects of biodeposition by oysters and invertebrate filter feeders typical of an oyster reef, Haven and Morales-Almo (1968) found that the production of feces and pseudofeces varied with season, peaking in September. The character of the biodeposits was 77-91 percent inorganic matter, mostly illite, chlorite, and mixed layer clays, and 4-12 percent organic carbon. Of the particles composing the biodeposits, 95 percent were under 3 microns in diameter, resulting in the conclusion that biodeposition may be important in initiating the sedimentation of these very fine particles. In a follow up to the previous study, Haven and Morales-Almo (1967) found that, at a single station in 9 m of water, in the White Shoals area of the James River, recognizable fecal pellets formed an average of 0.42 percent by weight of the total suspended solids at 1 m above the bottom and 0.14 percent by weight at 1 m below the surface during a 24 hour sampling period. Pellets retained on soil analysis sieves (mesh sizes 125 and 44 microns) however, were an average of 26.6 and 19.2 percent by weight, respectively, of the materials retained on the screens at the same depths. The conclusion drawn from these observations was that the pellets were being carried in suspension, and that biodeposits can be resuspended and redistributed by estuarine currents. The redeposition of this fecal material could alter the textural and chemical character of the sediments. In 1972, Haven and Morales-Almo summarized the results of their previous investigations in biodeposition and noted that the process of biodeposition must be considered as a significant factor in the future studies of the sedimentation of fine suspended solids in estuaries.

More recent research on the effects of biodeposition has been published by investigators from the University of Washington. Nowell, Jumars, and Eckman (1981) in laboratory flume studies, found that ambient or "free" sediment were more easily entrained than fecal mounds which were restrained from movement by mucous adhesion between the fecal coils. Isolated pellets were easily transported as bed load over a cohesive sediment surface.

James River

The first published survey of the oyster reefs of the James River was the effort, in 1878, of Lieut. Francis Winslow of the U.S. Navy, in command of the Coast and Geodetic Survey Schooner, Palmuries. The result of the investigation was a chart and text that delineated the general outline of the oyster bearing areas of the James River with a general description. A later investigation of the public oyster grounds of the James River was conducted by Mr. J.B. Baylor, of the Coast and Geodetic Survey, under the authority of the Commonwealth of Virginia in 1892. The purpose of the Baylor Survey was the delineation of boundaries of the public oyster grounds. These areas included recognized or reputed oyster bearing bottom, as noted by local authorities and barren bottom for further cultivation. No examinations were made of the oyster reefs.

In 1910, Moore published the results of a detailed investigation of the James River oyster reefs entitled, "The Condition and Extent of the Oyster Beds of the James River, Virginia". In this study, the oyster reefs within the public grounds were mapped by sounding with a lead line and by dragging a length of chain, attached to the sounding vessel with a copper wire, over the bottom. Whenever the chain touched a shell or an oyster, the shock or vibration was transmitted up the wire to the operator who recorded the information. To supplement this data, grabs were taken with oyster tongs on selected oyster reefs, to provide data on oyster density, size, distribution, and bottom type. The results of this study provided the management authorities with the first reliable data on the status and potential of the oyster reefs of the James River in 1910.

Marshall (1954) investigated the changes in the physiography of the oyster bars along selected transects in the James River. By comparing the depth observations from the Coast and Geodetic Study for the periods 1854-1855 and 1943-1948, and considering a sea level rise of 17 cm, Marshall found a mean loss of about 30 cm in the elevation of the oyster bars. From this, he concluded that the oyster bars were a dynamic changing form in response to environmental factors both natural and fishing related.

In 1981, Haven, Whitcomb, and Kendall reported on the results of an extensive three year survey of the present and future productivity of the Baylor Grounds in Virginia. Further analysis of the results of that report lead to the detailed account of the origin and extent of the oyster reefs in the James River (Haven and Whitcomb, 1983). In classifying the subtidal oyster reefs of the James River according to shape and orientation, the authors adopted the system previously exclusively applied to the intertidal oyter reef of the South Atlantic and Gulf Coast regions (Graves, 1905; Price, 1954; and Scott, 1968). The estuary bottom was classified into a consolidated oyster reef, mud-shell and sand-shell bottoms and other bottom unsuitable for oyster cultivation.

A detailed study of the macrofauna of the James River oyster reefs was conducted by Larsen in 1974, in which eight sites in the lower river represented the range of productive natural oyster reefs. Sampling was undertaken with a suction sampler, and all sites were sampled quarterly for one year. Based on the analysis of the samples taken, Larsen determined that the oyster reef assemblage appears to be one manifestation of a larger estuarine assemblage. The difference between it and the soft bottom assemblage is principally in the density characteristics and the reason for the higher densities in the oyster reef is the shell surfaces that provide the additional surface area. The variation in the faunistic data were related to season and the estuarine gradient between the sites.

An investigation of the sediments of the entire James River was made in the 1960's, with the procedural details and methods described in Moncure and Nichols (1968) and the results and conclusions described by Nichols (1972). According to Nichols, the James River estuary is a drowned river valley. The floor of the estuary consists of a central channel flanked by submerged shoals. Suspended sediment is transported mainly by alternating tidal currents and secondarily by the net nontidal estuarine circulation. Transport results in a sequence of grain size distributions reflecting the mixing of the two textural end members, sand and clay. The sediments in the middle estuary, the location of the Wreck Shoal study area, are classed as transitional type sediments, a mixture of sand, silt, and clay, with the possible addition of biogenic materials as oyster shells and fecal pellets that are mixed into the sediments by currents, waves, and organisms. The actual bottom sediment type on Wreck Shoal is noted to vary widely according to the local relief, intensity of environmental processes and rate of material supply from different sources. Deposition was found to be greatest in the middle estuary where salinity ranged from five to 14 parts per thousand.

Feuillet and Fleischer (1979) studied the clay mineral distribution of the James River and found that the estuarine circulation dynamics exerted the dominant influence controlling that distribution. Two characteristic clay suites were found in the James River estuary. The James River clay suite is kaolinite-illite-dioctahedral vermiculite and the Chesapeake Bay entrance suite is a illite-chlorite-montmorillonite suite.

Cutshall, Larsen and Nichols (1981) investigated the sedimentation rates in the James River using man-made radio-nuclides and the pesticide Kepone buried in the sediments. In the Wreck Shoal region of the James River estuary, sedimentation rates varied from less than 1 cm/yr on the relatively shallow oyster reefs to 8 to 10 cm/yr in the mud channel of Burwell Bay. Wong and May (1984) confirmed these sedimentation rates using a Cesium-137 geochronology.

The late Cenozoic geologic history of the area surrounding the James River estuary has been developed in a series of recent reports by Peebles (1984), Peebles, Johnson and Berquist (1984) and Johnson and Peebles, (1985). A depositional model is used to account for the stratigraphic sequences which accumulate during a marine transgression across the dissected coastal plain of southeastern Virginia. The model is applied to three mid to late Pliestocene formations that record three sea level oscillations respectively. This work builds on the basic geology of the region described by Johnson (1976) and Oaks and Coch (1973). The regional stratigraphic sequence includes Pliestocene sediments deposited in lagoonal, estuarine and barrier environments and Pliocene sediments (Yorktown, Chowan River and Bacons Castle Formations) deposited under marine conditions.

The general hydrography of the James River has been investigated in the field and with the use of numerical and physical models. Pritchard and Kent (1953) conducted a field investigation of the currents and salinity structure of the James River during the summer of 1950. Based on his analysis of this data, Pritchard (1952, 1954, 1955, 1956, and 1967) formulated the now classical descriptions of the circulation and salt balance in a coastal plain estuary, described in the previous section.

The James River is a type B, partially mixed, drowned river valley estuary. The principal characteristic of this type of estuary is that the dominant mixing agent is turbulence caused by tidal action. There is a net seaward flow in the upper layer that is about 20 times larger compared with the river flow itself. To balance this, there is a net inflow of more saline water along the bottom that is about 19 times larger than the river flow. Because of the earth's rotation, in the wide portions of the estuary there is a slight lateral salinity gradient. Thus, in the salt balance equation for the James River, the horizontal advective flux and the vertical diffusion of salt are the more important terms.

In the mid 1960's, an intensive field investigation of the physical and biological properties of the James River was conducted by Virginia Institute of Marine Science (VIMS) for the James River model to be constructed by the Waterways Experiment Station in Mississippi. Shidler and MacIntyre (1967) report on the data collected, and Hargis (1966) summarized results of Operation James River. Later, Nichols (1972b), using the results of the hydraulic model tests, reported on the effect of increasing the depth in the main channel on the salinity structure of the estuary. In the mid-estuary channel the lower water layer became slightly saltier and the upper water layer became slightly fresher. With respect to the oyster fishery, the results of these studies predicted that the channel deepening project would have no effect, because the changes in salinity and flow patterns in the middle estuary would be very small.

CONCEPTUAL MODEL FOR THE DEVELOPMENT OF A DROWNED RIVER VALLEY ESTUARY AND SUBTIDAL OYSTER REEFS

The James River is a classical example of a drowned river valley estuary (Nichols, 1972). According to Emery (1967), the modern estuaries were formed during the most recent rise of sea level, beginning 15,ØØØ years ago, when sea level rose from a depth of 125-15Ø m to its present position. The rate of sea level rise during this period has not been constant. This rise in sea level has progressively flooded the continental shelf. Lagoons were formed as sea level advanced slowly across the flat outer continental shelf. Between 12,ØØØ and 6,ØØØ years B.P., sea level rose at a rapid pace flooding the steeper portions of the inshore continental shelf profile. In this zone estuaries developed in the drowned river valleys. During the last 5,ØØØ years, the rate of sea level rise has slowed.

Once formed, estuaries function as sediment traps (Nichols and Biggs, 1984). Sediments are transported from the sea and land into the estuary causing a decrease in depth and a reduction in volume. This process continues until a balance is achieved between the tidal and river discharge and the estuarine basin geometry. Superimposed on these processes is the continuing Holocene rise in sea level and coastal subsidence. This results in the estuary moving upstream and widening as the banks of the river valley are flooded.

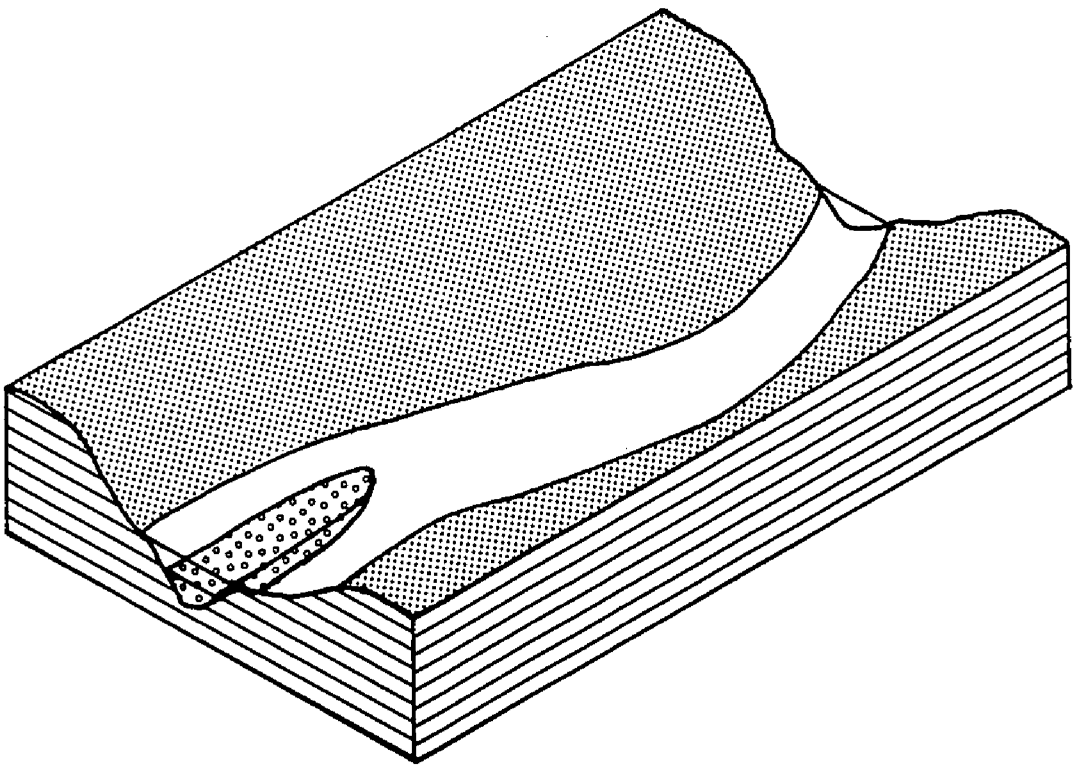
As noted previously, the James River is a partially mixed estuary. Assuming that 2,000 years ago, the balance between the tidal forces and fresh water discharge in the James River, was similar to that in existence at the present time, the development of the estuary during this period can be examined. At that time sea level was 4.5 m below its present level (Nichols, 1972). The gradient of the present James River estuary bottom is approximately 1 m per 10 km. Assuming a similar bottom gradient extends beyond the present estuary mouth, the head of the estuary would have been 45 km seaward of its present position 2,000 years ago.

The development of the James River estuary in response to a rising sea level is conceptually shown in Figures 2 and 3. At the time of lowered sea level, the head of the estuary is beginning to penetrate the illustrated section of the river. The salinity gradient ranges from 10 parts per thousand at the seaward limit of the section, and diminishes to less than 2 parts per thousand about one third of the distance along the section. After a rise in sea level of 4.5 m in 2,000 years, the estuary has transgressed landward and widened. The salinity gradient in the same section of the river ranges from 22 parts per thousand at the seaward limit of the section to less than 2 parts per thousand at the upstream limit of the section.

Figure 2

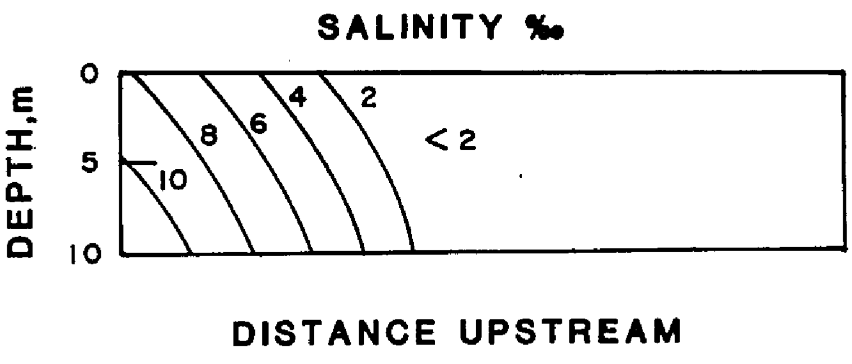
Development of a Drowned River Valley
Estuary in Response to a Rising Sea Level

Part I - Lowered Sea Level



(a)

GEOMORPHIC CROSS-SECTION



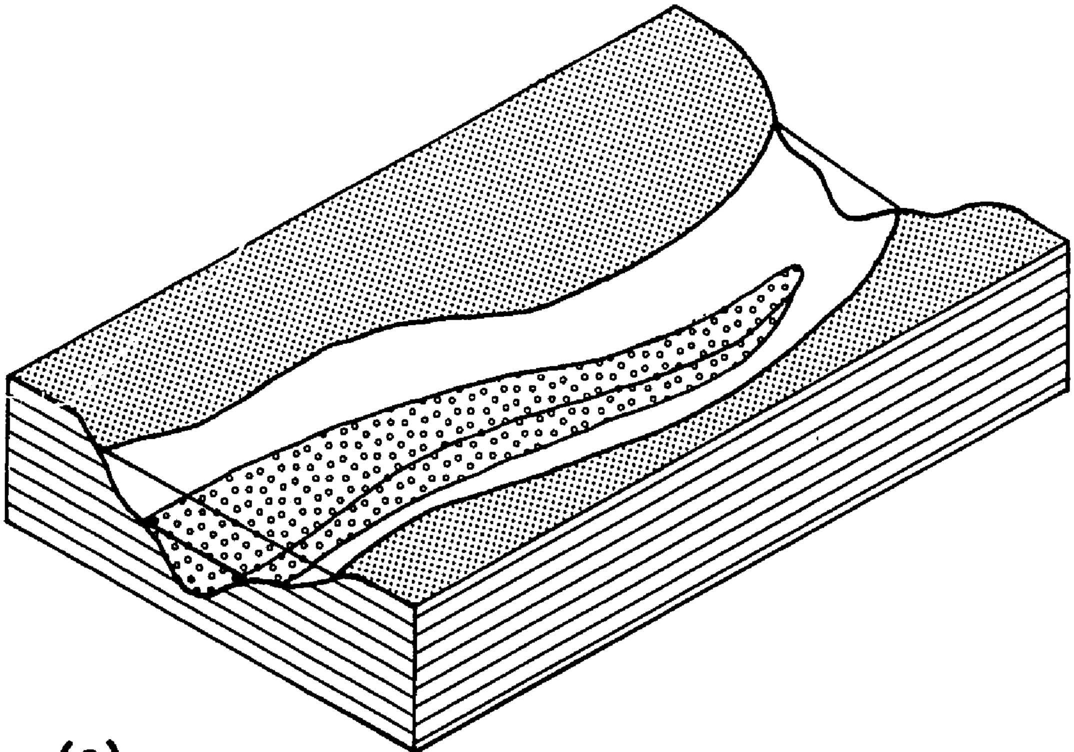
(b)

SALINITY DISTRIBUTION

Figure 3

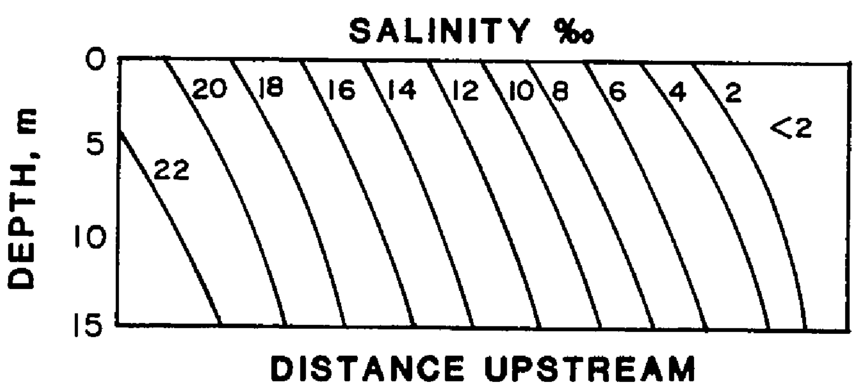
Development of a Drowned River Valley Estuary in Response to Rising Sea Level

Part II - Elevated Sea Level



(a)

GEOMORPHIC CROSS-SECTION



(b)

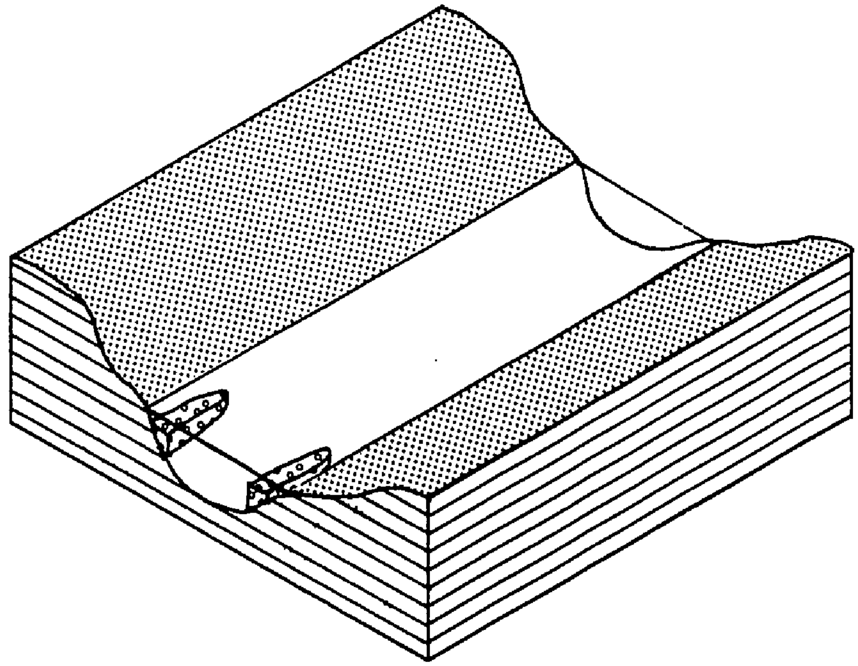
SALINITY DISTRIBUTION

As the drowned river valley estuary develops, in response to the rising sea level, the estuarine habitat also migrates upstream and widens (Figure 4). The fauna and flora of the estuary, constrained by their salinity tolerances, also move upstream. In that regard, the oyster reefs of the drowned river valley estuary have moved upstream and landward. As sea level has risen during the late Holocene, the oyster reefs have also developed vertically, thus maintaining their relative position in the water column, and avoiding burial due to estuarine sedimentation.

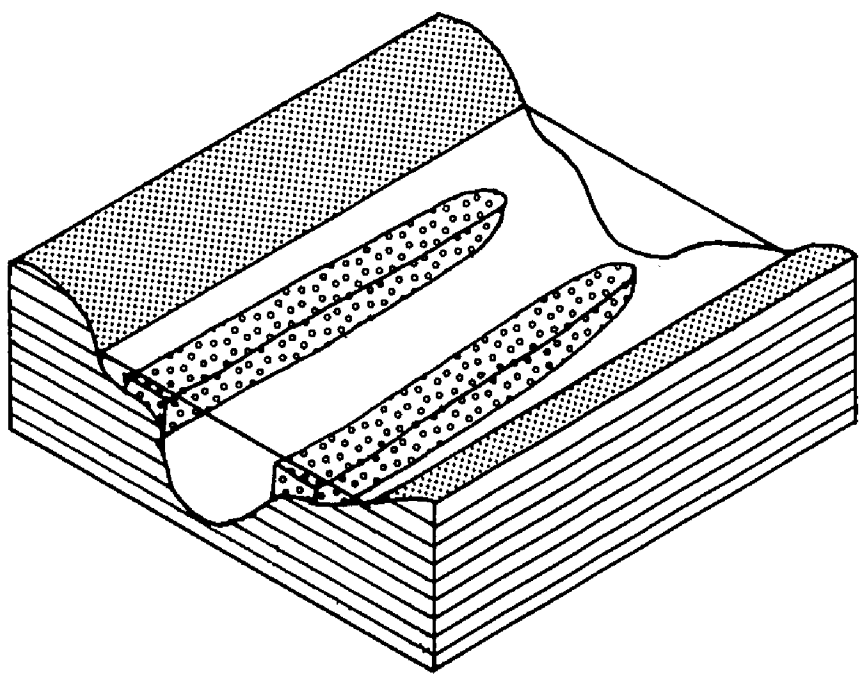
Based on the simple model presented herein, the James River estuary has migrated upstream at the rate of approximately 2.3 km per century during the last 2,000 years. Oyster production in the James River at present occurs over a 45 km section of the estuary where mean bottom salinities range from 20 parts per thousand downstream to 5 parts per thousand upstream. Given the present estuarine upstream migration rate, a particular oyster reef can potentially exist in the James River estuary for about 2000 years before passing out of the optimum production zone. This proposed model of the subtidal oyster reef development in a drowned river valley estuary is based on the evolution of the estuarine environment in response to a rising sea level. It is also noted that this model is applicable only to drowned river valley estuarine, subtidal reefs.

Figure 4

Development of Oyster Reefs
in an Evolving Estuary,
Responding to a Rising Sea Level



PART I - LOWERED SEA-LEVEL



PART II - ELEVATED SEA-LEVEL

The intertidal oyster reefs of the lagoonal, bar-built estuaries have developed in a different manner. Because the landward limit of the lagoons has not changed substantially as sea level has risen, the lagoonal estuaries have not migrated upstream, although they have narrowed as the barrier bars have migrated landward. With respect to the lagoonal oyster reefs, the landward limit for oyster reef development has not shifted, but the seaward limit for the oyster reefs has migrated landward as the barrier island has transgressed and buried the lagoon-marsh estuarine environment. Lagoonal oyster reefs do not therefore develop laterally, but do grow vertically in response to the rising sea level, until they are buried by the transgressing barrier island.

FORMULATION AND APPROACH

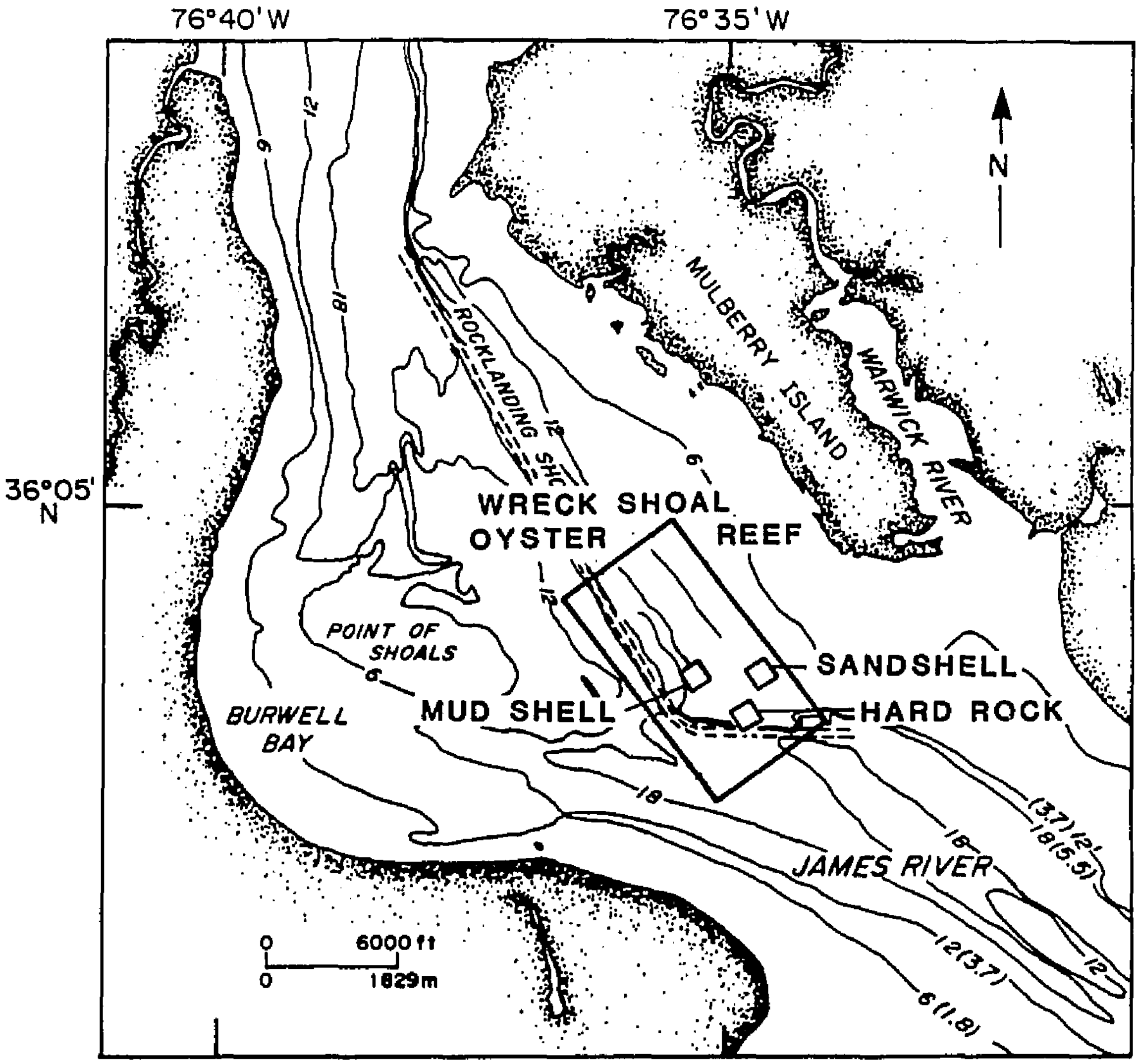
Delineation of Study Area Scales

This investigation into the sedimentary processes and geomorphic history of Wreck Shoal was divided geographically into three scales with respect to area. Each of the scales was matched to the degree of detail required to accomplish the specific objectives of the study.

The smallest scale study area encompassed the relatively large, approximately 1ØØ km^2, regional area of Burwell Bay and Wreck Shoal, from Mulberry Island on the northeast shore of the James River to Days Pt., Burwell Bay, and Tylers Beach on the southwest shore, (Figure 5 and Plate 1). Along the axis of the river, the regional study area included a deep natural channel (16.8 m or 55 ft), the dredged Rocklanding Shoal Channel (7.6 m or 25 ft), the shoaled and meandered Burwell Bay Channel(3.4 m or 11 ft), Wreck Shoal and Point of Shoals. The Wreck Shoal-Point of Shoals area is a point-bar complex, and Burwell Bay is the former main channel of the James River, meandering around the adjacent point bar (Onuschak, 1973). The investigations conducted in this regional study area were of a geologic and physiographic nature. The purpose of these regional

Figure 5

Delineation of the Study Area Scales



DELINEATION OF STUDY AREA SCALES
WRECK SHOAL BURWELL BAY
JAMES RIVER, VA. 1983
BASED ON NOAA CHART #12248

DEPTH CONTOURS IN FEET (meters)

investigations was to set the framework for the more detailed studies on Wreck Shoal oyster reef.

The intermediate scale study area included the Wreck Shoal oyster reef and some adjacent areas. The Wreck Shoal study area was 4 km along the axis of the River and 2 km wide, for a total area of 8 km^2. The Wreck Shoal oyster reef has depths ranging from 2.7 to 5.5 m (9-18 ft) at MLW. The major portion of the investigation of the sedimentary processes and the geomorphic history of Wreck Shoal was conducted within this study area.

The most detailed analyses of this investigation were conducted on three small, well-defined, but characteristic, subenvironments within the Wreck Shoal study area. The subenvironment study areas were 1Ø hectares (25 acres) each. Based on previous studies by Haven, Whitcomb, and Kendall (1981), it was believed that the three subenvironmental study areas represented different types of oyster reefs. These were therefore identified as the hard-rock, sand-shell, and mud-shell subenvironment oyster reefs according to classification scheme of the previous investigators.

Task Investigations

To investigate the specific objectives and to achieve the overall goal of this study, the project was logistically divided into five separate but complementary task investigations. The purpose of each of these individual task investigations is described in the sequel. The field and laboratory methods used in these task investigations are described in detail in the next chapter. The analyses and results of these task investigations are presented and integrated in a subsequent chapter according to the specific topical objectives noted previously.

Acoustic Surveys

Acoustic surveys were conducted on both the regional and intermediate scale Wreck Shoal study areas to further define these study areas. The bottom was mapped using a precision survey fathometer, a side scan sonar, and a sub-bottom profiler. The purpose of the fathometer survey was to provide a 1984 bathymetric chart that could be compared with historical bathymetry. The objective of the side scan sonar survey was to identify any particular features of the bottom that might influence the study and provide insight into sedimentation processes on Wreck Shoal. The goal of the sub-bottom profiler survey was to provide information on the subsurface geomorphology of Wreck Shoal and the adjacent area, as this would assist in understanding the geomorphic evolution of Wreck Shoal and in addressing the relationship between the geomorphology of Wreck Shoal and the contemporary sedimentation processes.

Comparative Bathymetry

Historical bathymetric data available from the 1850's to present was compared so as to investigate changes in the physiography of Wreck Shoal and the adjacent areas of the James River over the last 130 years. These changes are the direct result of the sedimentation processes operating during this period and provide a quantitative framework for the analysis of contemporary sedimentation processes on Wreck Shoal.

Subenvironment Descriptions and Comparisons

Based on the previous work of Haven and others (1981) and Moore (1910), coupled with the results of side scan sonar survey, three oyster reef subenvironment areas were selected for detailed investigation. The objective of this phase of the project was to study the biological and geological characteristics of these subenvironment oyster reef areas. The results were intercompared and tested for statistically significant differences and similarities . This work provided the basis for the remainder of the project, that is, to attempt to understand the similarities or differences between the subenvironments based on the contemporary sedimentation processes and geomorphic development.

Bottom Currents

The study of fine grain, suspended, estuarial sediment transport processes was dependent upon a description of the hydraulic regime that provides the energy and medium for sediment motion. In this regard, both spatial and temporal variations in the bottom currents over Wreck Shoal and the adjacent areas were investigated. The following hypotheses were examined:

1. That there are substantial spatial variations in the bottom current regime over Wreck Shoal including the subenvironments and that these are related to the morphology of Wreck Shoal.
2. That the temporal variations in the bottom current regime are primarily related to the tidal forcing, and therefore, that tidal currents predominately account for the sediment transport power of the estuary, while the net non-tidal circulation accounts for the general distribution of sediments in the estuary.

A general description of the circulation of the James River in the vicinity of Wreck Shoal and Burwell Bay was also made based on the analysis of existing numerical model data and historical field data.

Investigations of Sedimentary Processes

The study of contemporary sedimentary processes included field investigations, analyses of laboratory data of other investigators, and a numerical analysis of fine sediment transport processes on Wreck Shoal. The purpose of these studies was to gain an understanding of the contemporary sedimentary processes so as to explain the surficial geomorphic character of the subenvironment oyster reefs.

One aspect of the field studies was directed toward the observation of net results of sedimentation processes in the subenvironment areas over a fourteen month period. The objective was to investigate whether there would be observable or measurable change in the surficial sediment cover. A second aspect of the field studies included the observation of the accumulation of sediment on freshly placed reefs oyster shell and shale within the study area over the fourteen month period. The placed reefs had different characteristic roughnesses, and presumably, this should result in different sedimentation processes.

The significance of the biodeposition of feces and pseudo-feces by a productive subtidal oyster reef was evaluated based on laboratory data on the rates of biodeposition, and an estimate of the maximum standing crop of oysters that a subtidal oyster reef will support. The biodeposition of oyster shell material was also evaluated again considering the maximum standing crop on a subtidal oyster reef and reasonable annual mortalities. The results of these analyses of biodeposition permitted the evaluation of the significance of these parameters relative to estuarial fine sedimentation and harvesting activity by man.

A final aspect of the study of sedimentation processes was to investigate the significance of bottom roughness and magnitude of the bottom currents on the fine estuarial sediment transport processes. Bottom roughness was determined based on the measurement of near bed velocity profiles over the hard-rock and mud-shell subenvironments. From the bottom roughness and the observed bottom current time-series, and assuming near steady flow, a time-history of bottom shear stress was determined in each subenvironment. Applying critical shear stress values for erosion and deposition to the time history, the percentage of time that the bottom was either erosional, depositional, or null was estimated for each subenvironment. The results of these calculations were compared with the results of the visual observations of sedimentation processes of the fourteen month field study period.

FIELD AND LABORATORY METHODS

Acoustic Surveys

The purpose of the acoustic surveys was to investigate in detail bottom topographic features, surface textural patterns and sub-bottom stratigraphy that might assist in the development of the understanding of the geomorphic history and contemporary sedimentation processes operating on Wreck Shoal.

Two acoustic methods were used to distinguish topographic features of the study area. The instruments operate at relatively high frequencies of 100-200 KHZ. The conventional method is echo sounding, which employs a vertical axis acoustic beam. Another method, called the side looking, or side scanning sonar, uses an acoustic beam with its main axis slightly below horizontal. The beam is very narrow in the horizontal plane, yet sufficiently broad in the vertical plane to obtain echoes from a point on the bottom directly below the transducer to points 100-200 m abeam of the transducer. The combination of the beam shape and the very short length of the acoustic pulse length gives the side scan sonar the capability to resolve small topographic irregulatitities and differences in roughness in the sea floor. As the transducer is towed below the survey vessel, the reflected or backscattered echoes are graphically recorded in a form that approaches a topographic or plan view map. Projections above the bottom and acoustically rough surfaces are good reflectors or acoustic backscatters, and therefore darken the record. Depressions of the bottom or relatively smooth bottoms are represented by a lightening of the record.

Two different side scan sonar systems were used in this study, a Klien Hydroscan System and an E.G. & G. Seafloor Mapping System. The Klien system was operated with 100 KHZ transducer frequency, at the 100 m range, and displayed on a dual channel, analog, wet-paper recorder. The E.G.& G. system, was operated with 100 KHZ transducer frequency, at the 100 m range, displayed on a digital dry paper recorder, and had a digital magnetic tape recording capability. The unit also incorporated slant range correction and speed correction to provide a dimensionally non-distorted output record.

The initial acoustic survey of the Wreck Shoal study area was conducted on 25 and 26 June 1984, operating simultaneously the Klien side scan sonar system and a Raytheon DE-719 precision survey fathometer. Subsequent surveys were made on 7 July 1984 and 13 March 1985 using the E.G. & G. Seafloor Mapping System.

Navigation control for all the acoustic surveys was provided by LORAN C, using a Northstar 7000 system. The navigation unit was point calibrated at a known location

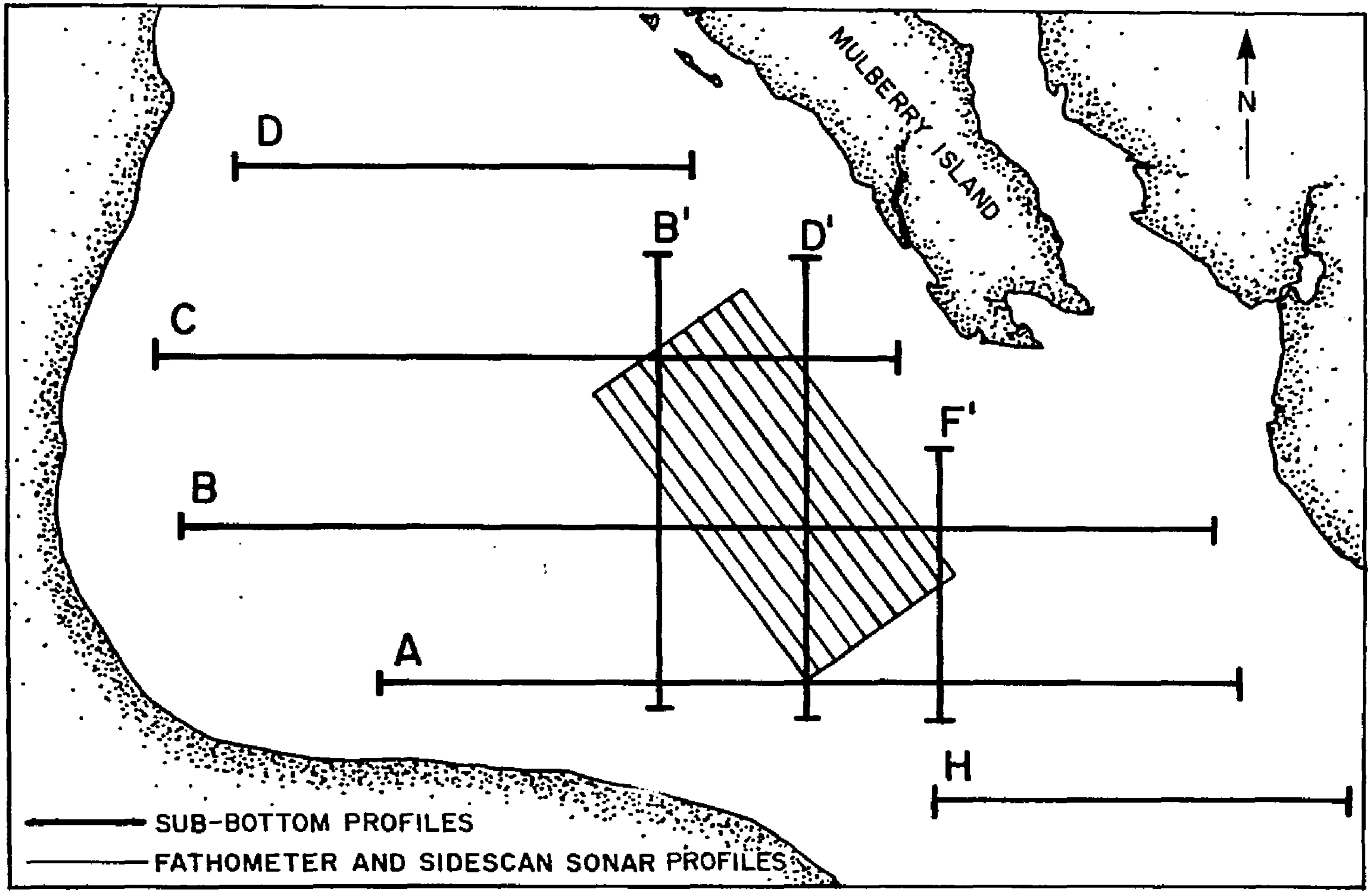
(U.S. Coast Guard Beacon # 12) at the beginning and end of each survey day. Fix marks were noted every 100 m along each transect. Navigational accuracy was approximately ± 20 m, or ± 0.1 micro-second of time difference in LORAN C signals.

As noted previously, the Wreck Shoal study area is 4 km long by 2 km wide, (Figure 6). The track lines for the initial Klien side scan sonar and the precision bathymetry were spaced 91 m apart. The Klien side scan sonar was operated at the 100 m range, and this resulted in approximately a 50 percent overlap in the records. The track lines for the E.G. and G. side scan surveys were spaced at 182 m, and the side scan sonar was operated at the 100 m range. This arrangement allowed only 10 percent overlap in the resulting records. A 50 percent overlap in the side scan records is considered optimal; a 10 percent overlap was considered acceptable for the resurveys in this study.

The initial Klien side scan sonar survey records were mosaicked at the full output record scale. The resulting mosaic was over 4.6 m long and 2.1 m wide, and too large and cumbersome to handle. However limited analysis of the mosaic of that survey and the detailed bathymetry that was taken simultaneously indicated several interesting patterns on the bottom that warranted further investigation. A resurvey of the Wreck Shoal study area was conducted two weeks later (7 July 1984), repeating the identical survey

Figure 6

Acoustic Survey Track Lines



ACOUSTIC SURVEY TRACK LINES
WRECK SHOAL BURWELL BAY
JAMES RIVER, VA 1983
BASED ON NOAA CHART #12248

tracks. The resulting data, having been recorded on magnetic tape, was rerun at the 200 m range, effectively reducing the record size by a half. These records were mosaicked, photographed, then mosaicked and photographed again. Another resurvey of the study area was conducted nine months later (13 March 1985), and similar procedures were followed.

The shallow or near surface stratigraphy (sub-bottom) was investigated using a low frequency, high power acoustic signal. The principle of operation of a sub-bottom profiler is that the stratigraphic layers or horizons in the river bottom are composed of materials of different density and will therefore each reflect acoustic signals, resulting in a record that graphically portrays the subsurface stratigraphic sequence.

The sub-bottom profile survey was conducted over the regional study area of Burwell Bay-Wreck Shoal. Track lines for this survey were oriented north-south and east-west along specific, predetermined parallels of latitude and meridians of longitude, and were spaced at approximately 2 km intervals, (Figure 6).

Several attempts using different instruments were made to collect sub-bottom profile data for the Wreck Shoal study area. Data collected with the Raytheon RTT-1000, and Klien Sub-bottom Profiles were not sufficiently clear for meaningful interpretation. A Datasonics Sub-bottom Profiler was successfully used during 11 and 12 July of 1985. A

Raytheon DE-719B precision survey fathometer was also operated concurrently during the sub-bottom profile surveys.

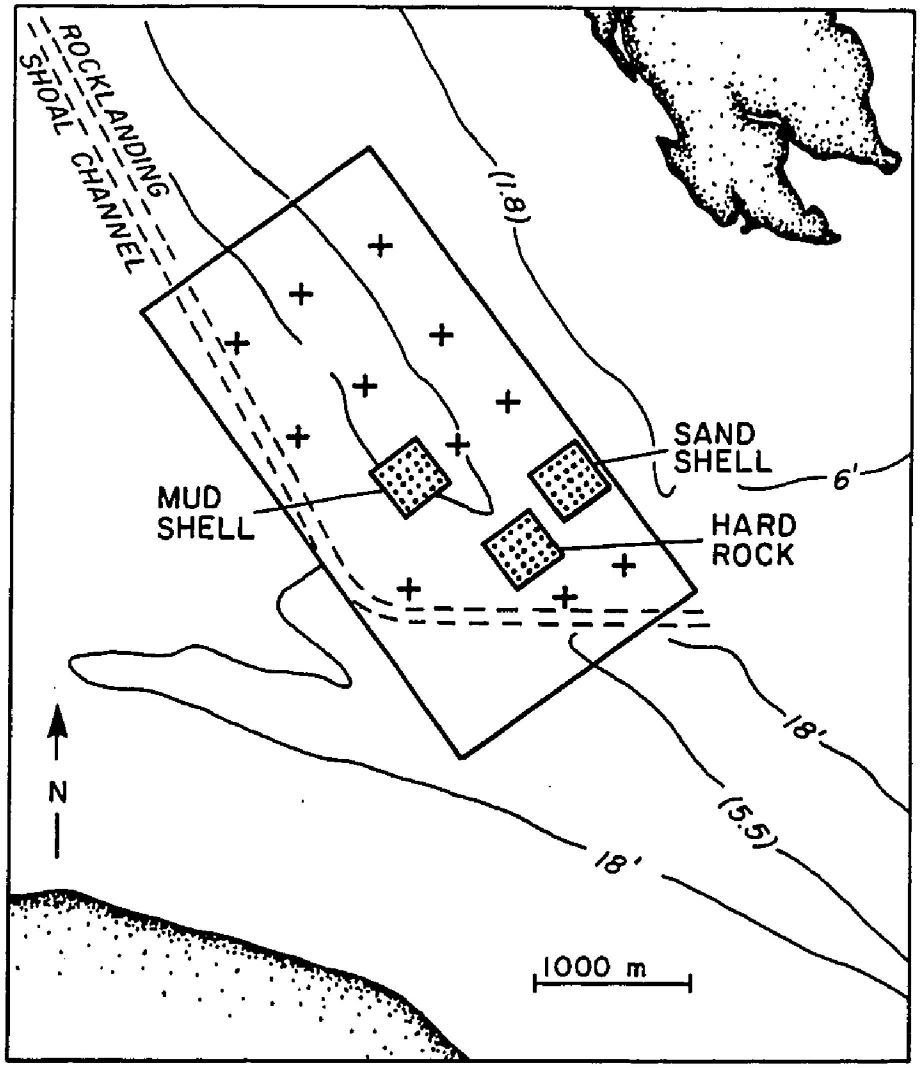
Subenvironment Sampling

To investigate the biological and geological characteristics of the subenvironment oyster reefs, a discrete sampling program was conducted encompassing both the entire Wreck Shoal study area on a broad scale and each of the subenvironments in detail. The purpose of the initial survey of the Wreck Shoal study area was to test the field techniques, to investigate the variability of the bottom, and to provide ground truth data for the acoustic surveys. The purpose of the intensive subenvironment sampling was to collect quantitative data that could be used to compare and contrast the characteristics of the subenvironment oyster reefs.

The initial field investigation of the Wreck Shoal study area consisted of identifying eleven station locations approximately evenly distributed over the 8 km^2 Wreck Shaol study area, (Figure 7). The field investigation in each subenvironment consisted of dividing the area using a grid into 25 station areas of Ø.4 hectares (1 acre) each (Figure 6). Station position determination was made using a LORAN C, accurate to Ø.Ø2 of a minute of latitude or longitude, ($\pm$2Ø m). At each station location, a single sample, using hydraulic patent tongs was taken of the bottom. The patent tong is a bottom grab sampler device that takes a Ø.9 m^2

Figure 7

Bottom Sample Locations



• SUBENVIRONMENT, SAMPLING STATIONS
+ WRECK SHOAL STUDY AREA, SAMPLING STATIONS

BOTTOM SAMPLE LOCATIONS

SUBENVIRONMENT AND WRECK SHOAL STUDY AREAS.

DEPTH CONTOUR IN FEET (meter)

sample. It is similar to the commercial fishing gear used by oystermen in Virginia. A SCUBA diver also made observations of the bottom. On the deck of the research vessel deck, the sample was sorted, counted and data recorded.

Interstitial sediment samples were taken from each patent tong sample, and returned to the laboratory for analysis. Approximately 85 samples were analyzed by wet sieving and drying for the gravel size, sand size, and silt/clay size fractions (Folk, 1974). A pipette procedure was used to separate the silt and clay fractions. All samples were also analyzed for the percent of water content by the oven drying method. Five samples from the center of each subenvironment area were analyzed in detail, in order that complete sediment statistics could be calculated for each sample. The gravel size fraction was sieved of 1/4 PHI intervals using the ROTAP shaker. The sand size fraction was run on the RSA (Rapid Sand Analyzer). The silt/clay fraction was analyzed on a Coulter Counter. The procedures used in this detailed sediment analysis scheme, as well as the program used to calculate the sediment statistics are described in Diaz and others (1985) and follow the methods outlined by Folk (1974). The carbonate percentage of the sand size fraction was also determined using the acidification techniques described by Carver (1971). The gravel size fraction was observed to be 100 percent carbonate, or oyster shell hash.

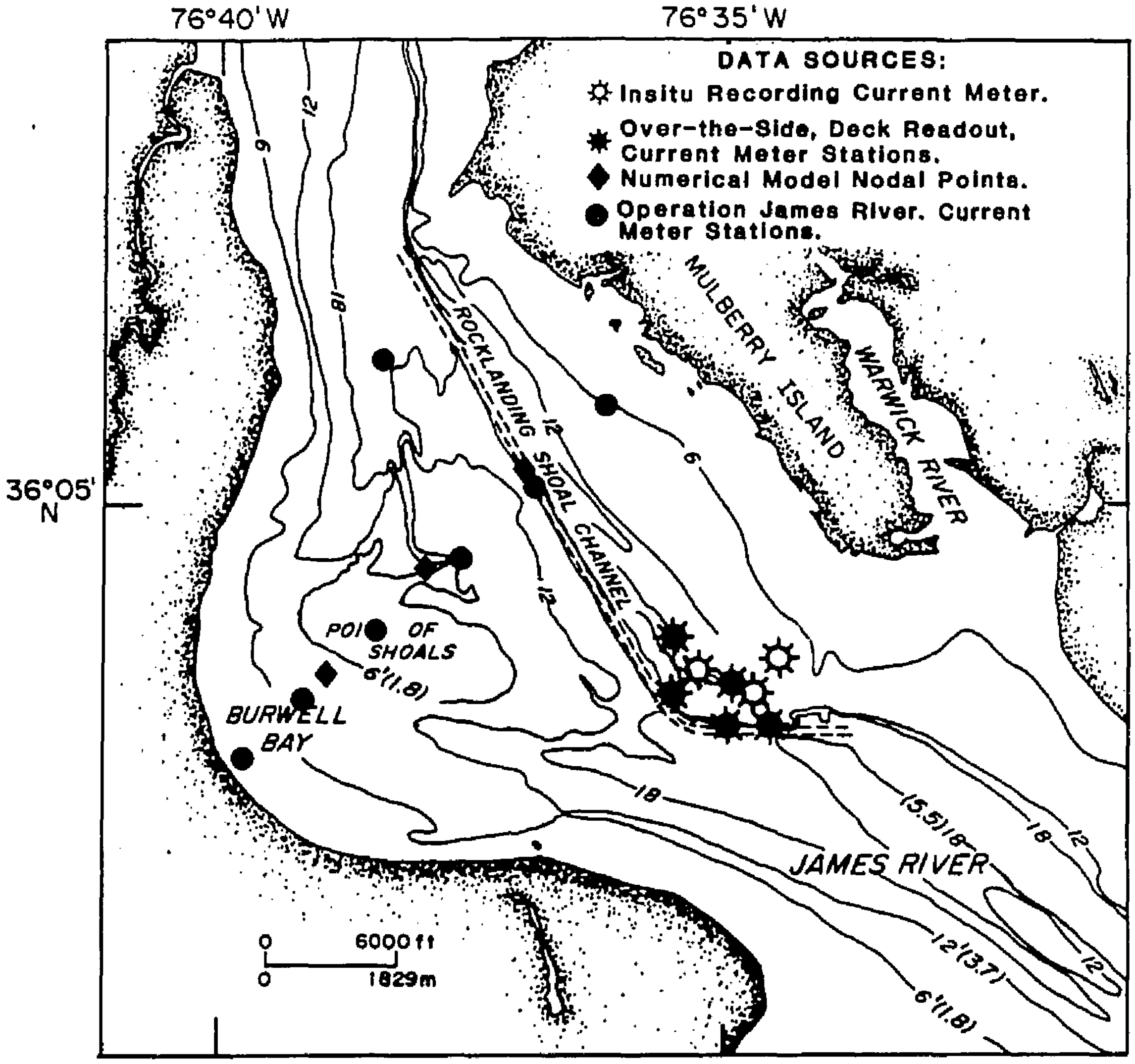
Bottom Current Studies

The analysis of the contemporary sedimentation process operating on Wreck Shoal required a description and understanding of the estuarine hydraulic regime; as it is the fluid motion that provides the energy for the transport of estuarine sediments. Temporal variations in the bottom currents over Wreck Shoal were investigated using recording current meters. An ENDECO 1Ø5 current meter was placed in the center of each of the three subenvironments for a 29 day period from 12 July to 1Ø August, 1984, (Figure 8). This instrument uses a ducted impeller to measure current speed. Speed and direction are averaged over a half hour period, and recorded on film inside the instrument. The current meter was tethered one meter above the bed in a taut-mooring system . The current meters were speed calibrated in the VIMS flume after the field deployment. The instrument films were processed by ENDECO, and a nine track data tape returned to VIMS for computer analysis.

Spatial variations in the bottom current regime over Wreck Shoal were also investigated to expand the bottom current data base beyond the three in situ current meter stations. A total of eight stations, (Figure 8), including the three in situ current meter stations were monitored for half tidal cycle periods using a small over the side ducted impeller current meter (Byrne and Boon, 1973). The data was collected at about half-hour intervals at each station during the half tidal cycle observation period. The

Figure 8

Bottom Current Data Station Locations



BOTTOM CURRENT DATA STATION LOCATIONS

WRECK SHOAL BURWELL BAY

JAMES RIVER, VA.

BASED ON NOAA CHART #12248

DEPTH CONTOURS IN FEET (meters)

instrument package was lowered to the bottom at each station with the sensor one meter above the bed, and a two minute time average observation of current speed was recorded. Current direction was noted by the orientation of the vane mechanism upon retrieval. This instrument was calibrated in the VIMS flume prior to the field work.

The field work with the over the side current meter was conducted during a one week period from 24 July to 1 August 1984. During the first three days, the ebb half of the tidal cycle was measured; during the last three days, the flood half of the tidal cycle was measured. On the first day of each half tidal cycle group, a single station was occupied (hard-rock) and bottom currents were measured for two minute intervals almost continuously. The purpose of this exercise was to test the hypothesis that two minute measurements every half-hour would accurately portray the bottom current velocity curve, and that the half-hour averages being taken by the in situ recording current meters were representative, and not masking higher frequency current surges.

Investigations of Sedimentary Processes

Temporal variations in the surficial sediment layer were investigated to address the question of the permanence or constancy of the observed initial sedimentary conditions of the subenvironment oyster reefs. Previous studies of this type, designed to monitor short-term temporal variations in bottom sediment texture and bottom elevation, have utilized stake fields to provide a frame of reference to measure the changes in bottom elevation that would be indicative of sediment accretion or erosion (DeAlteris and others, 1975). In this study, the stake fields were considered impractical because of the small scale of the measurements required over the oyster reef and due to the difficulty of maintaining stakes over actively worked oyster reefs for a full year. Therefore, the oysters themselves, because they are sessile organisms, were used as the reference.

During the summer of 1984, over 100 individual SCUBA dives were made at different stations within the three subenvironment areas, hard-rock, sand-shell and mud-shell. The visual observations of the thickness of the sediment cover on the reef made during these underwater excursions investigated both the uniformity of the bottom conditions within a single subenvironment area, and the constancy of the sedimentary conditions in that subenvironment during that period.

In addition to the monitoring of the subenvironments, two experimental plots, approximately 5 m by 5 m in size, were established adjacent to both the hard-rock and sand-shell subenvironments. These areas were planted, one with a 10 cm layer of clean oyster shell and the other with a 10 cm layer of clean crushed shale (1 cm to 3 cm size range). Although the principal objective of this study was to investigate the suitability of alternate cultch materials, these plots were also monitored for the accumulation of fine estuarine sediments. In reality, these experimental shell and shale plots investigated the sedimentation processes that would occur on freshly planted cultch. It was noted previously that it is the practice in the commercial cultivation of oysters on private and public bottom in Virginia to plant clean oyster shells in the late spring to provide a suitable substrate material for the developing oyster larvae to strike or attach, and that rapid or heavy estuarine sedimentation can cover this clean cultch rendering it useless for oyster spat collection.

During the period from September 1984 to August 1985, the three subenvironment areas, and the two shell and two shale experimental plots were monitored at about six week intervals. At each monitoring, visual observations by the author using SCUBA diving gear were made of the degree or amount of sediment cover on the oyster reefs in the subenvironments and on the shell and shale experimental plots. No actual measurements were made as the total amount of fine sediment cover because it never amounted to more than 1-2 mm on the hard-rock and sand-shell subenvironment oyster reefs, or more than 1-2 cm on the mud-shell oyster reef.

Bottom roughness in the subenvironment oyster reefs was also investigated in field studies. The objective of the experiments described in the sequel was to compare the hydraulic roughness of the hard-rock oyster reef to the mud-shell oyster reef and to determine characteristic bed friction factors for these reefs. This was accomplished by measuring near-bed velocity profiles, in the center of the two subenvironments oyster reefs over a full tidal cycle. From these data, the bottom shear stresses were calculated and the bottom drag coefficients deduced.

The velocity profile was measured with a series of three electromagnetic current meters (EMCM) placed on a weighted instrument platform at 1ØØ, 53 and 24 cm above the bed. The EMCM's were Marsh-McBirney instruments. The upper and lower instruments were Model 511, using 3.8 cm diameter sensors operating at a five second time constant. The mid-level sensor was also a Model 511 using an 3.8 cm diameter sensor, but operating at a Ø.2 second time constant. The instrument platform was lowered to the bottom, and hard wired to analog deck readout units. Although the instruments measured orthogonal components of the current, only a single component was utilized in the analysis, as the instrument platform had a directional vane, and therefore aligned itself into the flow on being lowered to the bottom. The platform was reoriented at the turn of the tide, to face into the return flow. Data was recorded at one minute intervals from the analog outputs for a ten minute period, every 3Ø minutes for 13 hours. This scheme was followed at the hard-rock station on 8 August 1985, and at the mud-shell station on 9 August 1985. The instruments were calibrated in the VIMS flume before and after the experiments.

RESULTS, ANALYSES AND DISCUSSIONS

Surficial Geomorphic Description of the Wreck Shoal Oyster Reef

1984 Bathymetric Survey

A contoured bathymetric chart constructed from the 1984 survey of the Wreck Shoal study area is presented in Figure 9. The raw data was corrected for observed tide elevation at the time of the survey, and the results are referenced to Mean Low Water (MLW), for the 1960-1978 National Tidal Datum Epoch. The 1984 bathymetric data is compared in detail to historical chart data in a later section of this chapter. In general, the topographic features of the Wreck Shoal oyster reef include a deep natural channel, oriented east-west in the southern portion of the study area, the Rocklanding Shoal dredged channel oriented northwest by southeast in the western portion of the study area, a relatively shallow ridge or shoal along the northern flank of the deep natural channel, and a pair of ridges and troughs oriented parallel to the dredged channel in the northwest portion of the study area.

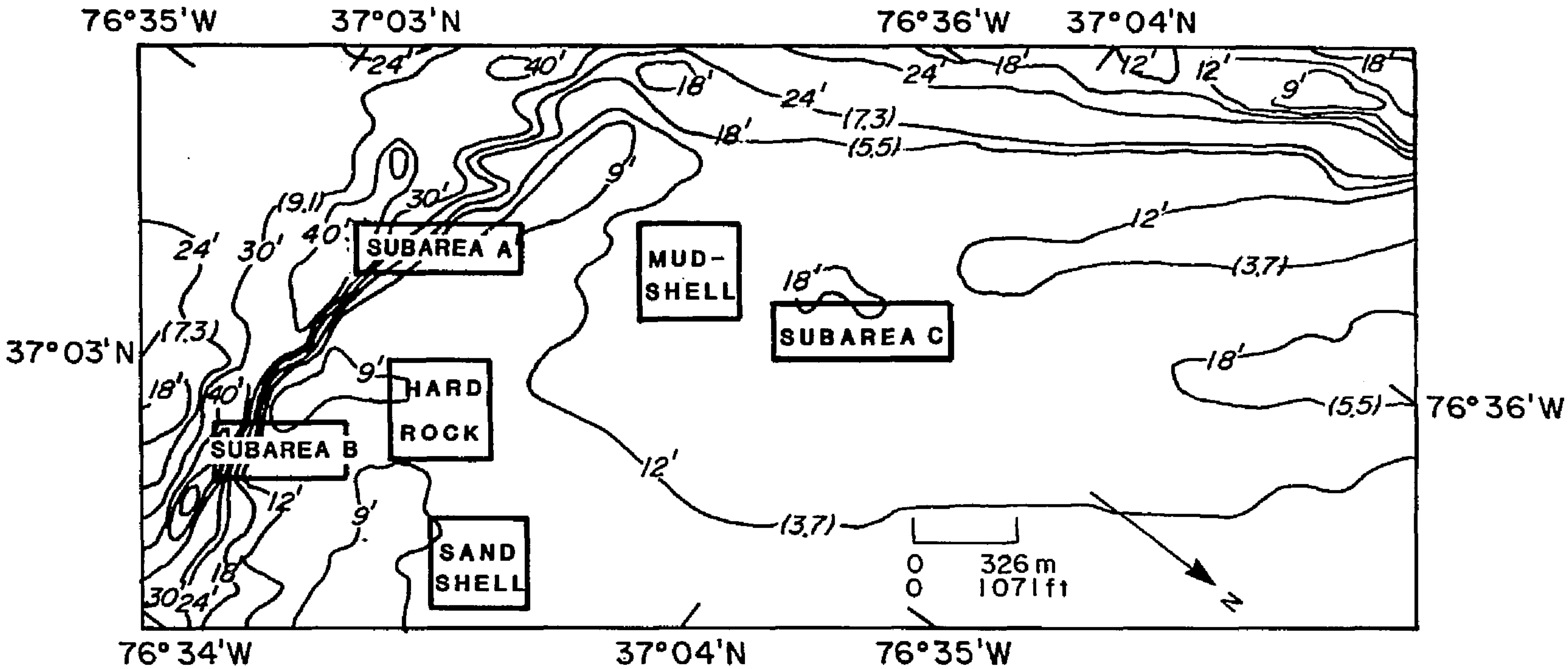
Side Scan Sonar Surveys

The results of the 7 July 1984 side scan sonar

Figure 9

Bathymetry of Wreck Shoal Study Area, 1984
Showing the Subareas and Subenvironments

BATHYMETRY OF WRECK SHOAL STUDY AREA, 1984
REF. MLW, DEPTH CONTOURS IN Feet (Meters)
SHOWING THE SUBAREAS AND SUBENVIRONMENTS

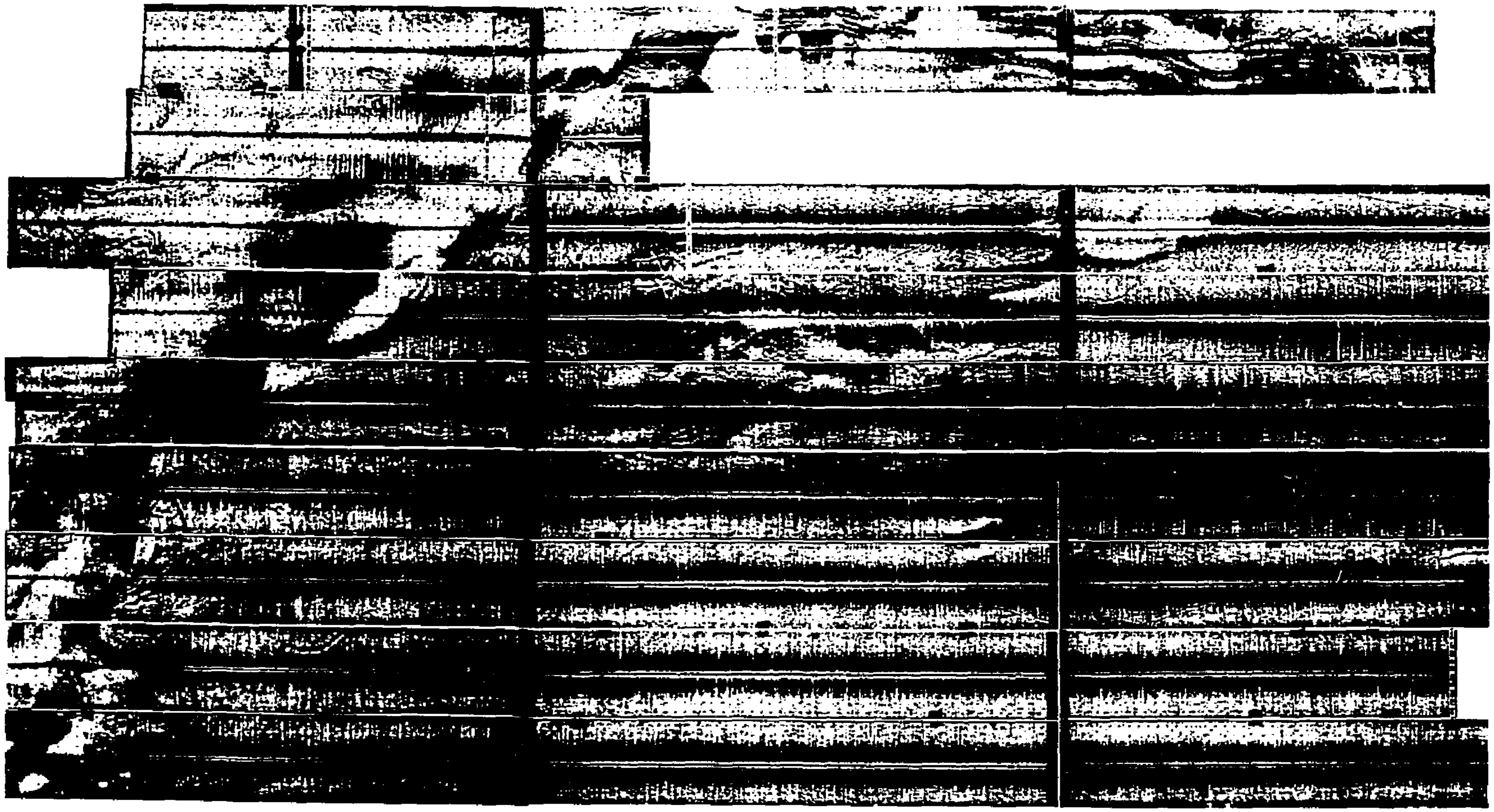


investigation of the Wreck Shoal study area are presented in Figure 1Ø. This is a photo reduction of a mosaic of photographs of the original mosaicked half-scaled side scan sonar output. The area covered by the mosaic is about 1.6 km wide by 4 km long. The two outside track lines (one inshore and one offshore) are missing. Some distortion in the length of longitudinal axis was caused by operator errors in the vessel speed input to the E.G.& G. Seafloor Mapping System. To assist in the interpretation of this data, the reader is referred to the bathymetric chart shown in Figure 9. The major portion of the mosaic covers the shallow region of the Wreck Shoal study area, and the most obvious feature in this area are long singular tracks or scars across the bottom. The tracks cross individual side scan sonar records, and are as long as 1 km. The total length of tracks indicated on the bottom of Wreck Shoal is 19.4 km . The natural channel of the James River is shown as a darkened area in the record suggesting a rough, dense bottom, indicative of a shell and gravel base. The smooth mud of the downstream flank of the natural channel is shown as a lightening of the record in the upper left hand corner of the mosaic. The dredged Rocklanding Shoals channel is shown across the upper right hand portion of the mosaic.

The results of the resurvey of the Wreck Shoal study area conducted on 13 March 1985, are shown in Figure 11. The techniques used in the collection of the data and in the

Figure 1Ø

Wreck Shoal Study Area,
Side Scan Sonar Photo Mosaic,
7 July 1984

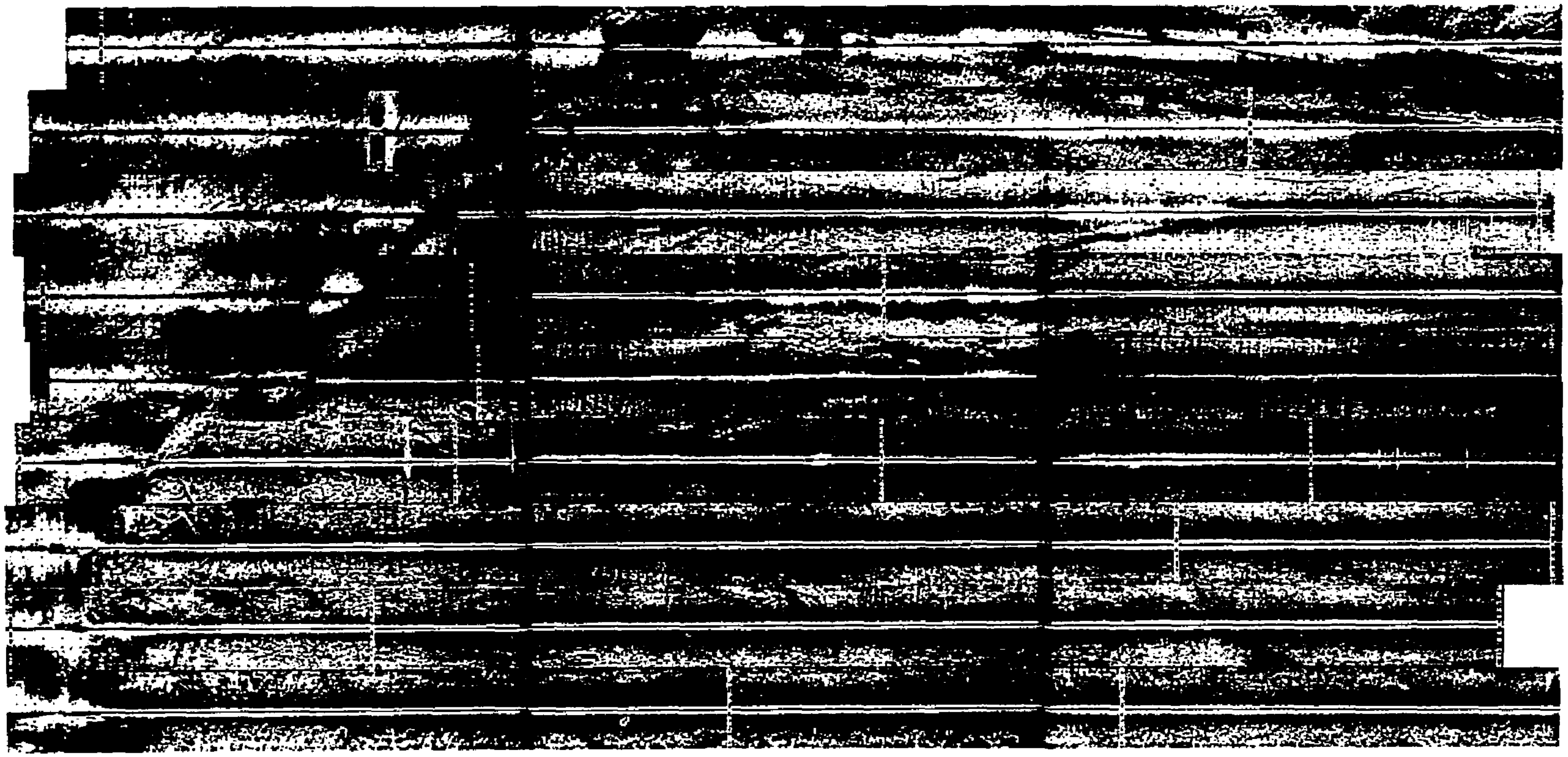


WRECK SHOAL STUDY AREA

SIDE SCAN SONAR - PHOTO MOSAIC 7 JULY 1984 SCALE 200 METERS

Figure 11

Wreck Shoal Study Area,
Side Scan Sonar Photo Mosaic,
13 March 1985



WRECK SHOAL STUDY AREA

SIDE SCAN SONAR - PHOTO MOSAIC   13 MARCH 1985   SCALE

200 METERS

assembly of the mosaic were identical to the previous survey. Small differences in the scales of the resulting mosaics were again caused by errors in the vessel speed input to the E.G.&G. Seafloor Mapping System. The 1985 mosaic appears remarkably similar to the 1984 mosaic. Again the most readily apparent features of this data are the tracks or scars on the bottom. On this mosaic there are 19.3 km of tracks or scars, and most are in identical positions to those previously observed in the 1984 survey.

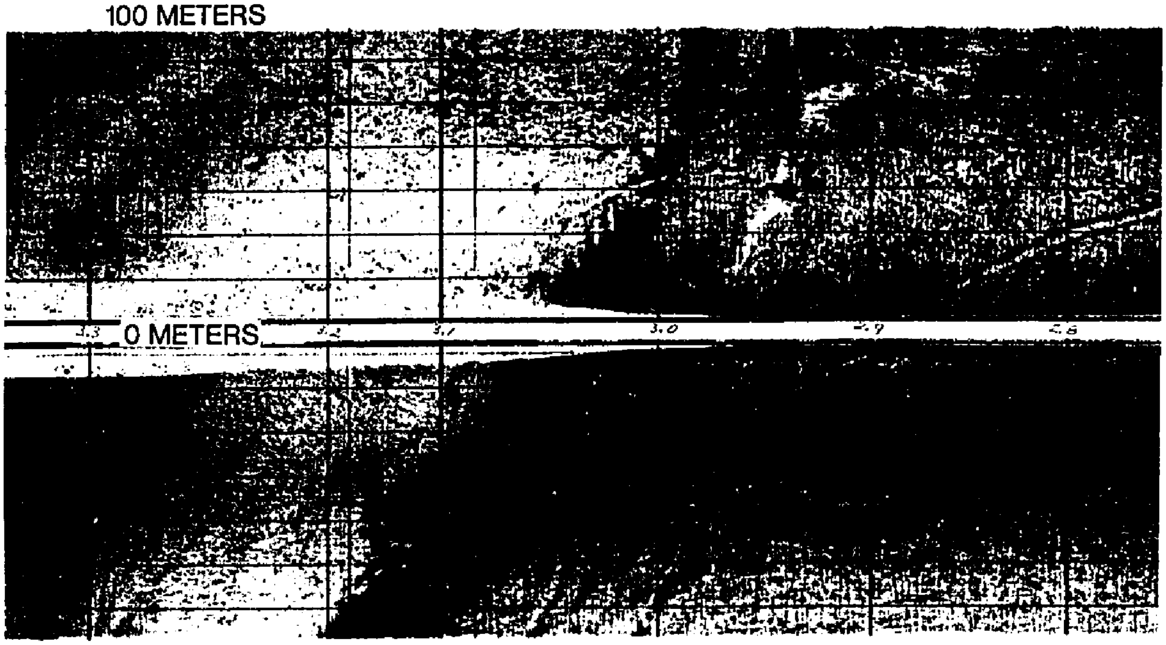
Three subareas were selected for detailed analysis and comparison of the results of the precision bathymetry and the side scan sonar surveys, (Figure 9).

Subarea A is located along the flank of the natural channel in the mid-portion of the Wreck Shoals study area. The precision bathymetry along the center line of the area and the original record of the Klien side scan sonar are shown in Figure 12. The lower bank of the channel between fix marks 3.3 and 3.1 (a 2ØØ m distance) appears to be a smooth mud (lightening of the record), in contrast to the upper bank of the channel which appears to be a dense, rough surface (darkening of the record) from a point between marks 3.1 and 3.Ø and beyond. A bottom scar crosses the center of the record beyond fix mark 2.9 and corresponds to a slight depression (Ø.5 ft or Ø.2 m) in the bottom as indicated in the fathometer record. Resurveys of the area on 7 July 1984 and 13 March 1984 with the E.G.& G. side scan sonar indicate identical features, (Figure 13).

Figure 12

Wreck Shoal Study Area,
Subarea A
Klien Side Scan Sonar and Raytheon Fathometer

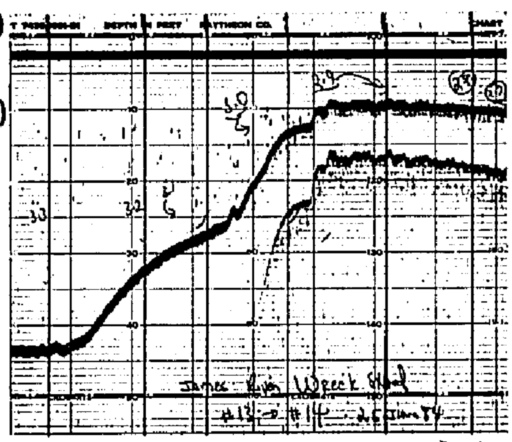
100 METERS



KLIEN SIDE SCAN SONAR 25 JUNE 1984

0 FT (0 M)

10 FT (3.05 M)



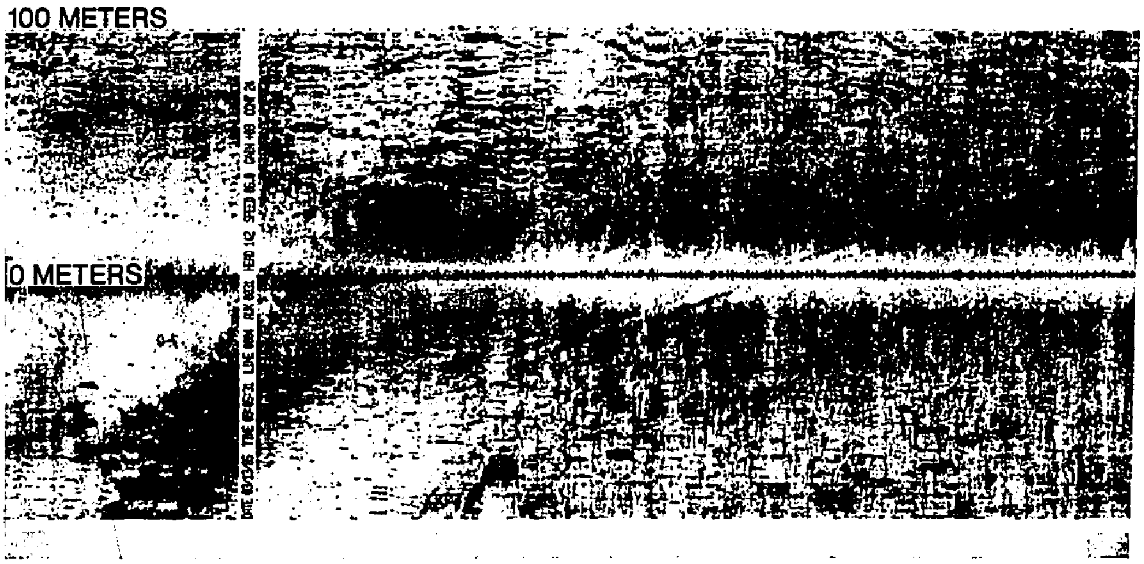
RAYTHEON FATHOMETER 25 JUNE 1984

WRECK SHOAL STUDY AREA SUB AREA A

Figure 13

Wreck Shaol Study Area
Subarea A
E.G. and G. Side Scan Sonar

EG&G SIDE SCAN SONAR 5 JULY 1984



EG&G SIDE SCAN SONAR 13 MARCH 1985

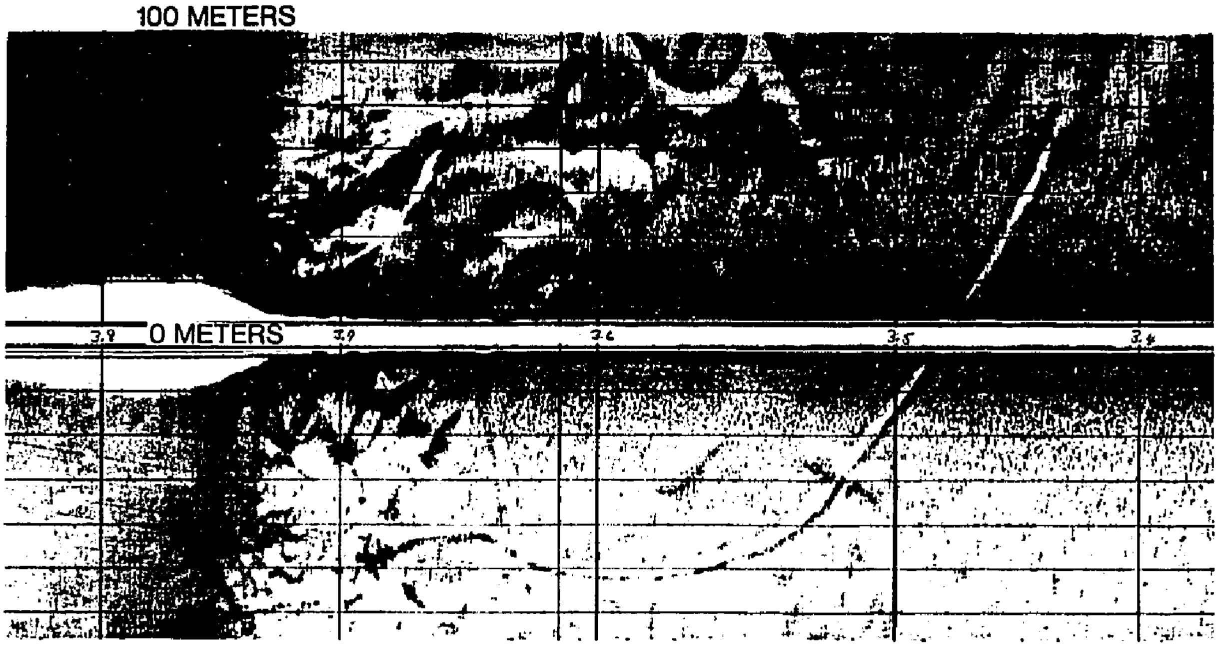
WRECK SHOAL STUDY AREA SUB AREA A

Subarea B is located along the flank of the natural channel on the inshore portion of the study area. The precision bathymetry along the centerline of the area and the original record of the Klien side scan sonar are shown in Figure 14. Fix mark 3.8 denotes the center of the channel, with steep rising bank to fix mark 3.7. The channel bank rises from 15.3 m (5Ø ft) to 6.1 m (2Ø ft) in a 3Ø m distance or about 1Ø m to 3Ø m, for a slope of about 2Ø degrees. This is relatively steep for a natural channel bank. Along the edge of the bank, there are a series of features of nearly uniform wavelength of 1Ø m and a height of Ø.3 to Ø.9 m (1 to 3 ft). On the shallow hard oyster reef portion of the study area beyond fix mark 3.5, a bottom scar passes the center of the record. This bottom scar is about Ø.3 m (1 ft) in depth. There is another distinct scar in the upper part of the Klien record. Resurveys of the area on 7 July 1984, and 13 March 1985 with the E.G.& G. side scan sonar reveal identical features on the bottom (Figure 15). Differences in the overall darkness of the E.G.& G. records are for accounted by different gain and contrast settings on the recorder.

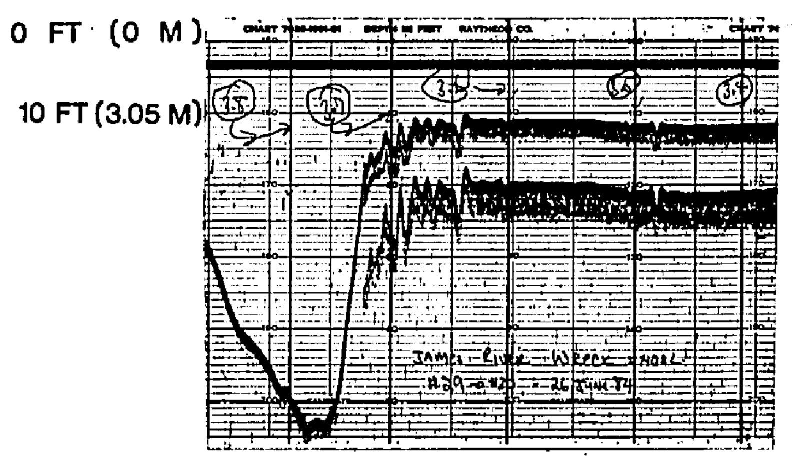
Subarea C is located in the central portion of the Wreck Shoal study area, in the relatively deep trough zone that makes up the mud shell oyster reef environment. Water depths range from 4.Ø to 5.5 m (13 to 18 ft) at MLW. The precision bathymetry and Klien side scan sonar record shows two segments of a continuous bottom track or scar, that

Figure 14

Wreck Shoal Study Area,
Subarea B,
Klien Side Scan Sonar and Raytheon Fathometer



KLIEN SIDE SCAN SONAR 26 JUNE 1985

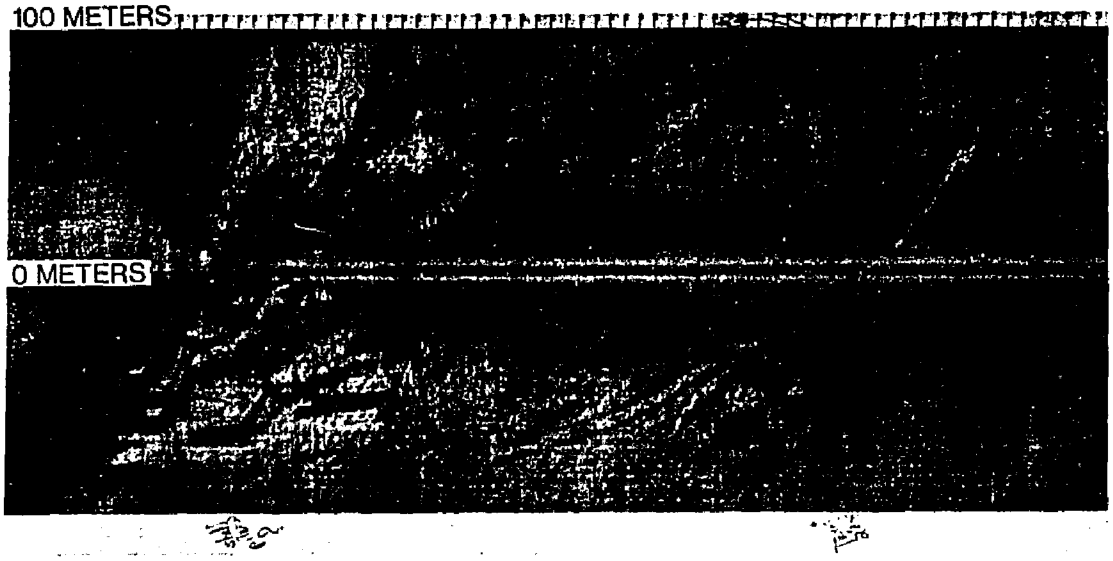


RAYTHEON FATHOMETER 26 JUNE 1985

WRECK SHOAL STUDY AREA SUB AREA B

Figure 15

Wreck Shoal Study Area,
Subarea B,
E.G. and G. Side Scan Sonar



EG&G SIDE SCAN SONAR 25 JUNE 1984

EG&G SIDE SCAN SONAR 13 MARCH 1985

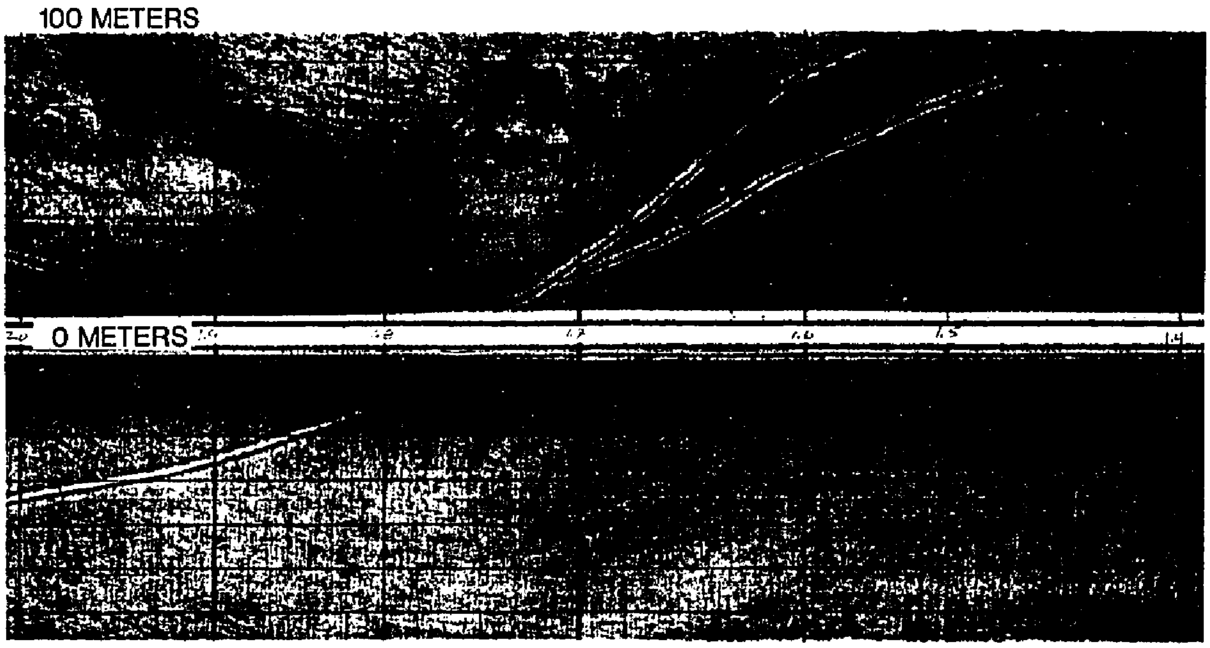
WRECK SHOAL STUDY AREA SUB AREA B

passes beyond this record, turns around, and passes back over this record, (Figure 16). The centerline of this transect passes over the scar between fix marks 1.8 and 1.7, and the fathometer record indicates the depth of the scar is Ø.2 m (Ø.5 ft). Resurveys of the area on 7 July 1984 and 13 March 1985, with the E.G. & G. side scan sonar, indicate identical features, Figure 17.

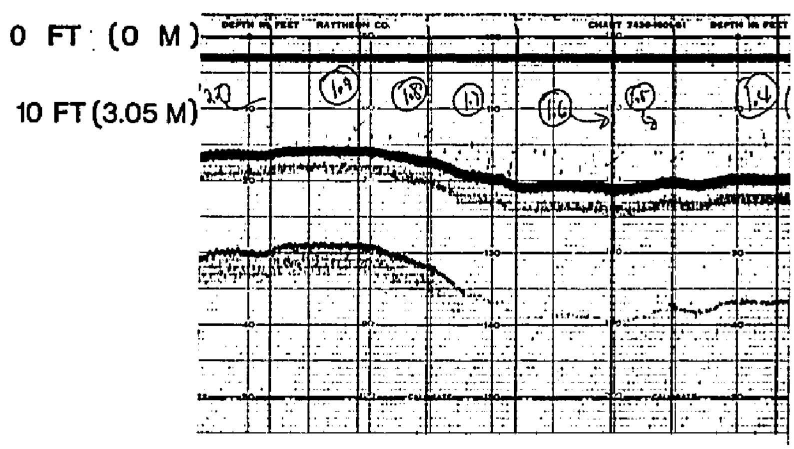
The objective of the side scan sonar surveys was to identify any textures or patterns on the bottom of the Wreck Shoal study area, that might assist in assessing the sedimentation processes operating on Wreck Shoal. In that regard, the results of the surveys are useful. All three side scan sonar surveys revealed very similar tracks or scars in the bottom. The origin of these bottom scars in not known; however a strong argument can be made that they have been caused by the passage of deep draft commercial vessels over the relatively shallow oyster reef. This case is further developed in Appendix A. The relative permanence of these scars on the Wreck Shoal oyster reef is of significance in this study. The implication of this observation is that in the nine month interval between the side scan sonar surveys, sediment transport processes on the shoal portions of the Wreck Shoal oyster reef were not very active, otherwise the bottom scars would have filled-in and disappeared. The second features of interest are rythmic undulations of the bottom at the bank of the deep natural

Figure 16

Wreck Shoal Study Area,
Subarea C,
Klien Side Scan Sonar and Raytheon Fathometer



KLIEN SIDE SCAN SONAR 25 JUNE 1984

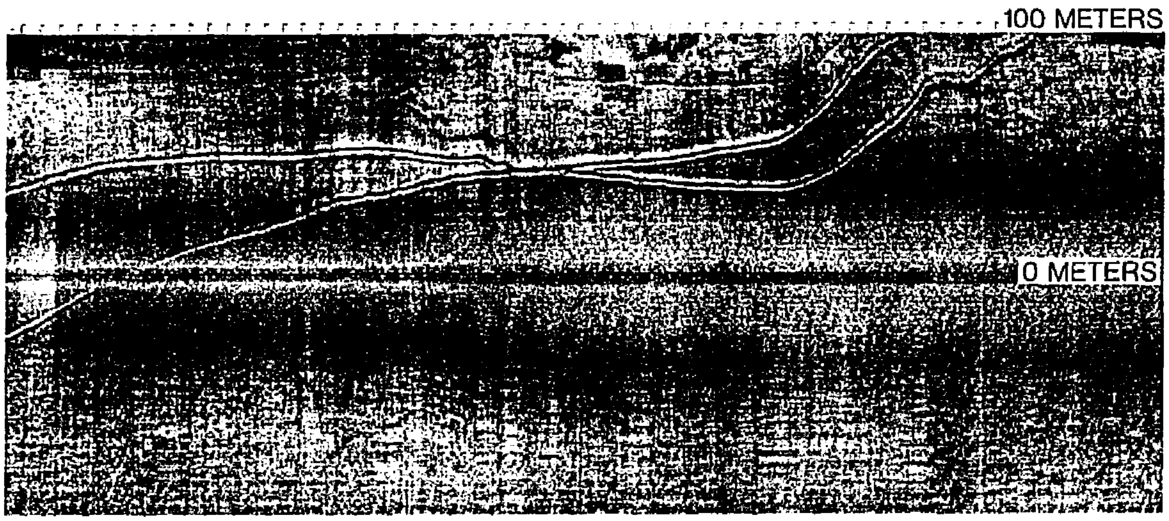


RAYTHEON FATHOMETER 25 JUNE 1984

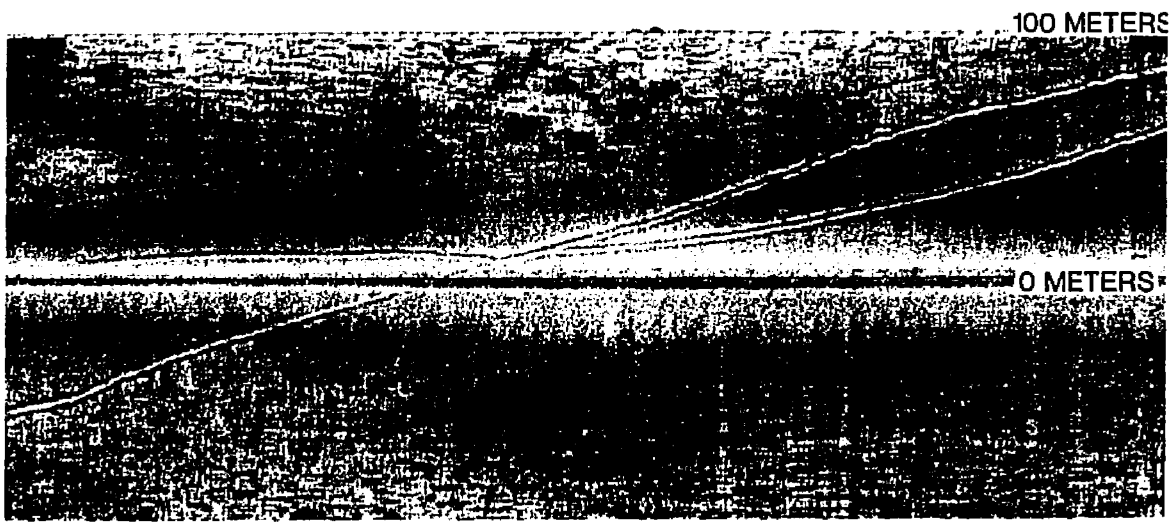
WRECK SHOAL STUDY AREA SUB AREA C

Figure 17

Wreck Shoal Study Area,
Subarea C,
E.G. and G. Side Scan Sonar



EG&G SIDE SCAN SONAR 5 JULY 1984



EG&G SIDE SCAN SONAR 13 MARCH 1985

WRECK SHOAL STUDY AREA SUB AREA C

channel shown in Subarea B. These features appear to be sand waves suggesting dynamic sediment transport processes along the flank of the channel. The darkened records along the channel axis also suggest coarse bottom sediments, and this also indicates areas of active sediment transport processes.

Subenvironment Description and Comparisons

The statistical comparison between the subenvironments was based on the following parameters: observed water depth, volume of exposed cultch, total number of live oysters, volume of live oysters, number of oyster boxes (recently dead oysters) and the percent gravel size, percent sand size, percent silt clay size of the interstitial bottom sediment. The 25 station sample values for each parameter were averaged, and are considered characteristic station sample values for that subenvironment. These mean values were then compared between two subenvironments using Student's T statistic (Steele and Torrie, 1960). In this case, the null hypothesis was that there was no difference between the two subenvironments for the parameter considered. Rejection of the null hypothesis indicated a significant difference. In comparing two means of 25 samples each, the value of T critical is based on 48 degrees of freedom.

A complete tabulation of sample station locations, sediment sample percentages, oyster reef sample data, and sediment sample statistics is presented in Appendix B.

The primary objective of the discrete sampling was to make the comparisons between the subenvironments. In that regard, the averaged data and the results of the subenvironment comparison are shown in Tables 1 and 2.

The oyster reef subenvironment comparison is summarized as follows.

1. The water depth of the subenvironments hard-rock and sand-shell both averaged 3.6 m (11.9 ft) deep and were significantly different from the average depth of 5.2 m (17 ft) in the mud-shell subenvironment.
2. The volume of exposed cultch at the hard-rock subenvironment was an average of 4.7 l (5 qt) per sample or 442 bushels per acre. That was significantly greater than the 1.9 l (2 qt) per sample or 171 bushels per acre at the sand-shell subenvironment and 2.3 l (2.5 qt) per sample or 220 bushels per acre at the mud-shell subenvironment. There was no significant difference between the sand-shell and mud-shell subenvironments.
3. The total number of live oysters in the hard-rock subenvironment was an average of 75 oysters per sample or 83 per m^2 and the sand-shell

TABLE 1

SUBENVIRONMENT SEDIMENT SAMPLE
MEANS AND STANDARD DEVIATIONS

Parameter	Hard-Rock Mean	Hard-Rock S.D.	Sand-Shell Mean	Sand-Shell S.D.	Mud-Shell Mean	Mud-Shell S.D.
Water Depth (ft)	11.9	0.9	11.9	0.6	17.0	1.8
(m)	3.6		3.6		5.2	
Volume of Exposed Cultch (qt)	5.0	2.8	2.0	1.2	2.5	1.4
(l)	4.7		1.9		2.3	
Total Number of Live Oysters	74.4	22.8	90.9	30.8	24.9	12.7
Volume of Live Oysters (qt)	5.3	1.4	4.9	1.2	3.1	1.3
(l)	5.0		4.6		2.9	
Number of Oyster Boxes	8.3	4.5	6.5	3.6	4.4	3.1
Sediment, Percent Gravel	39.4	6.2	34.0	7.4	8.1	8.7
Sediment, Percent Sand	38.0	6.1	41.6	7.2	25.5	6.2
Sediment, Percent Silt-Clay	22.5	5.0	23.8	5.4	66.5	7.9

TABLE 2

SUBENVIRONMENT COMPARISONS
STUDENT'S T-TEST

Parameter	HR-SS	HR-MS	SS-MS
Water Depth	Ø.37	12.54	13.58
Volume of Exposed Cultch (qt)	4.88	3.98	1.28
Total Number of Live Oysters	2.ØØ	9.48	1Ø.Ø1
Volume of Live Oysters (qt)	1.55	5.65	4.89
Number of Oyster Boxes	1.55	3.55	2.44
Sediment, Percent Gravel	2.85	14.2Ø	1Ø.89
Sediment, Percent Sand	1.91	6.88	8.Ø5
Sediment, Percent Silt-Clay	Ø.89	23.Ø3	21.66

α -level	Tc
Ø.Ø5	2.Ø
Ø.Ø1	2.68
Ø.ØØ1	3.5Ø

subenvironment was an average of 91 oysters per sample or 1ØØ per m^2. While these were not significantly different, they were both significantly different from the mud-shell subenvironment mean of 25 oysters per sample or 28 per m^2.

4. The volume of live oysters per sample in the hard-rock and sand-shell subenvironments was 5.Ø and 4.6 l or 472 and 432 bushels per acre respectively, and both were significantly different from the mean 2.9 l per sample or 254 bushels per acre in the mud-shell subenvironment.
5. The number of oyster boxes in the hard-rock, sand-shell, and mud-shell subenvironments was 8.3, 6.5 and 4.4 per sample, respectively. While there are significant differences between these means, the mortality is the percentage of dead oysters to live oysters. The mean mortality for the hard-rock, sand-shell and mud-shell subenvironments was 1Ø, 7 and 14 percent respectively and there were no significant differences between subenvironments.
6. With respect to the percent gravel size sediment, the hard-rock and sand-shell subenvironments were similar at 39 and 34 percent respectively and both were significantly different from the mud-shell at 8 percent.

7. With respect to the percent sand size sediment, the hard-rock and sand-shell subenvironments were similar at 38 and 41 percent respectively and both were significantly different from the mud-shell at 25 percent.
8. With respect to the percent silt clay size sediment, the hard-rock and sand-shell subenvironments were similar at about 23 percent and both were significantly different from the mud-shell at 66 percent.

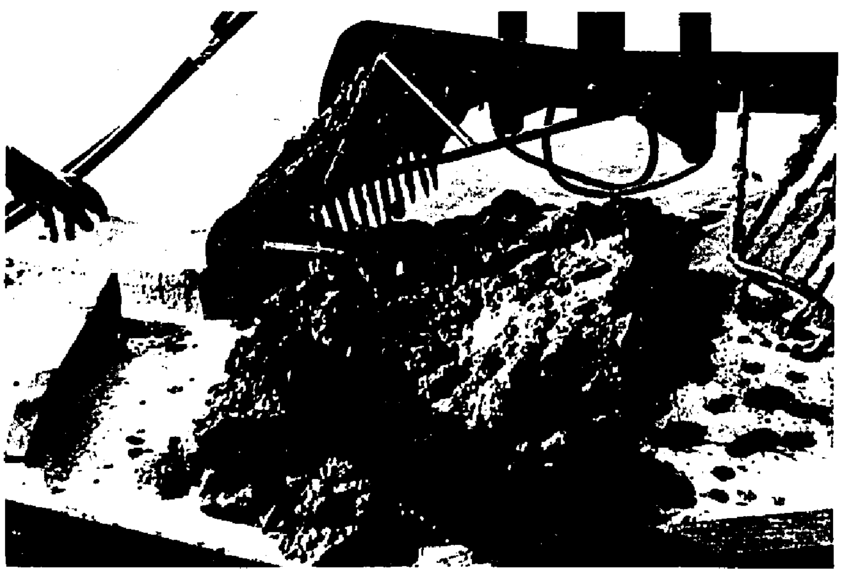
The conclusion that can be drawn from these analyses is that with the exception of the volume of exposed cultch, the hard-rock and sand-shell subenvironments are remarkably similar and both are significantly different from the mud-shell subenvironment.

The hard-rock and sand-shell subenvironments are characterized by a relatively thick shell layer, higher densities of live oysters, shoal water depth and a coarser interstitial sediment. In contrast, the mud-shell subenvironments are characterized by a very thin shell layer, considerably lower densities of live oysters, deeper water depth and a finer interstitial sediment. These characteristics are shown in the photographs of typical bottom grab samples from the hard-rock and mud-shell oyster reefs, (Figure 18).

Figure 18

Bottom Grab Samples,
Wreck Shoal Oyster Reefs

HARD ROCK OYSTER REEF



MUD - SHELL OYSTER REEF

BOTTOM GRAB SAMPLES OF THE WRECK SHOAL OYSTER REEFS.

Discussion

The specific objective of this part of the study was to investigate spatial and temporal variability in the surficial geomorphic character of the Wreck Shoal oyster reef. The results of the analyses described previously suggest that there is considerable spatial variability in the geomorphic character of the oyster reefs. The results of the subenvironment comparison indicate that two distinctly different types of oyster reefs coexist on Wreck Shoal, the hard-rock and the mud-shell. Previous investigators have classified the James River oyster reef in a variety of different manners. In fact, there may be a continuum in the variability of oyster reefs from 100 percent live oyster and shells to 100 percent sand or mud, with the majority of the oyster reefs grouped according to the results of this study. However, for the purposes of this investigation, Wreck Shoal oyster reef is considered to consist of two classes of oyster reef, the hard-rock and the mud-shell. The results of the repetitive side scan sonar surveys indicate a lack of activity in the sediment transport processes on Wreck Shoal. However the data also suggest that in the natural and dredged channels, and along the flank of the channels the sediment transport processes are very dynamic, scouring the channel and building sand wave features along the bank. The permanence of the bottom scars and the lack of change in other bottom features over the nine month interval between surveys also suggest little temporal variability in the surficial geomorphic character of the Wreck Shoal oyster reef.

Contemporary Circulation and Sedimentation Processes

Circulation Processes

The general circulation in the Wreck Shoal-Burwell Bay region of the James River was investigated based on the analysis of field and numerical model data. The field data was taken from a report tabulating the hydrographic data collected as part of Operation James River-1964 (Shidler and MacIntyre, 1967). These data were originally collected to provide information for the verification of the hydraulic model of the James River at Vicksburg, Miss. The numerical model data was taken from the results of a two-dimensional hydrodynamic mathematical model of the lower James River developed and reported on by Chen, Lukens, and Fang, 1979. The hydrodynamic system is based on the vertically averaged two-dimensional continuity and momentum equations.

Both the field and model data were extracted along a common single transect across Burwell Bay and Wreck Shoal, perpendicular to the river main axis. The objective of this analysis was to investigate spatial variability in the currents in the area surrounding Wreck Shoal. Previous investigators have alluded to the Burwell Bay channel as being ebb dominated and the Wreck Shoal/Rocklanding Shoal channel as flood dominated (Nichols,1972 a and Feuillet and Fleischer, 1979).

The field data from Operation James River-1964, was obtained for maximum flood and ebb tides on two separate tidal cycles, at six stations on the across river transect. Depending on the depth of the station on the transect, currents were available at one to four elevations. Because the currents were taken for this analysis at maximum flood and ebb, the directions of the current vectors were similarly aligned, and therefore the magnitudes of the current vectors were averaged to provide approximate vertically averaged current speed value.

The numerical model data was available for three nodal points on the finite element scheme for the same across river transect. Steady state values were taken for the magnitude of the maximum flood and ebb, to provide vertically integrated currents at these three points.

A comparison is made between field data and the model data along the across river transect for maximum flood and ebb tide in Figures 19 and 2Ø (see Figure 8 for station locations). Several observations regarding spatial variability of the currents in the Burwell Bay-Wreck Shoal region are made based on these data.

1. A remarkable similarity in the general distribution of the magnitude of the currents across the transect exists between the model and field data for both maximum flood and ebb tide. The currents over Rocklanding Shoal channel and Wreck Shoal are stronger by a factor of two than those in Burwell

Figure 19

Distribution of Current Speeds
Burwell Bay-Wreck Shoal,
Maximum Ebb Tide

DISTRIBUTION OF CURRENT SPEEDS
BURWELL BAY - WRECK SHOAL, MAXIMUM EBB TIDE

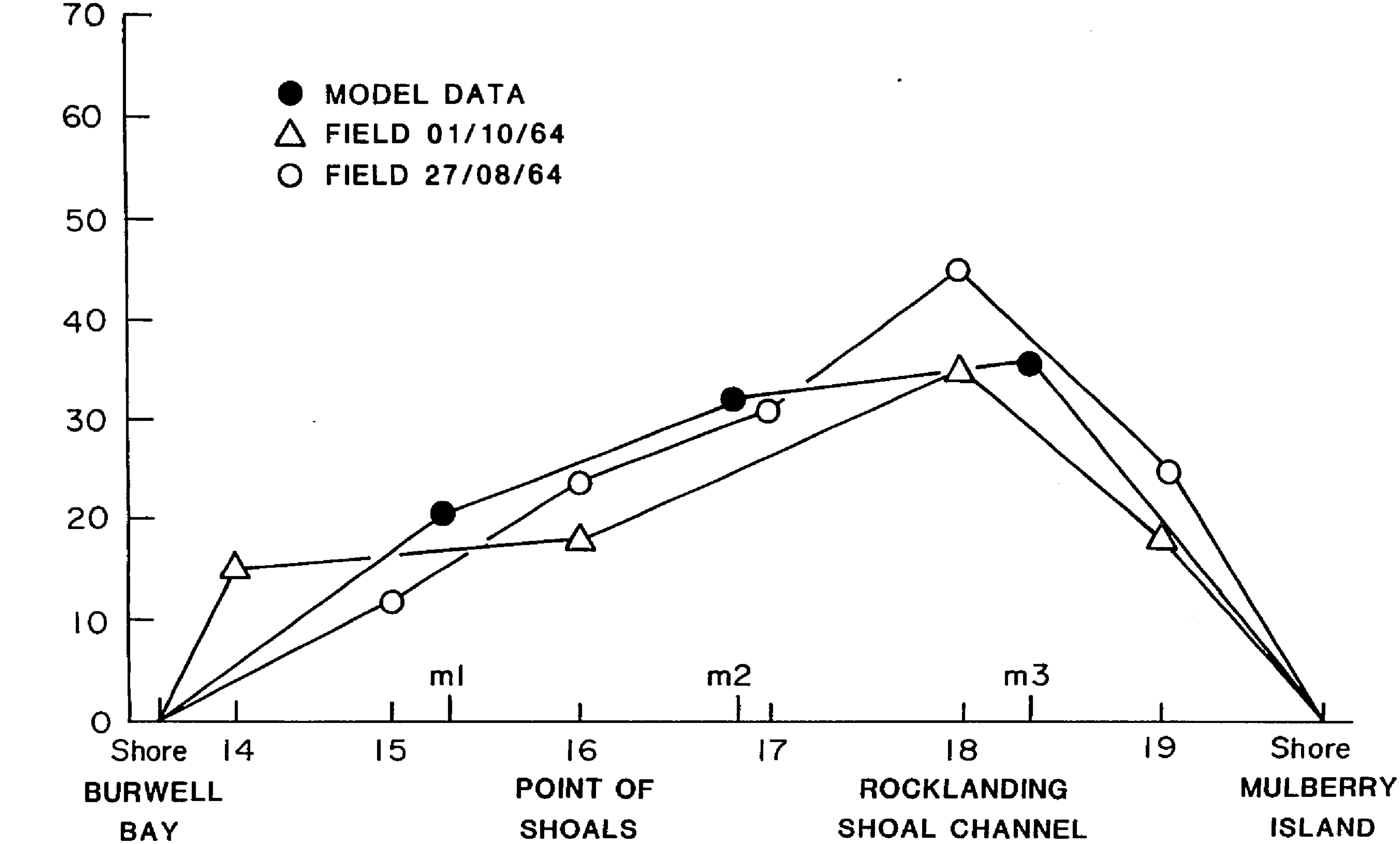
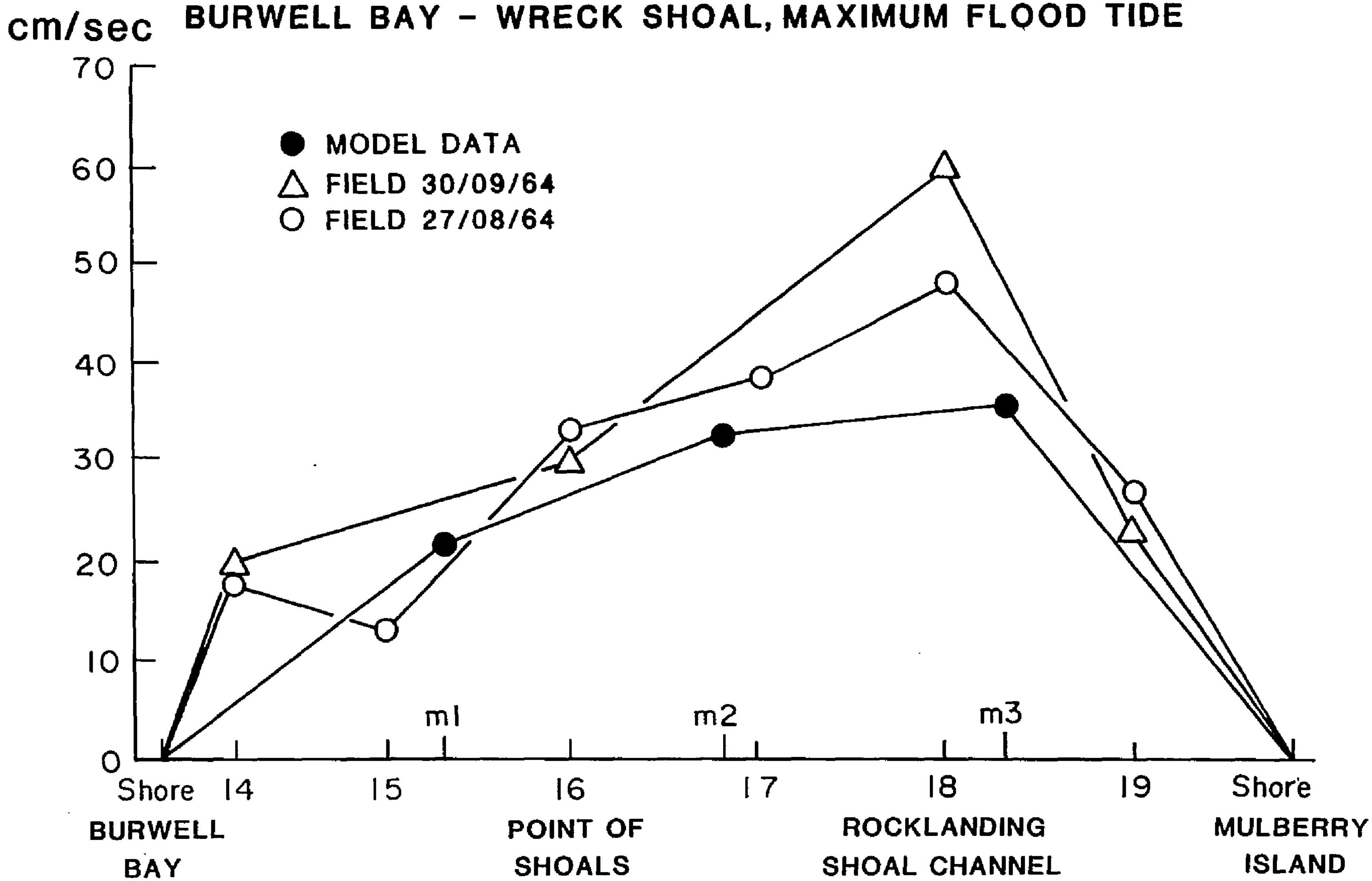


Figure 2Ø

Distribution of Current Speeds
Burwell Bay-Wreck Shoal,
Maximum Flood Tide

DISTRIBUTION OF CURRENT SPEEDS BURWELL BAY - WRECK SHOAL, MAXIMUM FLOOD TIDE



Bay. Thus, on a regional basis the currents are strongest in the relatively deeper, main dredged channel and the adjacent areas, and weakest in the shallow, shoaled area of Burwell Bay.

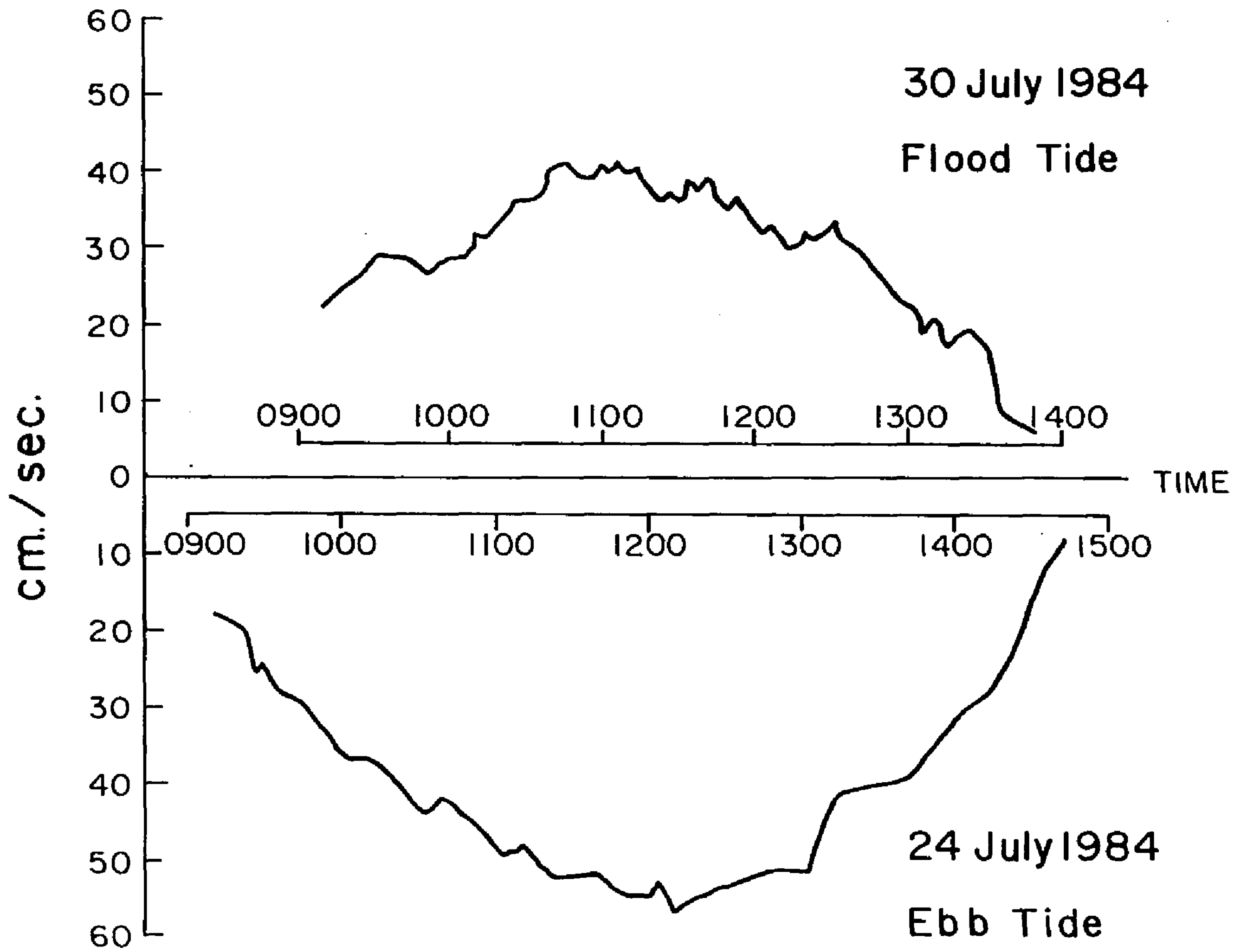
2. No clear asymmetry in the relative magnitude of flood and ebb currents appear in the Burwell Bay channel. In contrast, Rocklanding Shoal channel appears to be flood dominated based on the field data. This is consistent with the observations of a previous investigator (Nichols, 1972).

Spatial variations in the magnitude of the currents over Wreck Shoal were investigated using a small over the side current meter deployed at the various stations at about half hour intervals. The data analysis scheme began with the resulting half tidal cycle data sets initially being plotted. Figure 21 is an example of the plot of the flood and ebb high frequency sampling at the hard-rock station. Values were taken at concurrent half-hour intervals from all these plots and were compared to the hard-rock in situ current meter station as a reference to compensate for temporal variations in the flow. The comparison between the individual station over the side current meter data and the ENDECO in situ reference was made using regression analysis. These results were also normalized by dividing the individual station values for flood and ebb by the hard-rock station values. The final result was a

Figure 21

Bottom Currents, High Frequency Sampling
Station Hard-rock, Wreck Shoal

BOTTOM CURRENTS, HIGH FREQUENCY SAMPLING
STATION HARD ROCK, WRECK SHOAL



non-dimensional value for the magnitude of the flood and ebb currents relative to the hard-rock station. These are plotted in Figure 22.

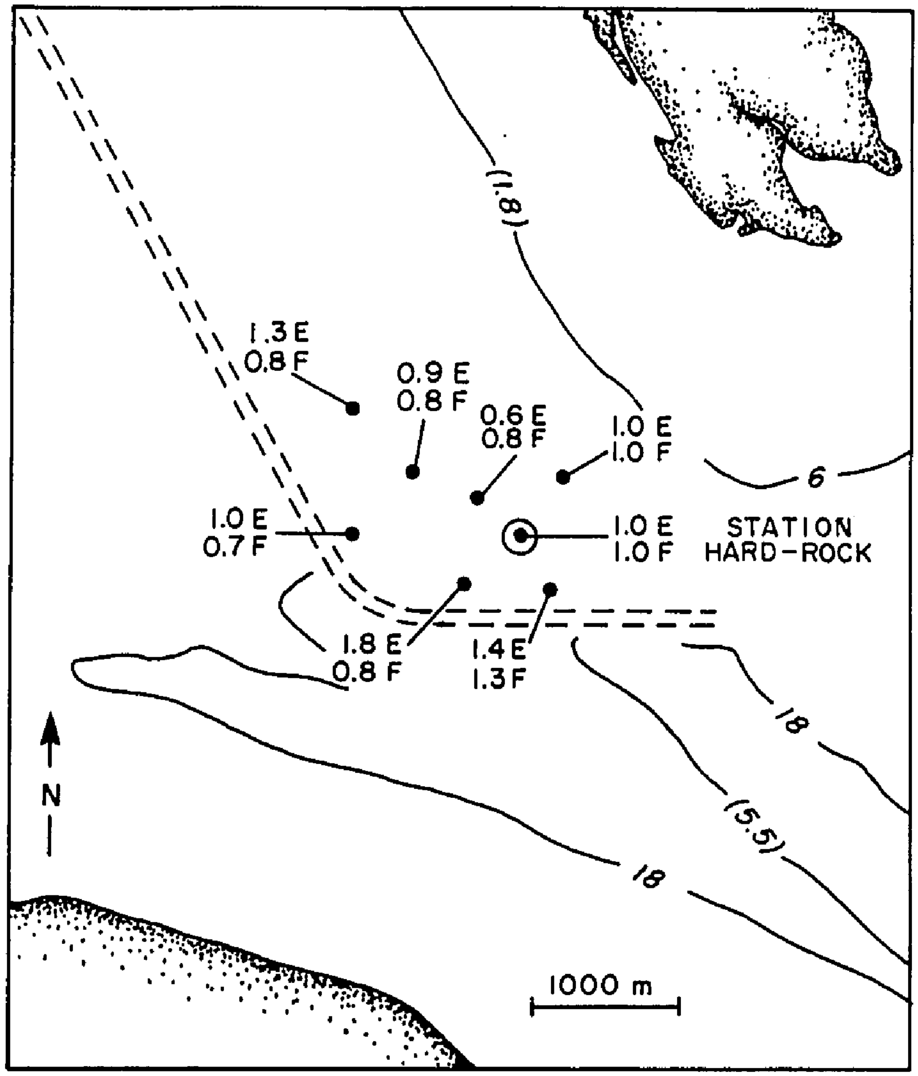
Several observations are made from these data analyses plots.

1. The individual high frequency sampling flood and ebb bottom current plots for the hard-rock station are remarkably smooth, indicating an absence of very large scale turbulence (periods greater than 2 minutes) or surges in the flow. This lends additional credibility to both the current meter data based on half-hour averages and to the analysis of spatial variations in the local bottom currents.
2. There are distinct spatial variations in the local flow regime over Wreck Shoal. The strength of the current varies from Ø.6 to 1.8 of the hard-rock reference station. The strongest currents are in the shallower water, the weakest currents are in the deeper water. In fact, there is an inverse correlation between the station normalized average current magnitude and the station observed low water depth, (R = -Ø.88).
3. It is clear that there are also definite asymmetries in the strength of the flood and ebb currents at particular stations. For example, at the station closest to the natural channel bank in

Figure 22

Spatial Variations in the Magnitude of
the Bottom Currents, Wreck Shoal Study Area

Normalized Values for Flood and Ebb Tide
with Reference to Hard-rock Station



● STATION LOCATION

SPATIAL VARIATIONS IN THE MAGNITUDE

OF THE BOTTOM CURRENTS

WRECK SHOAL STUDY AREA

DEPTH CONTOURS IN FEET (meter)

the southwest portion of the study area the flow varies from 1.8 of the hard-rock station on ebb tide to Ø.8 of the hard-rock station on flood tide. In contrast, the flow is symmetric in strength on flood and ebb tides at both the hard-rock and sand-shell stations. These data suggest that the shoal areas adjacent to the main channel and Rocklanding Shoal channel are ebb dominated, while the shoal areas on the interior of the reef are balanced with respect to tidal currents. This observation is contrary to the results of the previous analysis based on regional field and model data. A possible explanation for this, is that the Operation James River field data, and the numerical model data are vertically averaged speeds at maximum current, whereas the over the side current meter data are only bottom currents, over a tidal cycle, measured one meter above the bed. In this regard, bottom currents measured on a shallow shoal might be ebb dominated, due to the superposition of the upper layer estuarine net non-tidal circulation, on the tidal currents.

Temporal variations in the bottom currents over Wreck Shoal were investigated using an in situ recording current meters deployed simulataneously in each of the three subenviroments for a 29 day period.

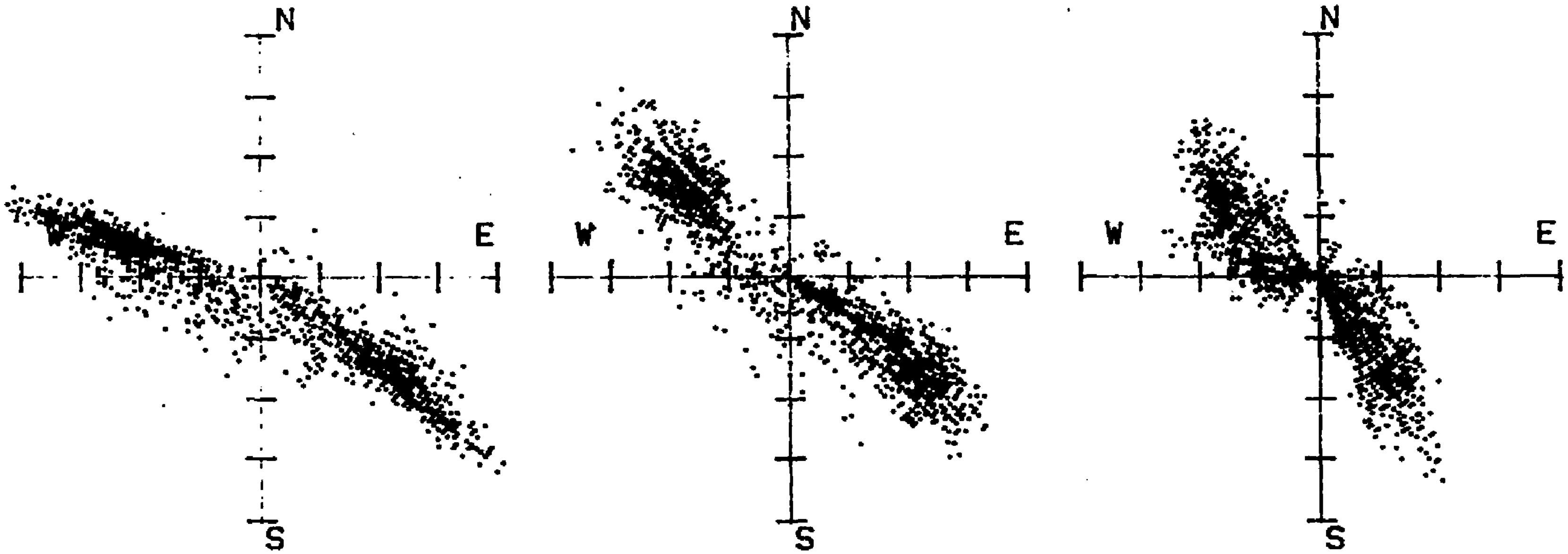
Initially, the current meter data was plotted on a polar coordinate scatter diagram to graphically illustrate the general alignment of the flow and the degree of scatter in the current direction (Figure 23). Based on these plots, it was determined to continue the analysis based on a general river alignment of 315° upstream and 135° downstream. Inspection of the three current meter scatter diagrams indicate symmetric, reversing flow at stations sand-shell and mud-shell and a skewed or offset plot at the hard-rock station. The assymetric nature of the directional plot for the hard-rock station suggests a veering of the flood currents as the tidal wave is deflected by the Wreck Shoal-Point of Shoals point bar complex.

The general magnitudes of the currents are similar for the hard-rock and sand-shell subenvironments with maximum currents of 5Ø cm/sec and 4Ø cm/sec, respectively. These are about 1Ø-2Ø cm/sec greater than the maximum currents at the mud-shell station of 3Ø cm/sec.

Each current time series file was next divided into components along and across the river axis. The mean current was calculated and removed from the series. The variance due to the undefined periodic currents was calculated. The resulting series were then harmonically analyzed for the amplitude and phase lag of the principal tidal constituents: S2, M2, N2, P1/K1, and O1 (Dronkers, 1964). The purpose of this analysis scheme was to identify,

Figure 23

Scatter Plot Bottom Currents,
Station Hard-rock, Sand-shell and Mud-shell



HARD ROCK STATION SAND SHELL STATION MUD SHELL STATION

SCALE 10 CM/SEC=

SCATTER PLOTS-BOTTOM CURRENTS
WRECK SHOAL-JAMES RIVER, VA

compare, and contrast the relative magnitudes of tidal current energy in the three subenvironments.

Harmonic analysis is a technique in which the frequency of a forcing function is specified, and the amplitudes and phase lag of that function are determined from a time series of responses resulting from a combination of the forcing function in question with other forces of different frequencies. Tidal currents, which are the result of water displacement under a tidal wave, may be evaluated in this manner. In general, the harmonic series for (m) constituents can be written in the finite Fourier series form (Bendat and Piersol, 1971, and Jenkins and Watts, 1968).

$$Y_t = A_o + \sum_{m=1}^{k} A_m \sin \left(\frac{2\pi t}{T_m} + B_m\right) \qquad (1)$$

where: Y_t = observed current component

A_o, A_m = harmonic amplitudes

T_m = period of the m constituent

B_m = phase lag of m constituent

Expanding the terms of equation

$$Y_t = A_o + \sum_{m=1}^{k} a_m \cos \frac{2\pi t}{T_m} + \sum_{m=1}^{k} b_m \sin \frac{2\pi t}{T_m} \qquad (2)$$

where:

$$a_m = A_m \sin B_m$$

$$b_m = A_m \cos B_m$$

or conversely:

$$A_m = (a_m^2 + b_m^2)^{\frac{1}{2}}$$

$$B_m = \tan^{-1} (a_m/b_m)$$

For a time series of N data points, in descrete time intervals, the coefficients a_m and b_m are given by:

$$a_m = 1/N \sum_{n=1}^{k} Y_n \cos 2\pi mn/N \text{ for } m = 1, 2 \cdots N/2-1 \qquad (3)$$

$$b_m = 1/N \sum_{n=1}^{N} Y_n \sin 2\pi mn/N \text{ for } m = 1, 2 \cdots N/2-1 \qquad (4)$$

where: n = harmonic number.

Y_n = observed value at n data point.

N = total number of data points.

The sampling interval for this current meter time series data was one half hour. The record length or fundamental period was 29.5 days or 708 hours. The number of data points was therefore 1416. The names and periods of the principal tidal constituent used in this analysis are listed below:

Constituent	Period Hours	Name
S2	12.00	Solar Semidiurnal
M2	12.42	Lunar Semidiurnal
N2	12.66	Lunar Elliptical
P1/K1	24.07/23.93	Solar Diurnal Soli-Lunar
O1	25.82	Lunar Diurnal

Upon completing the harmonic analysis, the variance due to the calculated tidal constituents was determined. The results of these analyses are listed in Tables 3, 4, and 5 and illustrated in Figures 24, 25, and 26.

Based on these analyses, the following observations are made:

1. All three sites have relatively small net or mean bottom currents compared to the total bottom currents. However, it is interesting to note that the net bottom currents are downstream. This is contrary to the theory of estuarine circulation, in which the net non-tidal circulation on the bottom is upstream. However, in this case, because the bottom currents are over a shoal, the net non-tidal component is probably representative of the upper estuarine layer, and therefore flows downstream.
2. In the along river axis direction, tidal currents account for 81 to 93 percent of the total observed periodic energy (variance) in the water.
3. In the across river axis direction, tidal currents account for only 18 to 84 percent of the total observed periodic energy (variance) in the water. At the hard-rock station, the across river axis variance is 14 percent of the along river axis, and the tidal model accounts for 84 percent of the across river axis energy. At the mud-shell

Table 3

CURRENT METER DATA ANALYSIS
STATION HARD-ROCK

Along River Axis

Observed Mean = -2.8 cm/sec

Observed Variance = 541.9 cm^2/sec^2

Constituent	Amplitude	Phase Lag (degrees)	RMSQ
O1	1.87	-31.4	7.0
P1	2.69	-3.4	14.5
N2	3.07	1.5	18.8
M2	15.25	-79.4	465.1
S2	0.04	-71.7	.0
		Total Tidal	505.4
		% of Observed	93.2

Across River Axis

Observed Mean = -4.2 cm/sec

Observed Variance = 78. cm^2/sec^2

Constituent	Amplitude	Phase Lag (degrees)	RMSQ
O1	0.55	-45.1	0.6
P1	0.81	-30.3	1.3
N2	0.76	- 0.5	1.2
M2	5.61	-84.6	63.0
S2	0.19	56.5	0.1
		Total Tidal	66.3
		% of Observed	84.6

Table 4

CURRENT METER DATA ANALYSIS
STATION SAND-SHELL

Along River Axis

Observed Mean = -1.7 cm/sec

Observed Variance = 5Ø1.7 cm^2/sec^2

Constituent	Amplitude	Phase Lag (degrees)	RMSQ
O1	1.61	-23.1	5.2
P1	2.21	-9.1	9.7
N2	2.71	6.8	14.7
M2	14.59	-76.1	426.3
S2	Ø.13	-58.9	Ø.3
		Total Tidal	456.3
		% of Observed	91.Ø

Across River Axis

Observed Mean = Ø.4 cm/sec

Observed Variance = 21.2 cm^2/sec^2

Constituent	Amplitude	Phase Lag (degrees)	RMSQ
O1	Ø.2Ø	-45.6	Ø.1
P1	Ø.11	-39.8	Ø.2
N2	Ø.Ø6	-16.4	Ø.Ø
M2	2.Ø4	81.6	8.3
S2	Ø.Ø4	33.8	Ø.Ø
		Total Tidal	8.6
		% of Observed	4Ø.1

Table 5

CURRENT METER DATA ANALYSIS
STATION MUD-SHELL

Along River Axis

Observed Mean = -0.2 cm/sec

Observed Variance = 243.6 cm^2/sec^2

Constituent	Amplitude	Phase Lag (degrees)	RMSQ
O1	1.72	-3.5	6.0
P1	1.92	15.1	7.4
N2	2.49	13.5	12.4
M2	9.29	-86.7	172.9
S2	0.04	-78.2	0.0
		Total Tidal	198.7
		% of Observed	81.6

Across River Axis

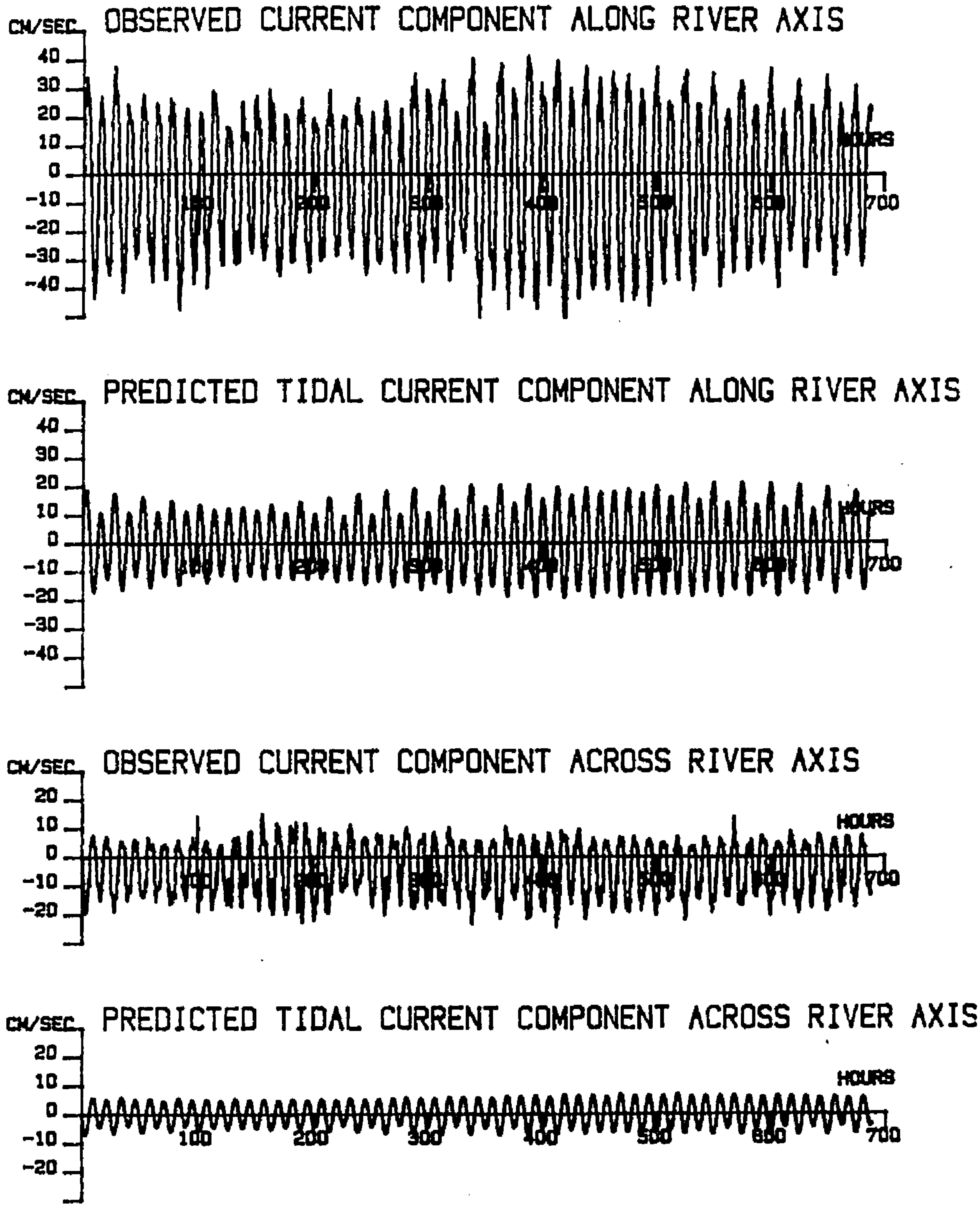
Observed Mean = -2.3 cm/sec

Observed Variance = 14.2 cm^2/sec^2

Constituent	Amplitude	Phase Lag (degrees)	RMSQ
O1	0.62	44.7	0.8
P1	0.48	75.4	0.5
N2	0.47	21.8	0.5
M2	0.64	13.1	0.8
S2	0.11	7.9	0.0
		Total Tidal	2.5
		% of Observed	18.3

Figure 24

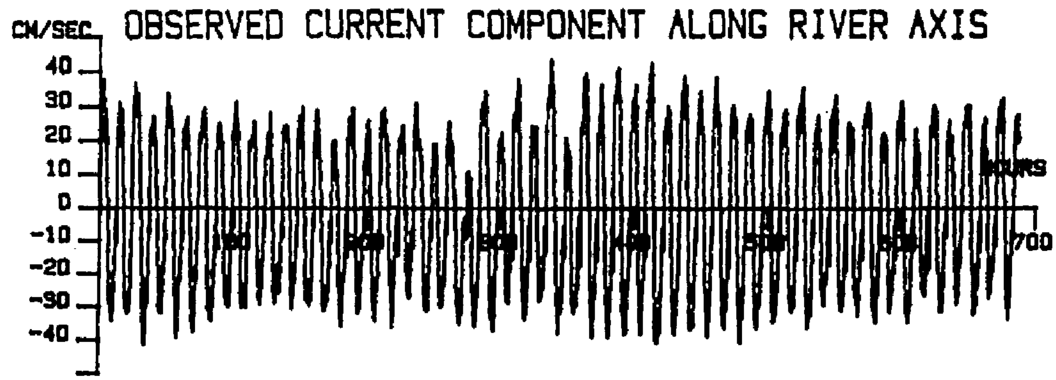
Observed and Predicted Current Components, Station Hard-rock

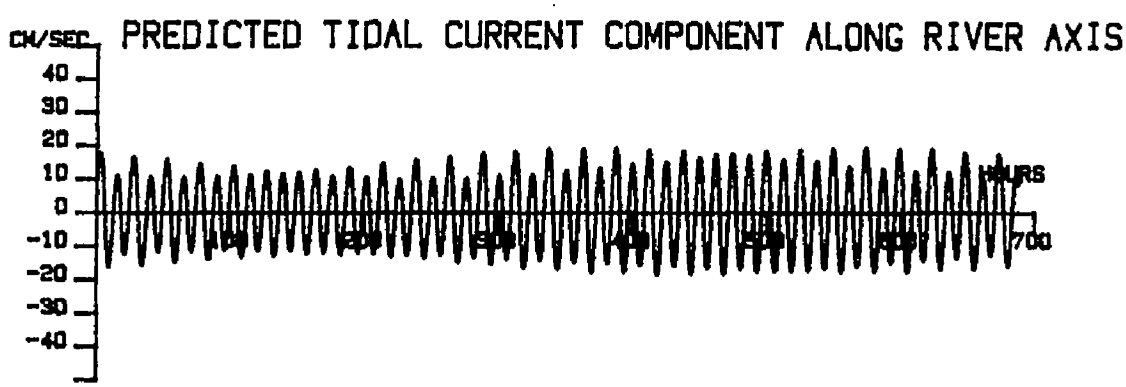


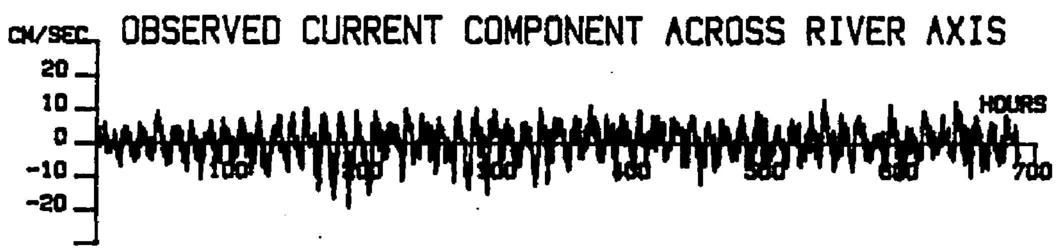
WRECK SHOAL, JAMES RIVER
STATION HARD ROCK

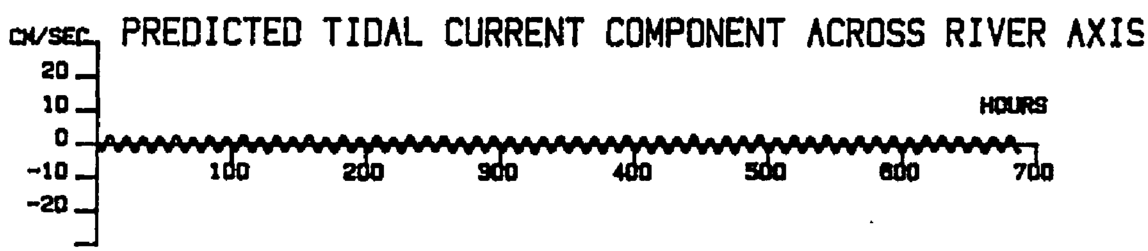
Figure 25

Observed and Predicted Current Components,
Station Sand-shell





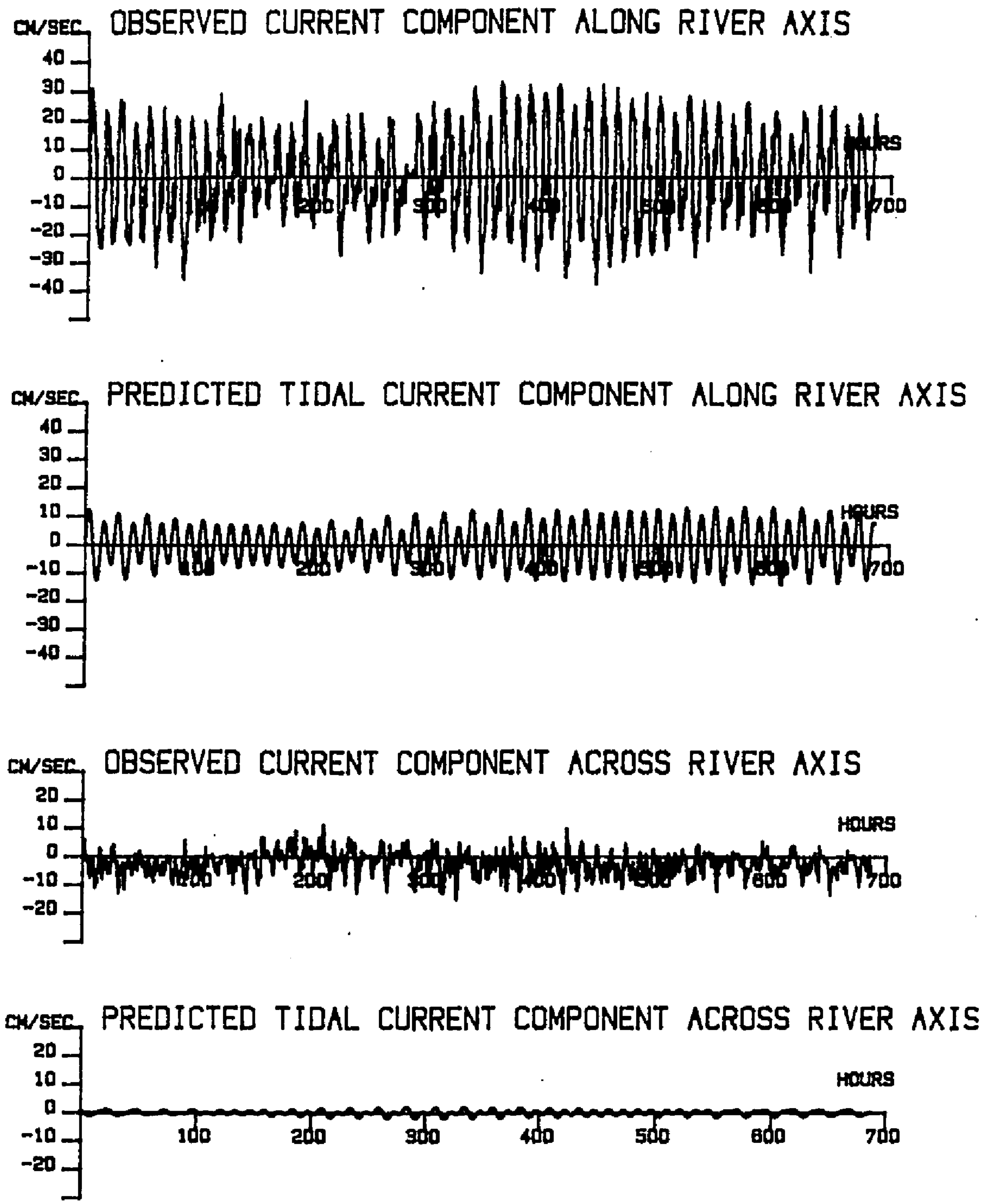




WRECK SHOAL, JAMES RIVER
STATION SAND SHELL

Figure 26

Observed and Predicted Current Components,
Station Mud-shell



WRECK SHOAL, JAMES RIVER
STATION MUD SHELL

station, the across river axis variance is only five percent of the along river axis, and the tidal model accounts for only 18 percent of the energy. For weak currents, the tidal model does not accurately portray the measured currents, because the non-tidal energy is relatively large compared to the tidal energy.

4. With respect to total observed periodic energy in the along river axis direction, the total energy is comparable between the hard-rock and sand-shell stations at 541.9 and 5Ø1.7 cm^2/sec^2, respectively. In contrast, the mud-shell station indicates only 243.6 cm^2/sec^2, or about half the energy of the other two stations. That is, the bottom currents at the shallower hard-rock and sand-shell stations are twice as energetic as the bottom currents at the mud-shell station.

Sedimentation Processes

Temporal variations in the surficial sediment layer of the Wreck Shoal subenvironment oyster reefs and the shell-shale experimental plots were investigated by making periodic diver observations of the bottom conditions over a 14 month period. On the subenvironment oyster reefs, no significant observeable change in the sedimentary conditions on the subenvironment oyster reefs was noted during the entire study period. On the shell and shale experimental plots, a slight amount of sediment cover was observed to accumulate over the fourteen month monitoring period. On the oyster shell plots, it began as a thin veneer, covering an increasing percentage of the clean oyster shell surface each monitoring period. By the spring of 1985, the fine sediment layer was about 1 mm thick and was 90 percent complete in its coverage. On the shale plot, the sediment layer appeared to accumulate at a more rapid rate, with greater coverage. By the winter of 1984-85, the sediment layer reached a thickness of 1-2 mm and the coverage was 100 percent complete. In late spring, early summer, June 1985, an interesting phenomena occurred, in that there was a reduction in the thickness of the sediment layer and in the percent coverage on both the shell and shale experiment plots. This apparent loss of fine sediment was not associated with a significant storm that would have provided additional energy to resuspend the accumulated sediments and remove them from the oyster reef.

Biodeposition is defined herein to be the process whereby sediments of biological origin are deposited on the bottom of the estuary or other bodies of water. On the oyster reefs of Wreck Shoal, the biodepositional sediments include feces, pseudo-feces and skeletal shell materials.

As noted earlier, oysters and other benthic invertebrates inhabiting the estuarine oyster reefs are filter feeders. These suspension feeding animals obtain their food by pumping large quantities of water through their gills or other ciliated feeding organs. This water contains plankton, detritus, and very fine suspended sediments. Material initially rejected in the form of loosely bound clumps is referred to as pseudo-feces. The remainder is ingested in the gut and egested as feces: fecal pellets or strings (Nichols, 1984). Haven and Morales-Alamo (1966) limited their definition of biodeposition to the process of filtration, compaction in the gut, and subsequent deposition. This form of biodeposition is significant as an estuarine sedimentary process in that very fine suspended sediment particles (1 to 3 microns) with extremely slow settling velocities, are concentrated and compacted into much larger fecal pellets, up to 3 mm in size. The resulting pellets have much faster settling rates than their component particles. Haven and Morales-Alamo (1972) estimated that an acre (Ø.4 h) of productive oyster reef would produce 4Ø5 kg (dry) of biodeposits per week. These biodeposits were approximately 85 percent inorganic clays, 1Ø percent organic carbon and 5 percent other material. This estimate was based on 25Ø,ØØØ oysters, of the 5 to 7 cm size, per acre (Ø.4 h), or 5ØØ soup size oysters per bushel (52.5 l) and 5ØØ bushels (26,25Ø l) per acre (Ø.4 h) as the standing crop. The rate of biodeposit production estimated by Haven and Morales-Alamo compares reasonably well with estimates of other investigators for densely populated bivalve reefs (Verwey, 1952 and Ito and Imal, 1955).

However, while this number appears large, the volume of actual sediment produced by that acre (Ø.4 h) of oysters is not that great when evenly distributed over the bottom. Assuming the bottom sediment to be 5Ø percent water by weight, the density of the dry material at 2.7 gr/cc, and the voids between the sediment particles filled by water and not gasses, then the weekly production of sediment by volume can be calculated. Summing this over a 26 week growing season, and distributing the volume over one acre (Ø.4 h), the thickness of sediment over an oyster reef due to biodeposition in one season is 3.5 mm (Ø.Ø1 ft). Assuming no resuspension, erosion, compaction or water loss of these pellets, this yields 35 cm (1.1 ft) of biodeposits per 1ØØ years. Based on these calculations, biodeposition of oyster feces and pseudo-feces does not appear to be an serious problem on oyster reefs, in that individual oysters grow at a rate of approximately 2.5 cm per year, and therefore should be able to keep ahead of being buried in their own feces.

Another source of material to the oyster reef is the deposition of oyster shells from the natural mortality of the oyster population. Typically, oyster reefs in good condition experience a natural annual mortality rate of about 5Ø percent by number (Mackin, 1961). With a standing crop of 5ØØ bushels (26,25Ø l) per acre (Ø.4 h), this yields a contribution of 25Ø bushels (13,125 l) of shells per year to the oyster reef. To set this in perspective, for an oyster reef to accumulate a layer of shells 35 cm (1.1 ft) thick due to the natural mortality of the oyster population, it would take about 100 years. It must be noted that this is only a first order estimate, because the standing crop is based on biomass and the mortality is based on animal numbers.

At this point, it is interesting to compare these estimates of the two biogenic sources of material contributed to the oyster reef, to the eustatic rate of sea level rise. Biodeposition of feces is estimated at 35 cm (1.1 ft) per 100 years, the deposition of the oyster shells is estimated at 35 cm (1.1 ft) per 100 years, and sea level is rising at about 40 cm (1.3 ft) per 100 years.

The void space in an oyster shell reef is approximately 50 percent depending on the shell size, (determined by volumetric measurement in this study). This space may be filled with fecal deposits that contribute to reef growth. If there were negligible resuspension and transport of fecal biodeposits, a productive oyster reef could develop vertically at a rate in excess of 50 cm per 100 years, resulting from the deposition of oyster shells and fine fecal muds in a dense matrix. In comparison to the present rate of sea level rise, it appears that an oyster reef could develop subtidally and evolve to an intertidal reef. However if shells and oysters were removed from the reef, an intertidal reef could revert to a subtidal reef. If there were considerable resuspension and transport of fecal biodeposits, the void space would probably continue to trap fine sediments; however the excess sediments would be removed, limiting reef growth to the rate of oyster shell deposition, which is slightly less than the present rate of sea level rise. If shells and oysters are removed from the reef through harvesting activity, the reef would recede into deeper water at an accelerated rate.

The roughness of the bottom in the subenvironments was determined based on measurments of the near-bed velocity profile over a complete tidal cycle. The sampling interval was one minute for a ten minute period every half hour. The data collected by each current meter at one minute intervals was averaged for the ten minute period to yield a mean value for that period. These mean values for each instrument were compiled to produce a velocity profile for each ten minute measurement period.

For steady, turbulent flow over a hydraulically rough boundary, the bottom roughness is determined from the quadratic shear stress law and the von Karman-Prandtl equations for the logarithmic velocity profile (Inman, 1963).

The boundary shear stress is defined as:

$$\tau = A_z \, (d\bar{u}/dz) \qquad (5)$$

where: A_z = the eddy viscosity in the vertical direction

z = the depth.

Prandtl's Mixing Length Theory defines the vertical eddy viscosity as:

$$A_z = \rho \, l^2 \left| d\bar{u}/dz \right| \qquad (6)$$

where: ρ = the density of the fluid and

l = the mixing length.

The mixing length, l, is then defined as:

$$l = k \, (z + z_o) \qquad (7)$$

where: k = von Karman's constant, Ø.4

z = depth measured positive upwards

z_o = roughness length and is related to the height of the roughness elements on the bottom.

Substituting equation 7 into equation 6:

$$A_z = \rho \, (k \, (z + z_o))^2 \left| d\bar{u}/dz \right| \qquad (8)$$

And substituting equation 8 into equation 5, results in "Prandtl's Mixing Length Hypothesis":

$$\tau = \rho \, (k \, (z + z_o))^2 \left| d\bar{u}/dz \right|^2 \qquad (9)$$

Rearranging equation 9:

$$d\bar{u}/dz = \sqrt{\tau/\rho} \, (1/k \, (z + z_o)) \qquad (10)$$

Integrating and solving for the shear stress:

$$\tau = \rho \, k^2 \bar{u}^2 / \ln \left(\frac{z + z_o}{z_o} \right) \qquad (11)$$

The friction velocity, (U_*) is defined as:

$$U_* = \sqrt{\tau/\rho} \qquad (12)$$

Then substituting, results in the von Karman-Prandtl equation for boundary currents over a rough surface:

$$\bar{U} = (U_*/k)\ \ln\left(\frac{z + z_o}{z_o}\right) \tag{13}$$

Rearranging the equation 13 provides:

$$\ln(z + z_o) = (k/U_*)\bar{U} + \ln z_o \tag{14}$$

This equation is used to obtain a graphic solution for z_o, the roughness length, by plotting on semi-log paper $\bar{U}$ versus height off the bottom, z.

Since U_* has dimensions of velocity and is proportional to the average velocity $\bar{U}$ at some distance z above the bottom, then:

$$U_*^2 = Cd\ \bar{U}^2 \tag{15}$$

where: Cd = a constant of proportionality, the drag coefficient.

Substituting equation 15 into equations 11 and 12:

$$\tau = \rho U_*^2 = Cd\,\rho\,\bar{U}^2 = \rho\, k^2\bar{U}^2/\left(\ln \frac{z + z_o}{z_o}\right)^2 \tag{16}$$

Thus, assuming hydrodynamically rough flow, for a given depth, once z_o, the bottom roughness length is known, the drag coefficient can be determined for a particular bed configuration.

The velocity profile data for the hard-rock and mud-shell stations are shown in Tables 6 and 7. Near slack tide, ± 1 hour, observations could not be made because the current was not sufficiently strong to orient the instrument

Table 6

VELOCITY PROFILES DATA AND ANALYSIS
STATION HARD-ROCK

Tide	Speed (cm/sec) at 1ØØ cm	Speed (cm/sec) at 53 cm	Speed (cm/sec) at 24 cm	Zo (cm)	R
E	22.9	-	1Ø.7	6.7	1.ØØ
E	22.Ø	-	11.Ø	5.8	1.ØØ
E	21.Ø	12	9.1	1Ø.9	Ø.94
E	21.6	12.5	8.5	11.6	Ø.96
E	16.2	8.8	3.4	17.5	Ø.99
F	8.2	6.4	2.7	11.5	Ø.99
F	12.2	1Ø.1	5.8	6.6	Ø.99
F	17.4	13.4	8.8	5.6	Ø.99
F	22.6	18.3	12.8	3.7	Ø.99
F	26.5	2Ø.1	14.6	4.4	Ø.99
F	25.9	2Ø.1	16.8	2.1	Ø.98
F	29.6	23.2	19.2	2.Ø	Ø.98
F	28.7	19.5	16.2	5.3	Ø.94
F	25.9	23.5	17.Ø	1.9	Ø.98
F	23.2	17.1	14.6	2.9	Ø.96
F	16.8	14.Ø	1Ø.1	2.8	Ø.99
F	15.8	13.7	8.8	4.1	Ø.99
F	19.5	13.4	9.8	6.6	Ø.98

Table 7

VELOCITY PROFILE DATA AND ANALYSIS
STATION MUD-SHELL

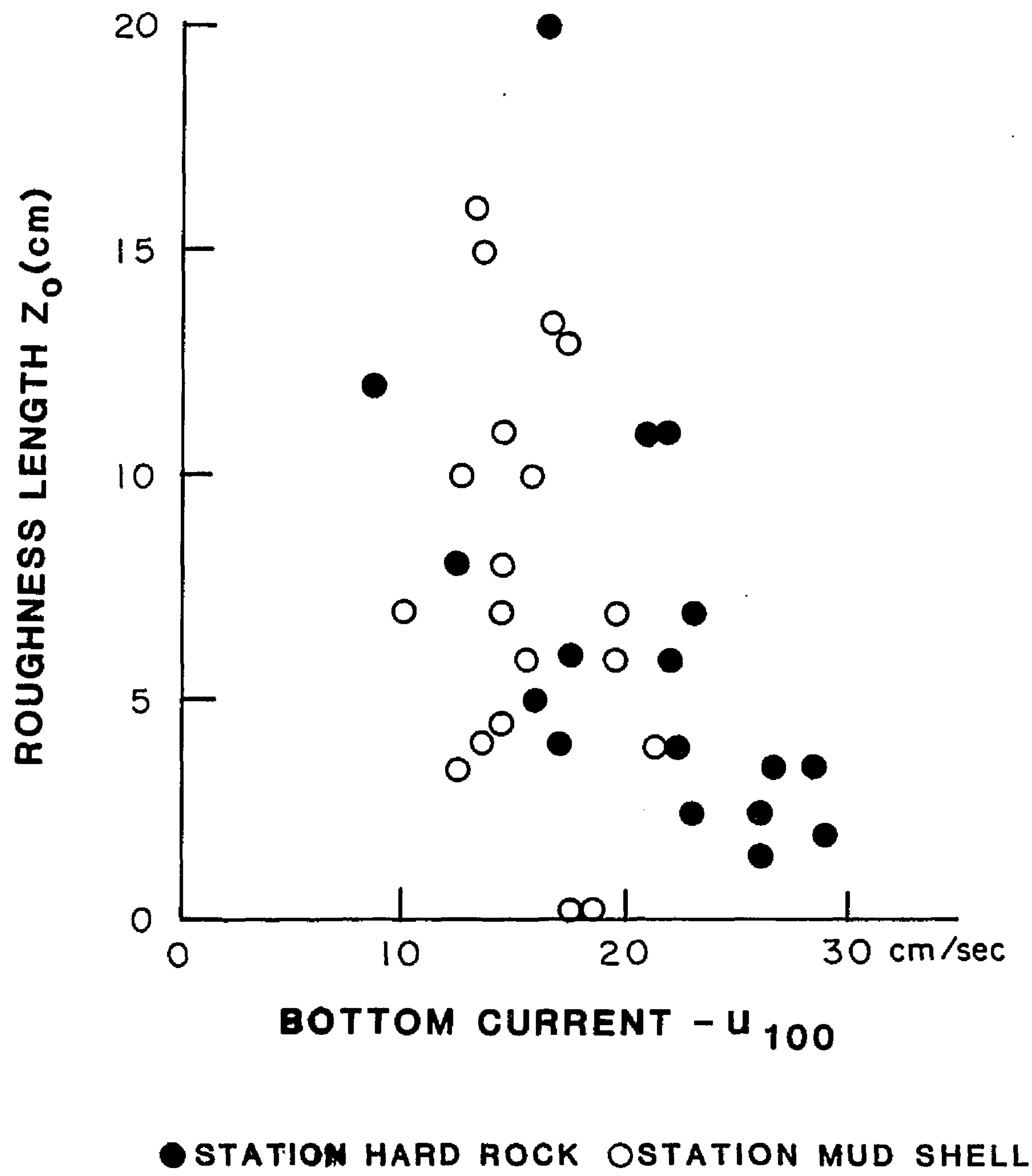
Tide	Speed (cm/sec) at 1ØØ cm	Speed (cm/sec) at 53 cm	Speed (cm/sec) at 24 cm	Zo (cm)	R
E	1Ø.1	9.4	4.6	8.3	Ø.94
E	16.8	9.8	5.8	12.8	Ø.98
E	13.7	9.7	4.9	1Ø.8	Ø.99
E	15.6	11.Ø	6.1	9.7	Ø.99
E	14.3	1Ø.1	6.1	8.6	Ø.99
E	11.3	8.5	2.9	16.Ø	Ø.99
F	13.4	8.8	3.9	13.5	Ø.99
F	12.8	1Ø.7	4.6	1Ø.8	Ø.97
F	17.1	9.8	5.8	13.3	Ø.97
F	17.4	15.5	13.8	Ø.1	Ø.99
F	13.6	17.Ø	14.5	Ø.2	Ø.99
F	18.6	14.6	13.4	1.1	Ø.93
F	14.3	12.2	7.6	4.8	Ø.98
F	13.4	11.Ø	7.6	3.7	Ø.99
F	12.5	1Ø.1	7.Ø	3.9	Ø.99
F	14.3	1Ø.4	6.1	8.3	Ø.99
F	19.5	14.9	9.4	6.4	Ø.99
F	15.Ø	12.8	7.9	5.2	Ø.99

platform. In fact, limited observations made during that period indicate reversals and rotations in the velocity profile within the lower 1 m of the water column. As the tidal velocity began to increase, with values of U_{100} greater than 10 cm/sec, the plots of the velocity profiles resulted in inordinately high values for z_o, the roughness length.

The data points for each profile were analysed with a least squares technique for the roughness length, z_o. A correlation coefficient was calculated, as this reflects the goodness of the straight line fit, to the logarithmic velocity profile. For the hard-rock station, the values of z_o ranged from 17.5 cm to 1.9 cm and almost all of the correlation coefficients were greater than 0.98. The roughness length values weakly tended to decrease with increasing velocity, and the correlation coefficent for this relationship was -0.49. For the mud-shell station, the values of z_o ranged from 16.0 cm to 0.1 cm, and again, almost all of the correlation coefficients were greater than 0.98. These roughness length values also weakly tended to decrease with increasing velocity, and the correlation coefficient for this relationship was -0.34. These relationships are illustrated in Figure 27. An attempt was made to improve the fit of the velocity profiles to a logarithmic straight line by applying a zero shift, and thus removing any curvature (Grant and others, 1983). However,

Figure 27

Bottom Roughness Length
as a function of Bottom Current Speed


ROUGHNESS LENGTH Z_0 (cm)
20
15
10
5
0
0
10
20
30 cm/sec
BOTTOM CURRENT – u_{100}
● STATION HARD ROCK ○ STATION MUD SHELL

this technique did not substatially improve the fit, or change the results and conclusions.

Sternberg (1968) found a similar range of variability in the roughness lengths determined from velocity profile measurments in the tidal channels of Puget Sound. At low velocities, and therefore low Reynold's numbers, the flow is not fully rough, but is transitional. In transitional flow, the value of drag coefficient is a function of both the bed roughness and the flow, and therefore is higher than for fully rough flow where the drag coefficient depends only on the bed configuration. Based on the criteria developed by Nikuradse (1933), and modified by Sternberg (1968 and 1970) for coastal waters, the hard-rock and the mud-shell reefs are always in the hydraulically rough range. The roughness Reynolds number, $(U_* z_0/\nu)$ for this data ranges from 234 to 556 for the hard-rock reefs and from 15 to 33 for the mud-shell oyster reefs, easily exceeding Sternbergs criteria for nonuniform boundary conditions found in the field.

Soulsby and Dyer (1981) also investigated the form of the near-bed velocity profile in accelerating and decelerating tidal flows. The results of their work indicated that compared to the steady flow case, accelerating currents cause the underestimation of the friction velocity and boundary roughness, and decelerating currents cause the overestimation of friction velocity and boundary roughness.

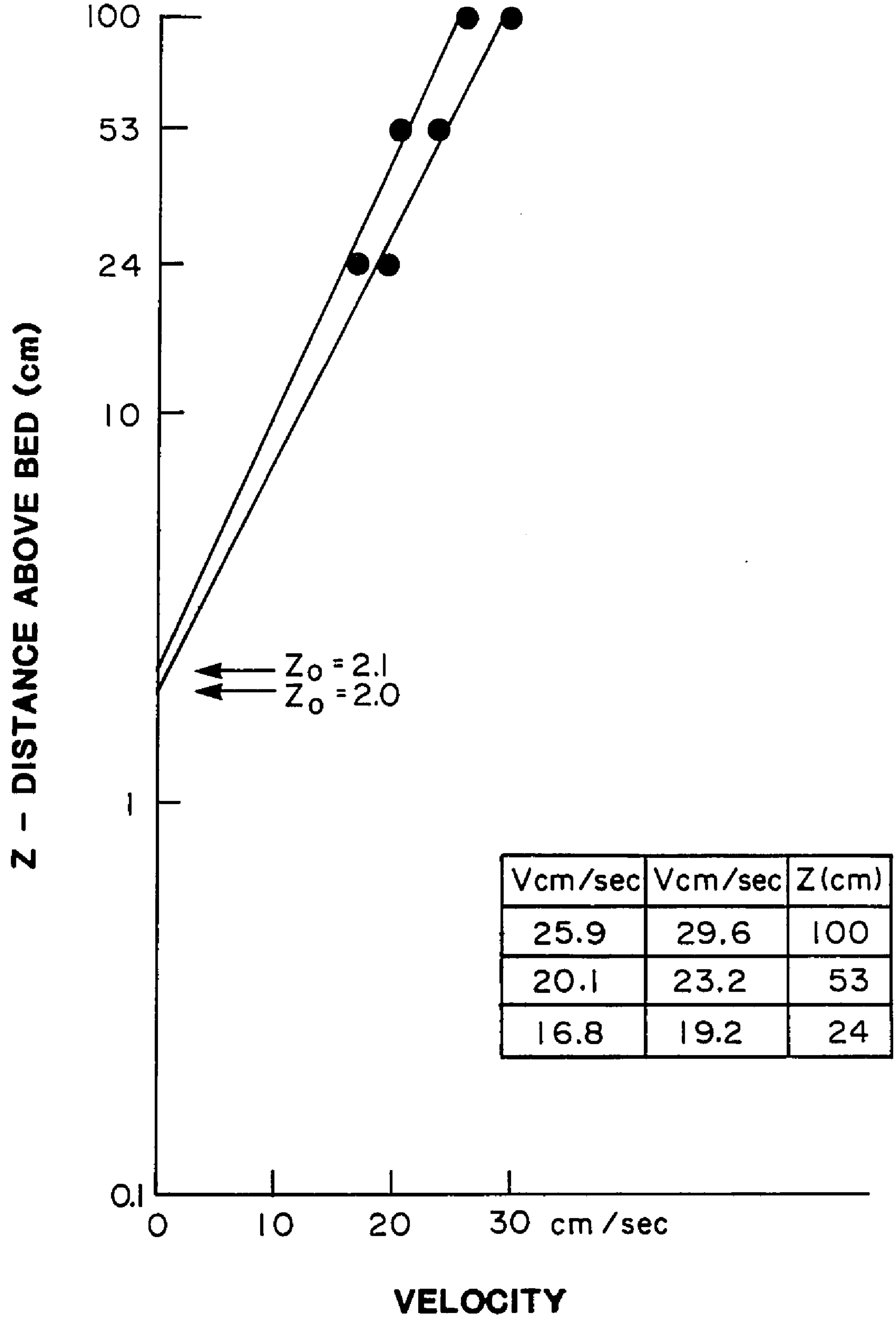
These limited velocity profile data taken through a full tidal cycle indicate that the boundary roughness is simply overestimated at low velocity, probably due to both acceleration and deceleration, stratification, non-uniform flow, and other complications unique to estuaries.

At maximum current, the velocity profiles for the hard-rock and mud-shell stations produced the most reasonable data, and these profiles are illustrated in Figures 28 and 29. Least squares analysis of this profile data resulted in roughness lengths of 2.0 and 2.1 cm for the hard-rock oyster reef and 0.1 and 0.2 cm for the mud-shell oyster reef. These roughness lengths were averaged for each of the oyster reefs and converted to a characteristic drag coefficient for each oyster reef. The calculated values of Cd are 10.3×10^{-3} for the hard-rock oyster reef and 3.7×10^{-3} for the mud-shell oyster reef. Thus, based on this analysis, it appears that the hard-rock oyster reef is substantially rougher than the mud-shell reef. However, it must also be noted that this analysis is based on a limited number of "good" velocity profiles.

While it was previously of interest to consider the velocity of the current for descriptive purposes, in the following analysis of estuarial fine suspended sediment transport, only the magnitude of the current is considered. The rationale for this methodology is that the problem being investigated is not one of the direction of net sediment transport but whether a particular subenvironment area is

Figure 28

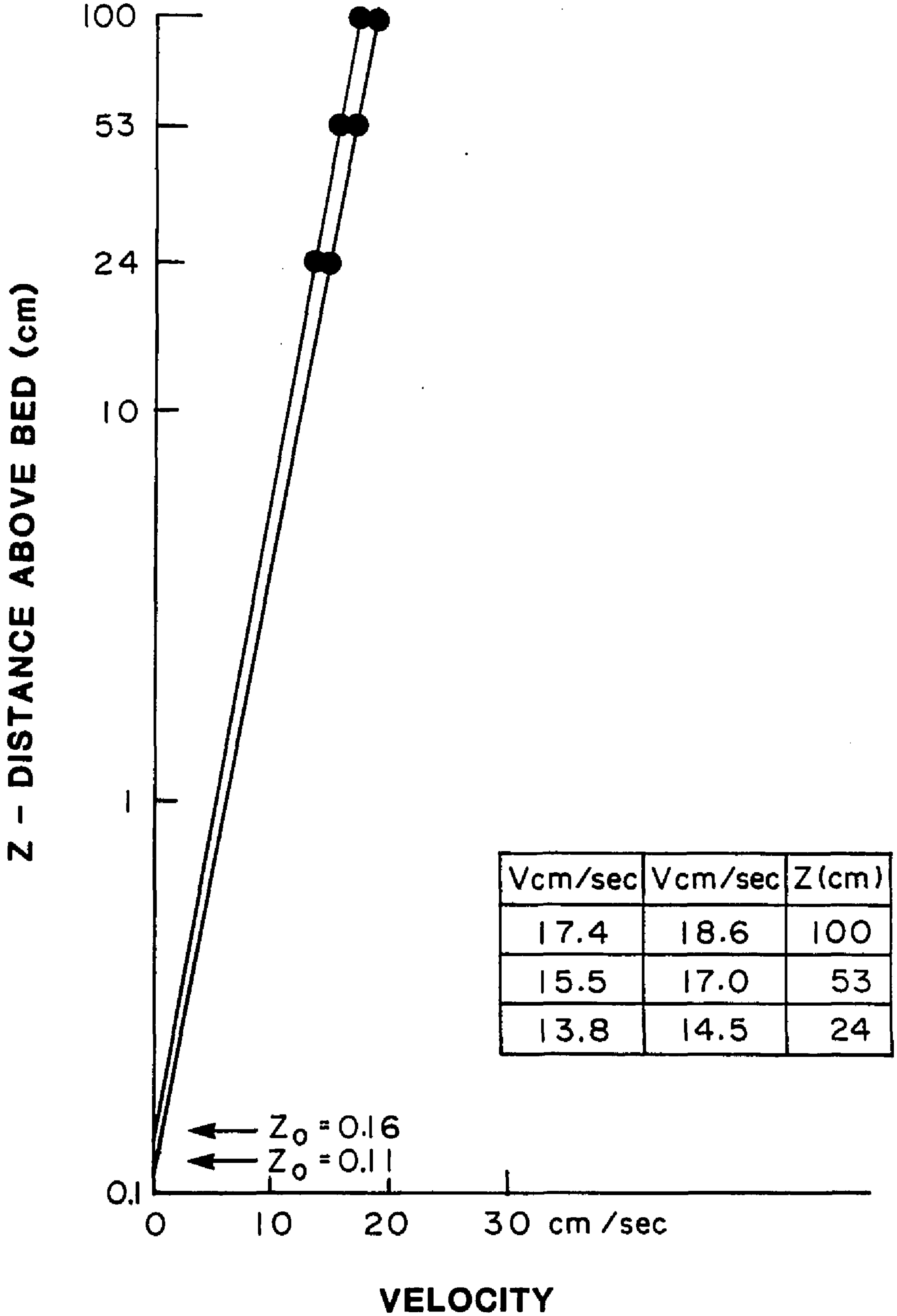
Velocity Profiles: Station Hard-rock



Vcm/sec	Vcm/sec	Z(cm)
25.9	29.6	100
20.1	23.2	53
16.8	19.2	24

Figure 29

Velocity Profiles: Station Mud-shell



Vcm/sec	Vcm/sec	Z(cm)
17.4	18.6	100
15.5	17.0	53
13.8	14.5	24

simply depositional, erosional, or both with respect to fine, estuarine sediments.

Sedimentation processes in estuaries include both the deposition and resuspension of fine suspended estuarine sediments and the deposition and erosion of coarser bedload sediments. Estuarine suspended sediments are the fine sands, silts, and clays derived from the adjacent sea, the river, the erosion of the estuary margin, and from biological sources. The coarser bedload sediments are derived from the reworking of the estuarine sediments and the erosion of the margin. In this study, the analysis is restricted to a consideration of estuarine fine sediment transport as it is this aspect of the sedimentation processes that is related to oyster reef productivity. It is the deposition of fine, estuarine sediments that smother the oyster reefs.

Estuarine fine sediment transport on a large scale is controlled by the non-tidal circulation of the estuary (Meade, 1972 and Schubel, 1971). However, on a smaller scale, the local deposition, resuspension processes are controlled principally by the bottom shear stress. The phenomena of fine sediment deposition and erosion has been investigated intensively in both the field and laboratory for the last two decades by Krone (1962 and 1978), Partheniades (1962 and 1971), Mehta (1973 and in preparation) and others. The method of analysis of fine sediment transport utilized in this study follows the principles developed by these previous investigators. The objective of the analysis described herein is to characterize and intercompare the sedimentary conditions of the three subenvironments based on the observed current meter data and bottom roughness. The assumptions made in this analysis scheme are that the 29 day current meter time-series are representative of the general bottom current conditions in the subenvironments, and that the tidally oscillating estuarine currents may be considered quasi steady for the purpose of bottom shear stress estimation.

A measure of the steadiness of the flow is given by the acceleration parameter z/Λ (Soulsby and Dyer, 1981). The acceleration length scale, Λ , is defined as:

$$\Lambda = z/\gamma + \frac{kzU(z)}{2\dot{U}(z)} \, dU/dz \left[1 + \left(1 + \frac{8z\dot{U}(z)}{k\gamma U_*^{2}}\right)\right] \quad (17)$$

where:

z = the reference depth of the currents,

γ = 0.04

k = von Karman constant, 0.40

$U(z)$ = current velocity at depth, z

$\dot{U}(z)$ = the acceleration of the current at z

dU/dz = the velocity profile, taken to be 100cm

For perfect steady flow, where $\dot{U}(z)$ approaches zero, the acceleration length scale (Λ) approaches infinity, and the acceleration parameter (z/Λ) approaches zero. The limit of near steady flow is defined to be the range of the acceleration parameter (z/Λ) greater than zero, but less than 0.005. The James River subenvironment current meter data exceeded this criteria 11.7 percent of the time in the hard-rock oyster reef, 13.5 percent of the time in the sand-shell oyster reef, and 16 percent of the time in the mud-shell oyster reef. For the most part, the violations occurred near slack water and at low velocities when the accelerations and decelerations were large relative to the small velocities. Therefore these violations will be neglected in the estimation of bottom shear stress for sediment transport purposes.

The deposition of fine suspended sediment occurs when the shear stress on the reef is not sufficient to resuspend sediment particles that contact and bond with the bed. Mehta (1973) found the critical shear stress for the deposition of kaolinite to be Ø.1 N/m^2. Other investigators have noted values of Ø.Ø4 to Ø.15 N/m^2 (Mehta, in preparation). Erosion or resuspension of the fine sediment occurs when the bottom shear stress exceeds the shear strength of the sediment. Based on the laboratory work under abiotic conditions Parchure and Mehta (1983) found the critical shear stress for the resuspension of soft muddy deposits in salinities of 1Ø parts per thousand to be Ø.39 N/m^2. However, it should be noted that the critical shear stress for erosion in the natural esturaine environment may be higher due to mucous adhesion (Nowell and others, 1981).

Relating the results of these previous investigator's work to Wreck Shoal on the James River, an estimate was made as to the nature of the sedimentary conditions in the three subenvironments. When the bottom shear stress is less than Ø.1 N/m^2, the sedimentary environment is considered depositional. When the bottom shear stress is greater than Ø.4 N/m^2, the sedimentary environment is considered erosional. In the range of bottom shear stress between Ø.1 and Ø.4 N/m^2 neither net accretion nor erosion is occurring at the bed.

The current meter data for the three subenvironments was plotted with respect to current speed alone, and the results are illustrated in Figure 3Ø. From these plots it is clear that station hard-rock experienced the strongest currents with peaks of 5Ø cm/sec and a mean of 23.5 cm/sec. The currents of station sand-shell are slightly less, with peaks of 4Ø cm/sec and a mean of 21.2 cm/sec. The currents of station mud-shell are weaker with peaks of 3Ø cm/sec and a mean of 14.1 cm/sec.

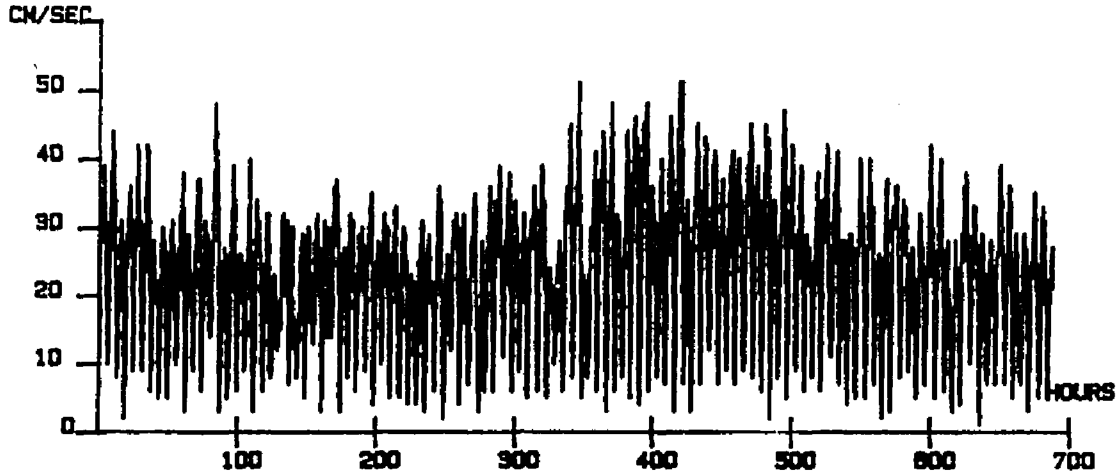
A time-series of bottom shear stress was calculated based on the current meter data, and the experimentally determined drag coefficients for each of the subenvironments using the quadratic shear stress law. In this case, application of the quadratic sheer stress law assumes quasi-steady flow, over a hydraulically rough boundary, where the drag coefficient is related only to bed configuration.

The resultant time-series of bottom shear stress for the three subenvironments are shown in Figure 31. In

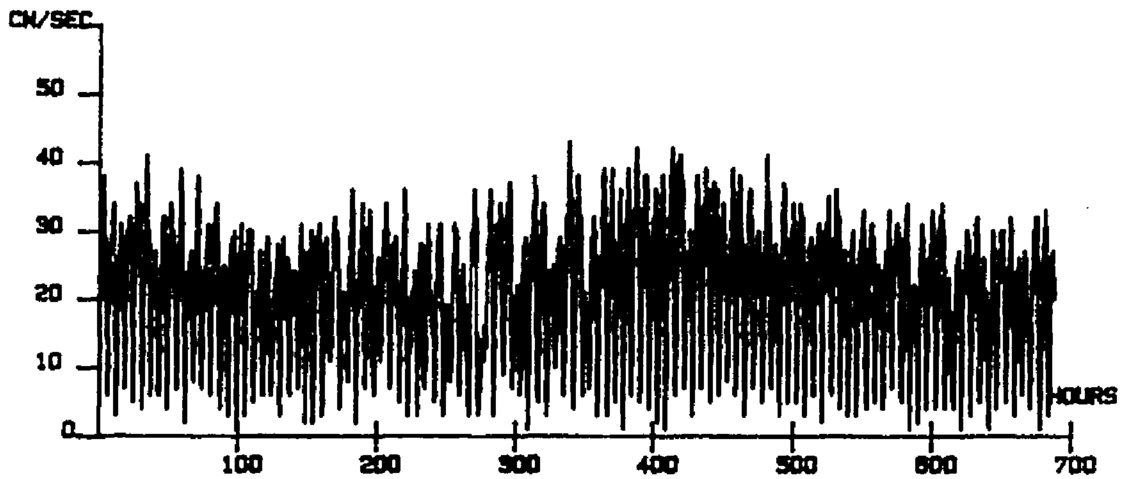
Figure 3Ø

Bottom Currents, Stations Hard-rock,
Sand-shell, Mud-shell

BOTTOM CURRENT, STATION HARD ROCK, WRECK SHOAL



BOTTOM CURRENT, STATION SAND SHELL, WRECK SHOAL



BOTTOM CURRENT, STATION MUD SHELL, WRECK SHOAL

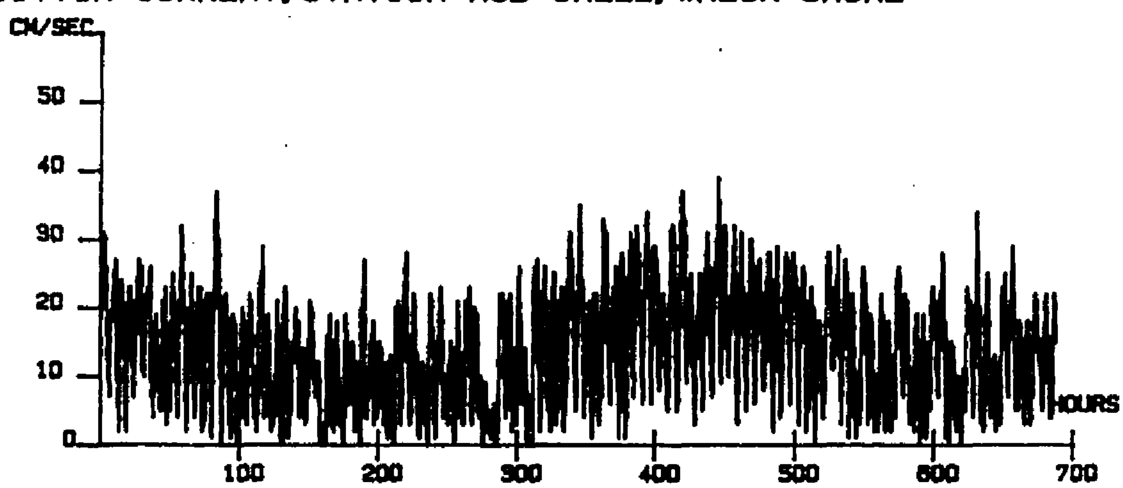
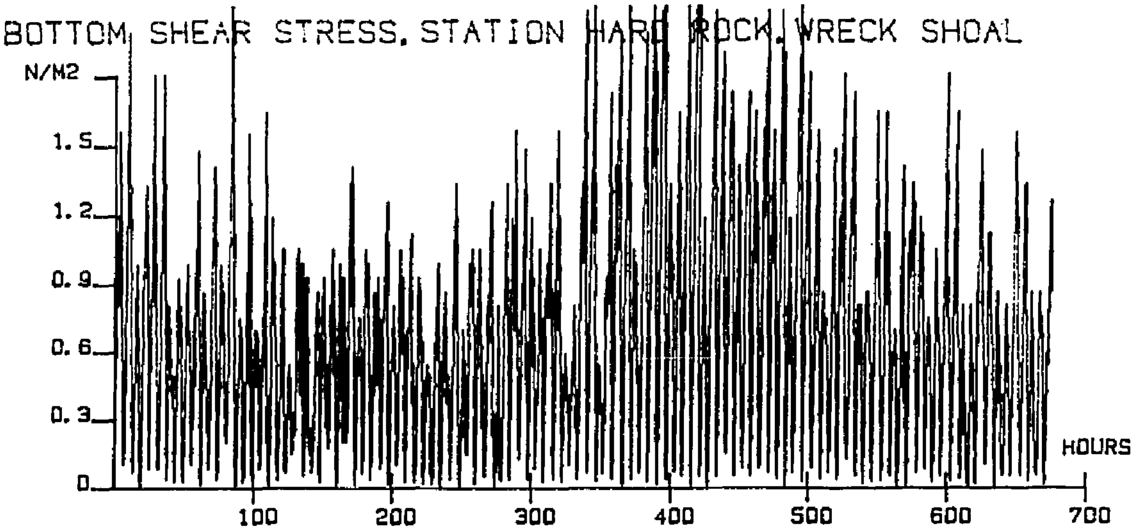


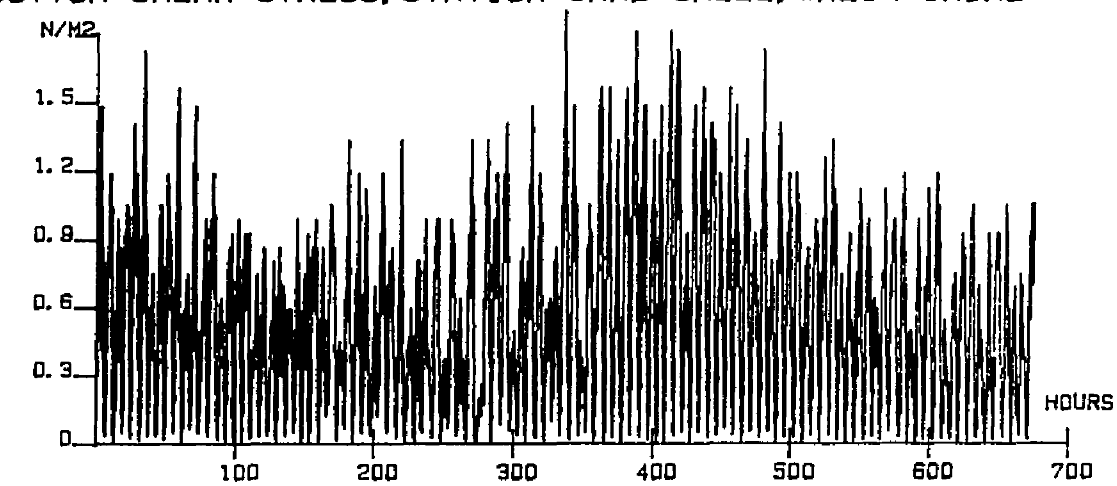
Figure 31

Bottom Shear Stress, Stations Hard-rock,
Sand-shell, Mud-shell

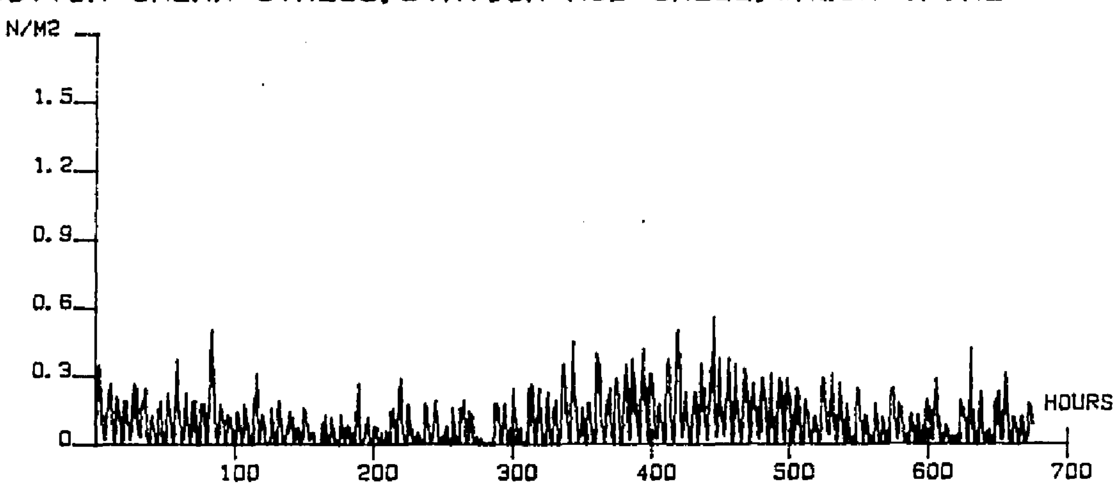
BOTTOM SHEAR STRESS, STATION HARD ROCK, WRECK SHOAL



BOTTOM SHEAR STRESS, STATION SAND SHELL, WRECK SHOAL



BOTTOM SHEAR STRESS, STATION MUD SHELL, WRECK SHOAL



contrast to the comparison of bottom currents, the comparison of bottom shear stresses indicates substantial differences between the mud-shell subenvironment and both the hard-rock and sand-shell subenvironments. Based on 0.1 N/m^2 as the critical shear stress for deposition and 0.4 N/m^2 as the critical shear stress for erosion, the percentage of time that each subenvironment was erosional or depositional with respect to fine sediments was calculated. The mud-shell subenvironment was depositional 58 percent of the time and was erosional one percent of the time. In contrast, the hard-rock subenvironment was erosional 68 percent of the time and was depositional 10 percent of the time. The sand-shell subenvironment was erosional 61 percent of the time and was depositional 14 percent of the time. The sensitivity of the determination of the bottom shear stress to the value of the drag coefficient must be noted, and in that regard it is emphasized that the bottom shear stresses calculated are used for comparison purposes only and are not absolute values.

The logical extension of this work would be to attempt to calculate the rates or erosion and deposition of the fine sediments, and to determine if the hard-rock and sand-shell subenvironments are net erosional or depositional based on the hydraulic data. The results could be compared to the field observations for verification. Unfortunately, this next step in the analysis requires additional data on suspended sediment concentrations and settling velocities, and on the erodability of the deposited beds. These data must be based on field and laboratory measurements or additional assumptions must be made. At this time, the data based on measurements are not available, and it is believed that further analysis based on additional assumptions would be without sufficient basis to be credible.

Discussion

The specific objective of this part of the study was to investigate the contemporary hydraulic and sedimentary processes so as to explain spatial and temporal variability in the geomorphic character of the oyster reef.

The circulation of the James River in the vicinity of Wreck Shoal and Burwell Bay was studied by investigating in the field both temporal and spatial variations in the local flow regime over the Wreck Shoal oyster reef and by reanalyzing existing field and numerical model data. The analysis of in situ current meter data collected from each of the subenvironments indicates that tidal forcing dominates the bottom current regime. Currents on the shallow hard-rock and sand-shell subenvironments were twice as energetic as the currents in the relatively deeper mud-shell subenvironment. The analysis of spatial variations in the bottom currents further reinforces the notion that on a localized basis the magnitude of the bottom current is inversely correlated with the water depth. In contrast, on a regional basis, considering the entire Wreck

Shoal-Burwell Bay area, on a single transect across the river axis, the current strength is correlated to water depth. Both the historical field data and the numerical model data indicate the strongest currents in the deep main channel and weaker currents in the shallow shoals.

Contemporary sedimentation processes on the Wreck Shoal oyster reef were investigated from several different aspects. Periodic observations by a SCUBA diver of the sediment cover on the subenvironment oyster reefs were made over a 14 month period. On all three subenvironment oyster reefs, the sediment cover remained basically unchanged during the observation period. The hard-rock and sand-shell subenvironment oyster reefs consistently had a light veil of sediment, 1-2 mm, covering the oysters and shell. The mud-shell subenvironment oyster reef had a blanket of fine soupy sediments, 1-2 cm thick covering the oysters and shell. On the mud-shell reef, only the bill or upper half of the oysters was exposed to the estuarine water, the lower half of the oysters was buried in soft mud.

Biodeposition processes on the oyster reefs were defined to include the generation and deposition of feces, pseudo-feces and skeletal shell material by the dominant animal of the reefs, the oyster. Based on standing crop of 500 bushels (26,250 l) of oysters per acre (0.4 h), and measured rates of feces production in the laboratory it was estimated that these oysters can produce a sediment layer of fecal material 35 cm thick per 100 years. Likewise, considering an annual natural mortality rate on the oyster reef of 5Ø percent, and that same standing crop of 5ØØ bushels (26,25Ø l) per acre (Ø.4 h), it is estimated that the oysters deposit a layer of oyster shells 35 cm thick per 1ØØ years. The void space in the shell layer is about 5Ø percent and it is probably filled with fecal material. The present rate of sea level rise is 4Ø cm per 1ØØ years. If there is some resuspension and transport of the fecal deposits, it appears that the vertical rate of oyster reef growth is about equal to the sea level rise, thus maintaining the reef at a given depth in the evolving estuarine system. If there is no resuspension of fecal biodeposits, the reef could develop subtidally and evolve into an intertidal reef. However, if oysters and shell material are removed through harvesting activity, then the oyster reef could lose elevation in the estuary.

An experiment was conducted to measure and compare the hydraulic roughness of the hard-rock and mud-shell oyster reefs. The hypothesis was that the hard-rock oyster reef presents a hydraulically rougher surface to the estuarine flow than the mud-shell oyster reef. The results of that experiment confirmed that condition at the point of maximum current.

The final aspect of this study was the investigation of the effects of differing bottom roughness on the fine sediment transport power of the bottom current in each of the subenvironments. A time-series of bottom shear stress was determined based on observed current data and experimentally determined bottom roughness values. The results of this analysis indicate a clear difference in the sediment transport power of the estuarine fluid of the hard-rock and sand-shell subenvironments as compared to the mud-shell subenvironment.

The hydraulically rougher hard-rock and sand-shell subenvironments, that experience the stronger currents and flourish in shoal water, are depositional with respect to fine estuarine sediment less than 15 percent of the time and erosional more than 60 percent of the time. In contrast, the hydraulically smoother mud-shell subenvironment that experiences the weaker currents and exists in deeper water, is depositional 58 percent of the time and erosional one percent of the time. Thus, there exists an equilibrium between the bottom shear stress, a function of the observed bottom roughness and the estuarine tidal currents, and the oyster reef geomorphic character, a function of the oyster reef productivity and resultant sediment transport processes. This equilibrium accounts for the stationary geomorphic character of the oyster reefs. The spatial variability in the geomorphic character of the reef is related to the spatial variabiltiy in the hydraulic regime, which is related to the local topography of the shoal.

Recent Geomorphic History:
Comparative Bathymetry 1850-Present

The bathymetric comparison included historical data from the 1850's, 1870's, 1910, and the 1940's. The data was taken from U.S. Coast and Geodetic Survey Hydrographic Boat Sheets (Table 8). Each set of data was reviewed for completeness, and because the density of soundings was greatest for the 1871-1872 and 1946-1948 surveys, the initial comparison is based on the 70 year period from the early 1870's to the mid 1940's. A detailed bathymetric survey was made of the 8 km^2 Wreck Shoal study area in June, 1984. The second comparison is based on the 40 year period from the mid 1940's to 1985.

Because each historical bathymetric survey was related to a local mean low water (MLW) determined during the time of the survey, it was first necessary to adjust each survey to a common time and sea level. As the density of soundings was greatest in the 1940's survey, this was taken to be the most complete survey, and therefore was used as the basis for comparison. Earlier and later surveys were adjusted to the MLW reference for 1946-1948.

Two corrections were made to the original data to adjust for eustatic sea level change and for coastal subsidence. Changes due to seasonal sea level variations were not considered because most of the surveys encompassed months and years (Byrne, Hobbs and Carron, 1982). Eustatic sea level rise was assumed to be +1 mm/year and coastal subsidence was taken to be -3 mm/year for subsidence of the

Table 8

HISTORICAL HYDROGRAPHIC CHARTS FROM
U.S. COAST AND GEODETIC SURVEY

Date	U.S.G.S. Reg. No.	Area	Scale
1854-1855	529	Burwell Bay, James River	1:2Ø,ØØØ
1877-1872	1179A	Newport News to Point of Shoals	1:2Ø,ØØØ
1873	1179B	Burwell Bay to Cobham Bay	1:2Ø,ØØØ
191Ø	3Ø45	Newport News to Mulberry Point	1:2Ø,ØØØ
191Ø	3Ø45A	Pagan Creek to Point of Shoals	1:2Ø,ØØØ
1946-1948	716Ø	Burwell Bay, James River	1:1Ø,ØØØ
1943-1947	6928	North of James River Bridge	1:1Ø,ØØØ

study area (Holdahl and Morrison, 1974). Together, these combined to give an apparent rise is sea level of +4 mm/year, that was assumed to be constant over the 130 year period from the 1850's to present. Based on the interval between the survey date and the 1946-1948 reference date the following corrections were applied to the bathymetric data.

Date	Correction
1854-1855	(+0.37 m, +1.2 ft)
1871-1872	(+0.30 m, +1.0 ft)
1910-1911	(+0.10 m, +0.5 ft)
1946-1948	Reference
1984	(-0.15 m, -0.5 ft)

In order to quantify the absolute sounding error in each bathymetric data set, the crossing differences were determined for each data set, where there were sufficient crossings (1854-55, 1871-72, 1946-48, and 1984). Following the methods described by Byrne and others (1982), the crossing differences are the absolute values of the differences in depth from two lines of bathymetry where the lines cross. Because the soundings from separate lines were seldom coincident, crossing values were derived from linear interpolation along separate lines.

For two soundings at the same location, a crossing:

$$a = d + Ea$$

$$b = d + Eb$$

where a + b are soundings at a crossing, d is the true depth and Ea, Eb are the respective errors from d. The difference is

$$a - b = Ea - Eb$$

and

$$(a - b)^2 = Ea^2 - 2EaEb + Eb^2$$

For comparison at a large number of locations, EaEb is assumed small compared to Ea^2 and Eb^2, and that $\Sigma Ea^2 \simeq \Sigma Eb^2$. Also, if Ea and Eb are random deviations with zero mean and the same standard deviation then the variance is approximated by:

$$\sigma^2 = 1/2 \ (\overline{a - b})^2$$

The number of crossings and the variance of the crossing differences are shown below.

Survey Date	No. of Crossings	$\sigma^2 m^2$	$\sigma^2 ft^2$
1854-1855	2Ø	Ø.13	1.41
1871-1872	59	Ø.75	Ø.81
1946-1948	7Ø	Ø.Ø4	Ø.42
1984	38	Ø.Ø3	Ø.27

The variance of the differences progressively decreases with the most recent survey having the greatest accuracy. The pooled variance arising from a comparison of individual soundings at a given location is

$$\sigma_{1,2}^2 = \sigma_1^2 + \sigma_2^2$$

and the standard deviation is

$$s_{1,2}^2 = (\sigma_{1,2}^2)^{1/2}.$$

The 95 percent confidence interval is 1.96 $S_{1,2}$. Thus, for a comparison between co-located individual depths on separate surveys, a depth difference greater than 1.96 $S_{1,2}$ has a 5 percent probability of being due to survey error.

The pooled variance for the 1871-72 and 1946-48 bathymetric comparison is Ø.11 m^2 (1.23 ft^2) and the standard deviation is Ø.34 m (1.11 ft). The 95 percent confidence interval is Ø.67 m (2.2 ft).

The pooled variance for the 1946-48 and 1984 bathymetric comparison is Ø.Ø6 m^2 (Ø.69 ft^2), and the standard deviation is Ø.25 m (Ø.83 ft). The 95 percent confidence interval is Ø.49 m (1.6 ft).

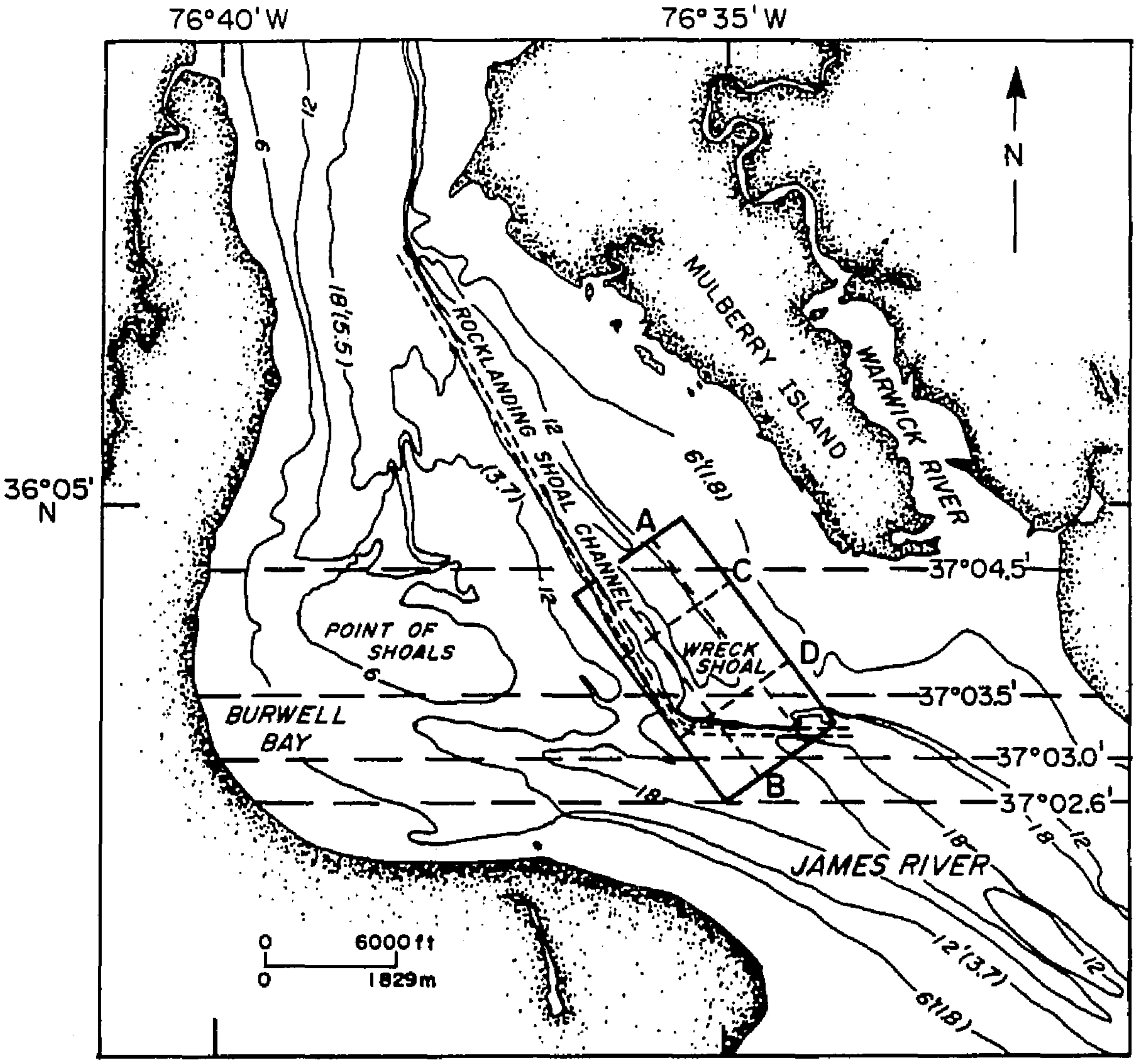
Two techniques for making the bathymetric comparisons were used in this analysis (Sallinger, Goldsmith and Sutton, 1975):

1. Data point profile comparison along defined transects,
2. Grid point comparison on a Ø.1 minute of latitude and longitude matrix.

The data point profile comparisons are made at two scales, a smaller scale to cover the larger study region of Burwell Bay and Wreck Shoal, and a larger scale to cover, in greater detail, the small defined study area of Wreck Shoal. The grid point comparison and the resulting contour map of bathymetric change is restricted to the smaller, defined Wreck Shoal study area (Figure 32).

Figure 32

Bathymetric Comparison Profile Lines
Wreck Shoal-Burwell Bay



BATHYMETRIC COMPARISON PROFILE LINES

WRECK SHOAL BURWELL REGION

JAMES RIVER, VA. 1983

BASED ON NOAA CHART # 12248

DEPTH CONTOURS IN FEET (meters)

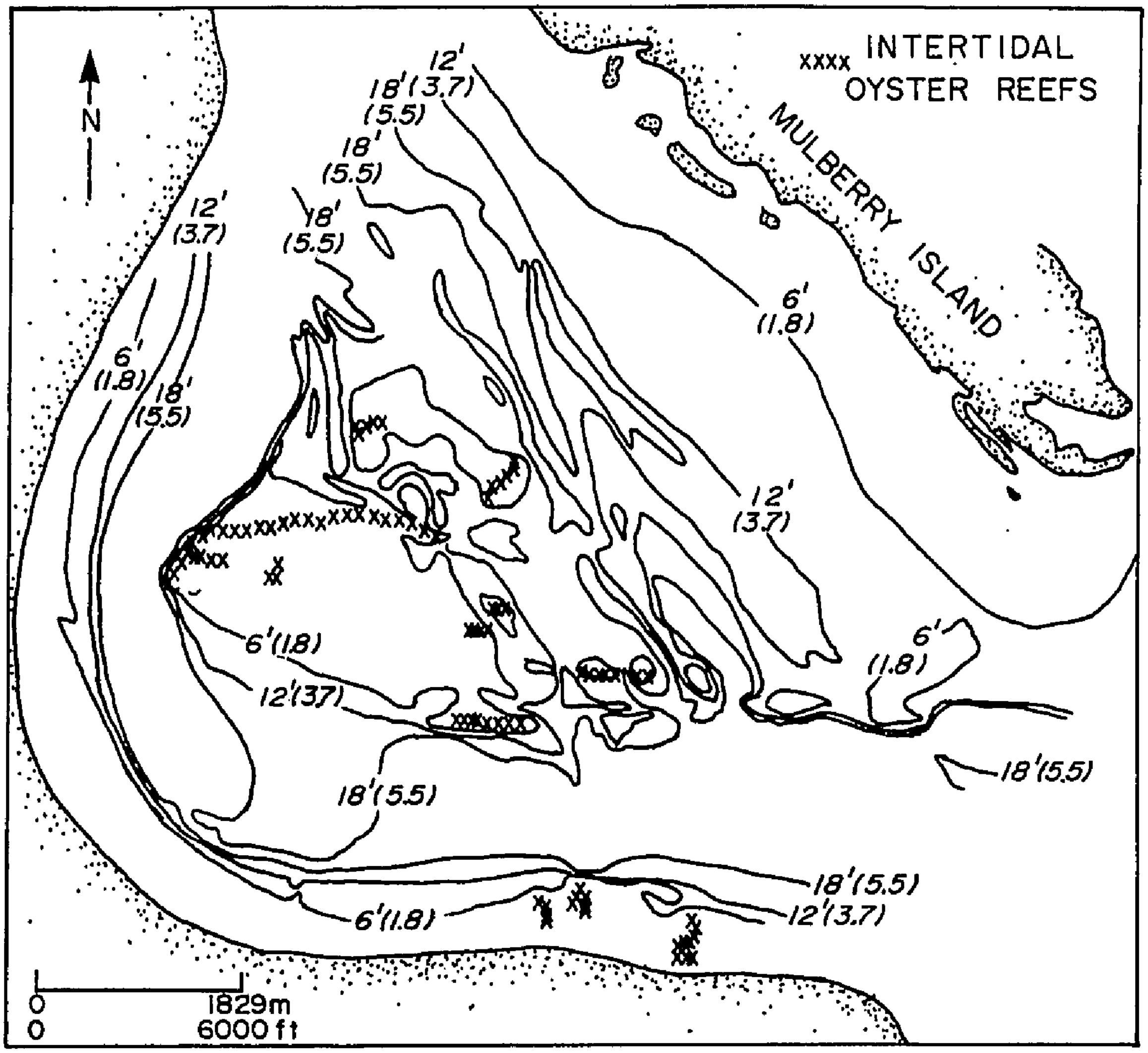
Besides the detailed quantitative data point profile and grid point comparisons, a more basic observation can be made by comparing and contrasting the historical charts with present conditions based on the maximum channel depths and the amounts of intertidal oyster reefs. In the 1870's, the maximum channel depths downstream of Wreck Shoal reached 48.8 m(160 ft); there were 6.4 km of transverse intertidal oyster reef stretching across the Point of Shoals area; and the Burwell Bay Channel had an average maximum depth of 7.6 m (25 ft), (Figure 33). In the 1980's the maximum channel depth below Wreck Shoal is 16.8 m (55 ft); there are no intertidal oyster reefs; and the average maximum depth in the Burwell Bay channel is 4.0 m (13 ft), (Figure 32).

The results of the regional profile comparisons between 1871-72, 1946-48 and 1985 are shown in Figures 34 and 35. The profiles were taken at latitudes 37°04.5′ N, 37°03.5′ N, 37°03.0′ N, and 37°02.6′ N across the Burwell Bay-Wreck Shoal region (Figure 32).

There are several important observations that can be made based on these profiles. First is the filling-in of the old channel on the western side of the region as shown in the profiles at latitudes 37°04.5′ N and 37°03.5′ N. Between longitudes 76°40′ W and 76°38′ W, the channel experienced 4.6-6.1 m (15-20 ft) of sedimentation in the period from the 1870's to the 1940's, and 0.6-1.5 m (2-5 ft) of sediment accumulation in the period from the 1940's to 1985. The average cross-sectional area of the channel

Figure 33

Wreck Shoal-Burwell Bay
James River, 1870's



WRECK SHOAL BURWELL BAY

JAMES RIVER, VA 1870'S

BASED ON U.S.C.S.-SHEET #1 REGISTER #1179A

DEPTH CONTOURS IN FEET (meters)

Figure 34

Comparison of Bathymetric Profiles
37°Ø4.5′ N and 37°Ø3.5′ N

COMPARISON OF BATHYMETRIC PROFILES: BURWELL BAY - WRECK SHOAL REGION

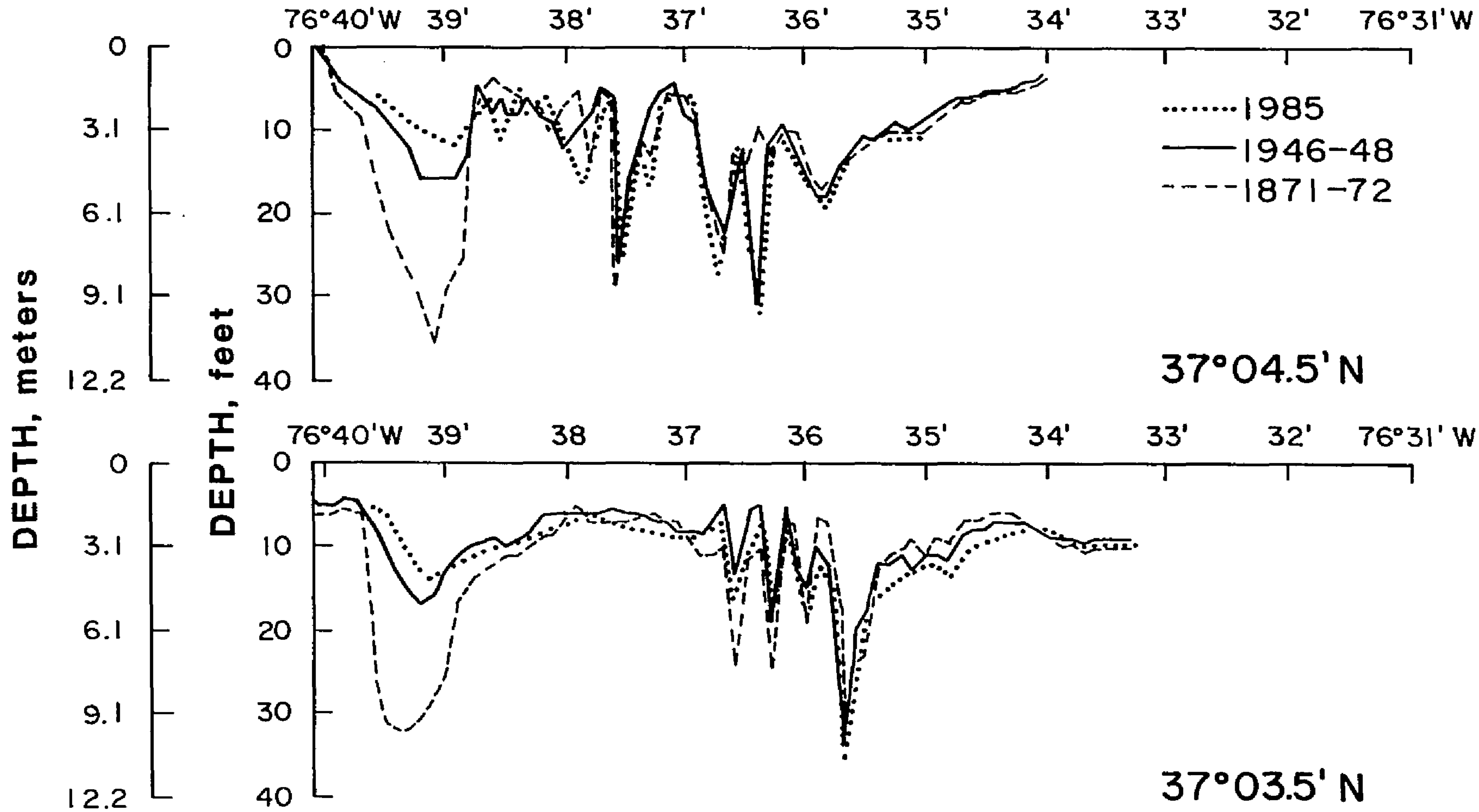
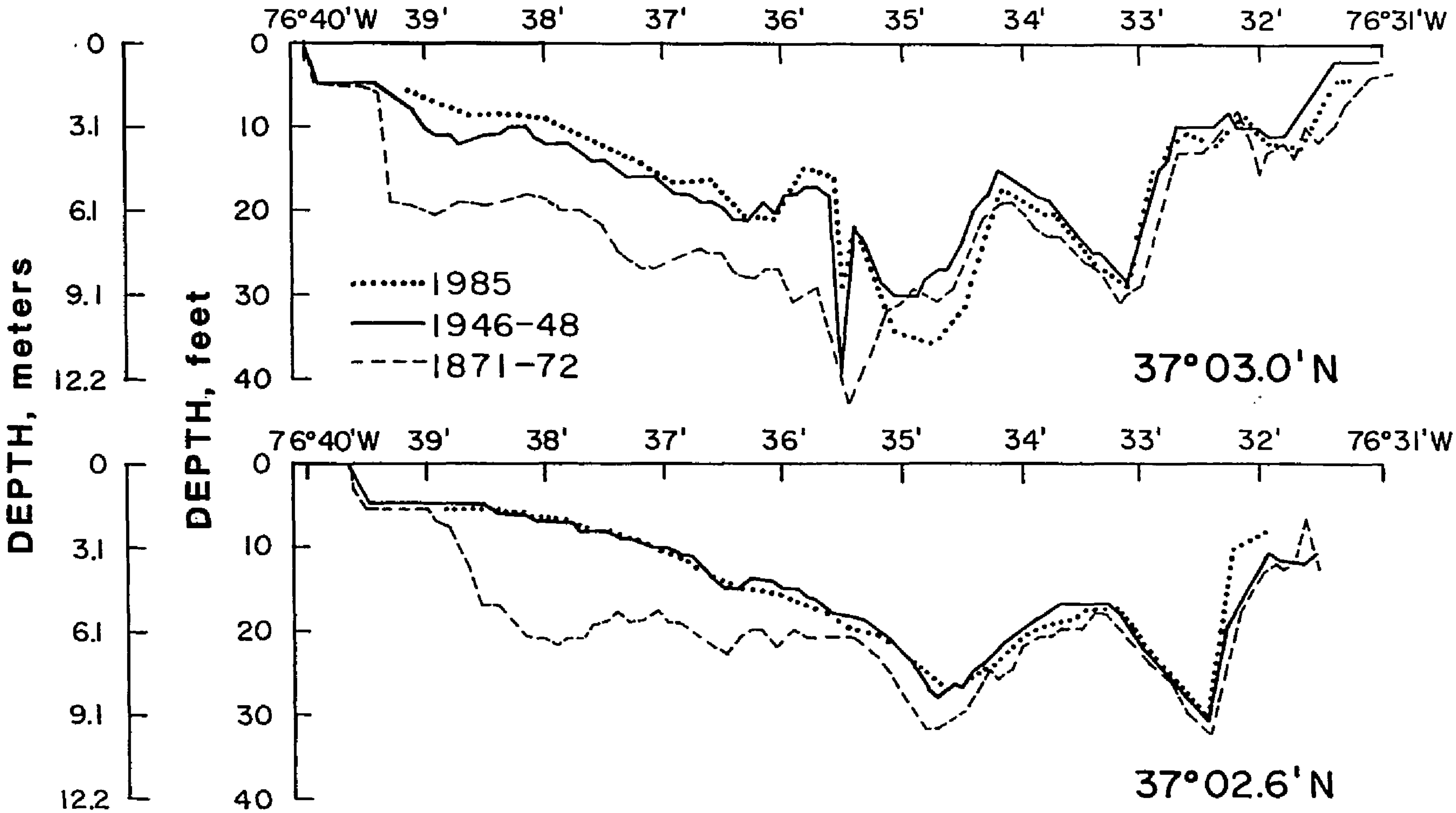


Figure 35

Comparison of Bathymetric Profiles
37°Ø3.Ø′ N and 37°Ø2.6′ N

COMPARISON OF BATHYMETRIC PROFILES: BURWELL BAY - WRECK SHOAL REGION



decreased by 43 percent from the 1870's to the 1940's and by 16 percent from the 1940's to 1985. In contrast, the profiles at latitude 37°04.5' N and 37°03.5' N in the area of Wreck Shoal from longitude 76°36.5' W to 76°33.5' W are very similar and indicate changes only on the order of 0.3 to 0.9 m (1-3 ft). The regional profiles at latitudes 37°03.0' N and 37°02.6' N indicate a continuation of the trend of rapid sedimentation on the western side of the profile from 1.5 to 4.6 m (5-15 ft) during the period from the 1870's to the 1940's. and 0-0.9 m (0-3 ft) from the 1940's to 1985. This sedimentation resulted in reduction of water depths by almost 50 percent over the entire western half of the profile. The eastern half of the profiles at latitudes 37°03.0' N and 37°02.6' N are south of the Wreck Shoal study area, and in the main channel, but also indicate limited sedimentation on the order of 0.3 to 0.9 m (1-3 ft).

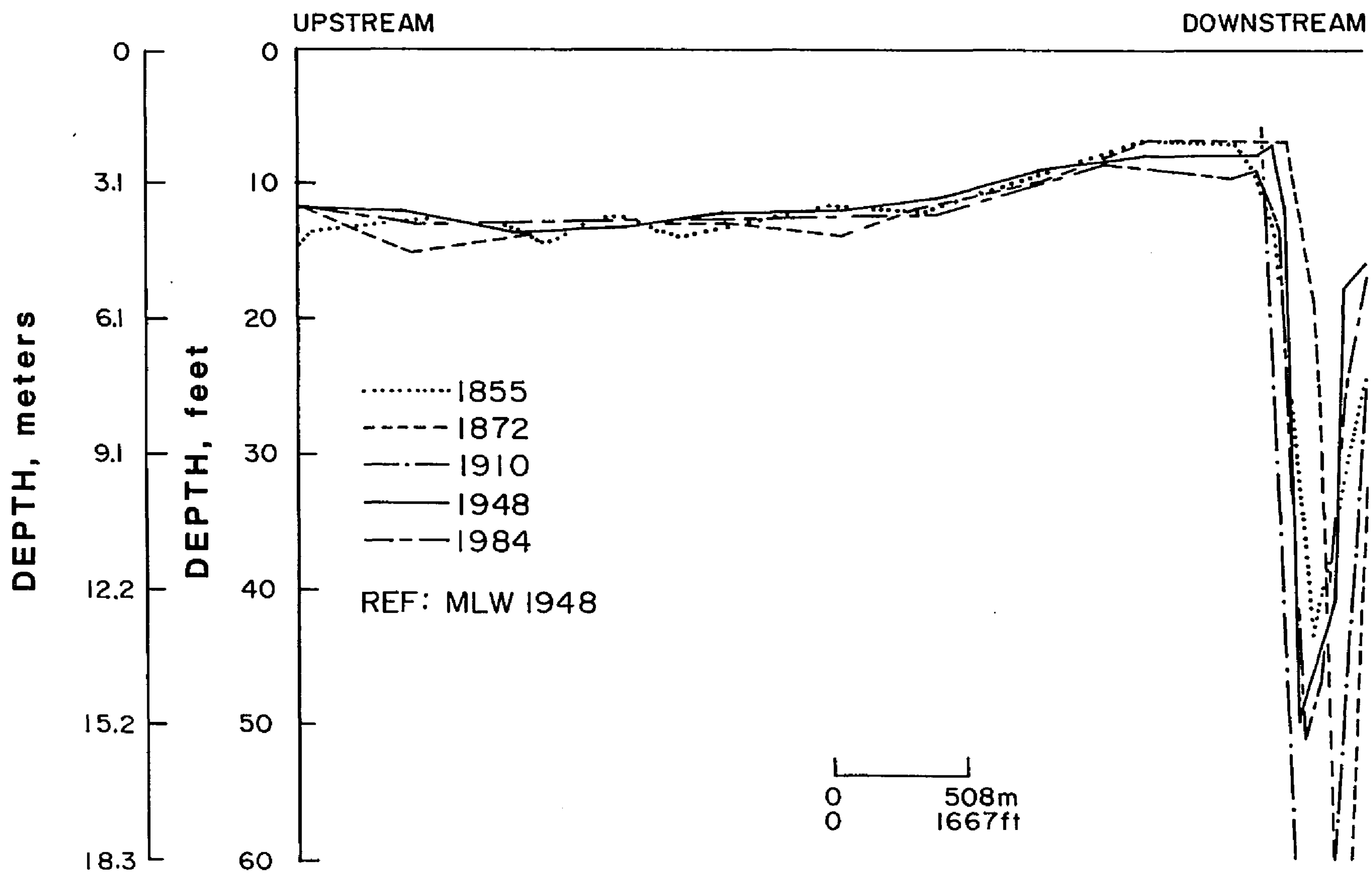
Within the 8 km^2 Wreck Shoal study area, profiles A and B are oriented along the longitudinal axes of the study area and profiles C and D are located along transverse axes of the study area (Figure 32). These profiles include data from 1850's, 1870's, 1910, 1940's, and 1984.

Profile A (Figure 36) inshore along the longitudinal axis from upstream to downstream, indicates virtually no bottom elevation change in the mid-portion of this profile on Wreck Shoal, but near the downstream boundary of Wreck

Figure 36

Historical Bathymetric Comaprison
Wreck Shoal Study Area
Profile A

WRECK SHOAL STUDY AREA PROFILE A



Shoal, there is a general loss of elevation of the bottom on the order of Ø.9 m (3 ft) during the period from the 187Ø's to 1984. In the channel, immediately downstream of Wreck Shoal, the 187Ø's chart indicates a maximum depth of 45.7 m (15Ø ft); the 1911 chart indicates a maximum depth of 29.3 m (96 ft); the 1948 chart indicates a maximum depth of 15.3 m (5Ø ft); while the 1984 survey recorded 15.5 m (51 ft). A 1942 Corps of Engineers survey of the channel indicates a maximum depth of 21.9 m (72 ft), and notes that the deep channel trough would be used as a disposal area for maintenance dredging of Rocklanding Shoal channel in the mid 194Ø's. The 1946-48 survey confirms that the area had been used as a disposal area. In any case, natural sedimentation in the river accounted for a reduction of the maximum channel depth by 5Ø percent, from 45.7 m (15Ø ft) in the 187Ø's to 21.9 m (72 ft) in 1942.

Profile B (Figure 37), offshore, along the longitudinal axis from upstream to downstream, indicates limited sedimentation (Ø.9 m or 3 ft) in the central portions of the profile, a small loss of elevation (Ø.9 m or 3 ft) at the downstream boundary of Wreck Shoal, and limited sedimentation (1.2 m or 4 ft) in the channel adjacent to Wreck Shoal.

Profile C (Figure 38), upstream, along the transverse axis from offshore to inshore, indicates substantial changes in the bottom topography in the offshore portion of the profile that are associated with the dredging of Rocklanding

Figure 37

Historical Bathymetric Comparison
Wreck Shoal Study Area
Profile B

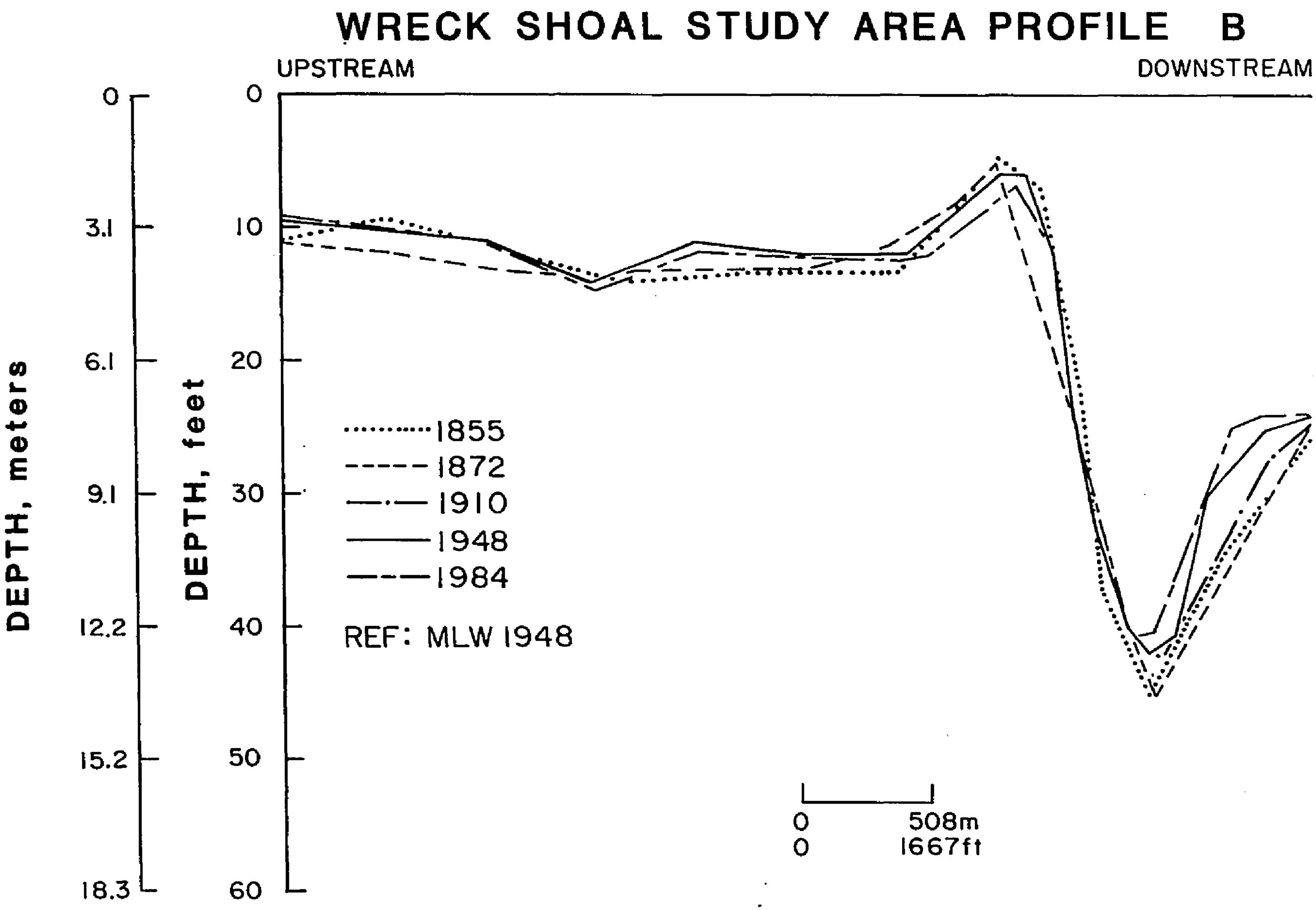
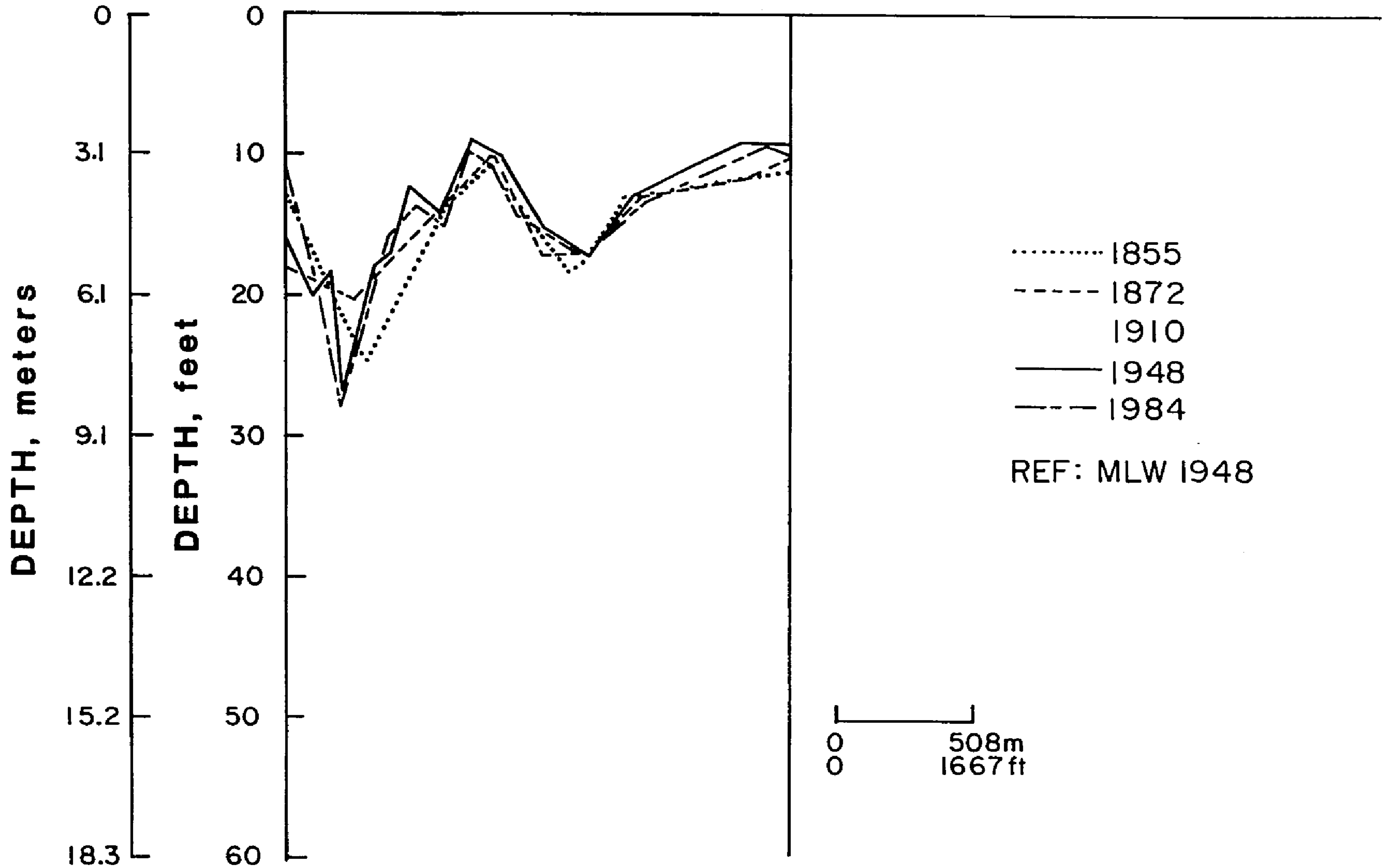

WRECK SHOAL STUDY AREA PROFILE B
UPSTREAM
DOWNSTREAM
DEPTH, meters
DEPTH, feet
0
3.1
6.1
9.1
12.2
15.2
18.3
0
10
20
30
40
50
60
1855
1872
1910
1948
1984
REF: MLW 1948
0 508m
0 1667ft

Figure 38

Historical Bathymetric Comparison
Wreck Shoal Study Area
Profile C

WRECK SHOAL STUDY AREA PROFILE C



Shoal channel in the mid 1940's. The mid-portion of the profile is stable, while inshore portion indicates a slight amount of sedimentation (0.6 m or 2 ft) from the 1870's to present.

Profile D (Figure 39) downstream along the transverse axis, from offshore to inshore, indicates a relatively stable main channel flank offshore, a general trend of elevation loss (0.9-1.8 m or 3-6 ft) along the crest of Wreck Shoal, and a very stable bottom inshore.

The detailed bathymetry of the Wreck Shoal study area is shown in Figure 40. This chart is based on the U.S.C.& G.S. boat sheets for 1946-48. The natural main channel, is oriented East-West and parallels latitude 37°03.2′ N before intersecting the dredged Rocklanding Shoal channel. These two channels form the downstream and offshore boundaries of the Wreck Shoal oyster reef. The shallow depths of the reef crested at 1.8 m (6 ft) in the 1940's, with a trough area trending NW/SE upstream of the prime oyster reef zone.

Contoured changes in the bathymetry of the Wreck Shoal study area, between the 1870's and the 1940's are shown in Figure 41. In the SW corner of the study area, there is a general pattern of substantial sedimentation in the trough of the main channel. Along the crest of the Wreck Shoal oyster reef, and along the flank of the main channel, there is a pattern of slight erosion or loss of bottom elevation. Along the axis of the Rocklanding Shoal Channel, there are alternating areas of positive and negative bottom change

Figure 39

Historical Bathymetric Comparison
Wreck Shoal Study Area
Profile D

WRECK SHOAL STUDY AREA PROFILE D

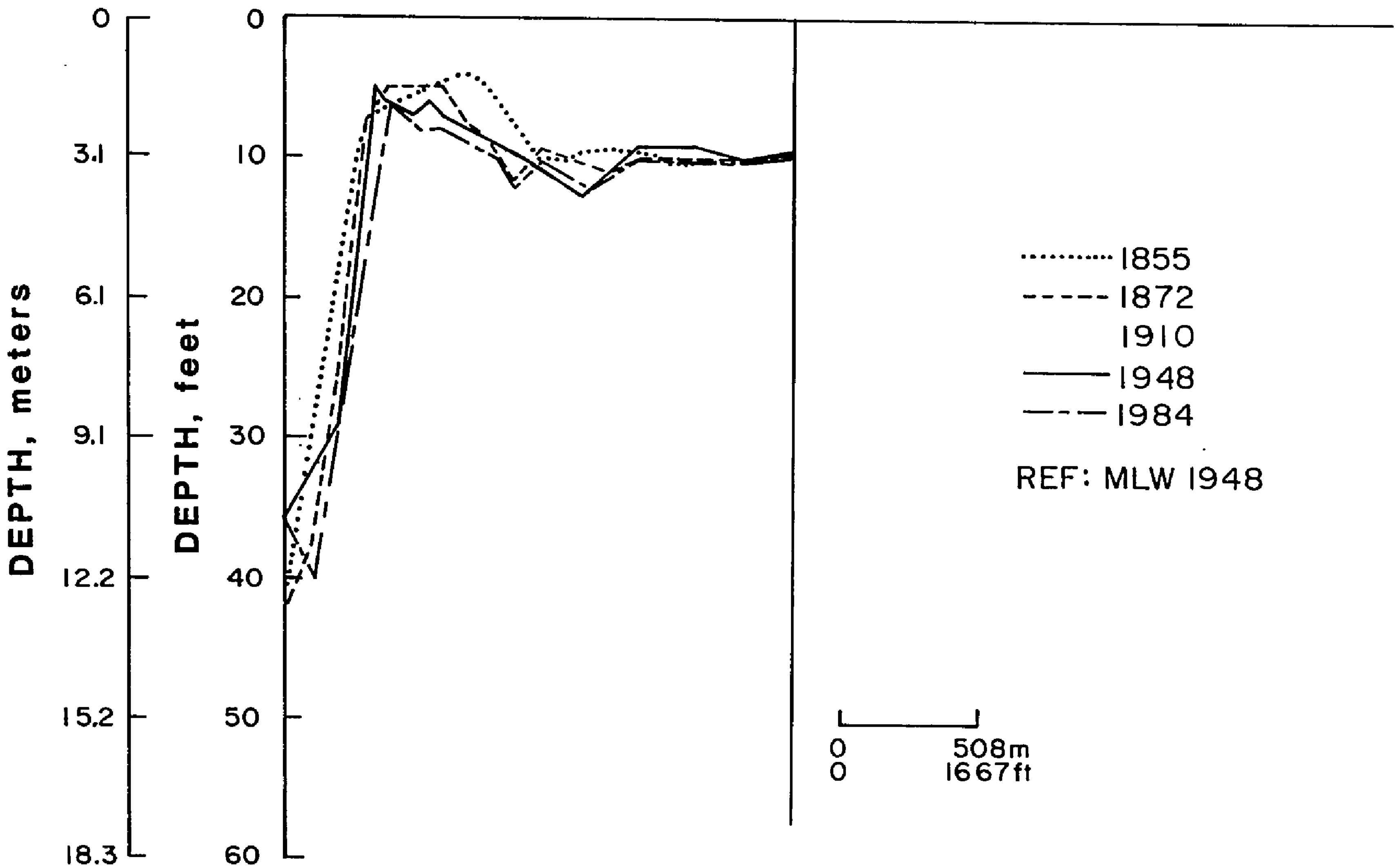


Figure 4Ø

Bathymetry of the Wreck Shoal Study Area,
1946-1948

BATHYMETRY OF WRECK SHOAL STUDY AREA
1946–1948, REF. MLW, FROM U.S.C. & G.S., H-7160
DEPTH CONTOURS IN feet (meters)

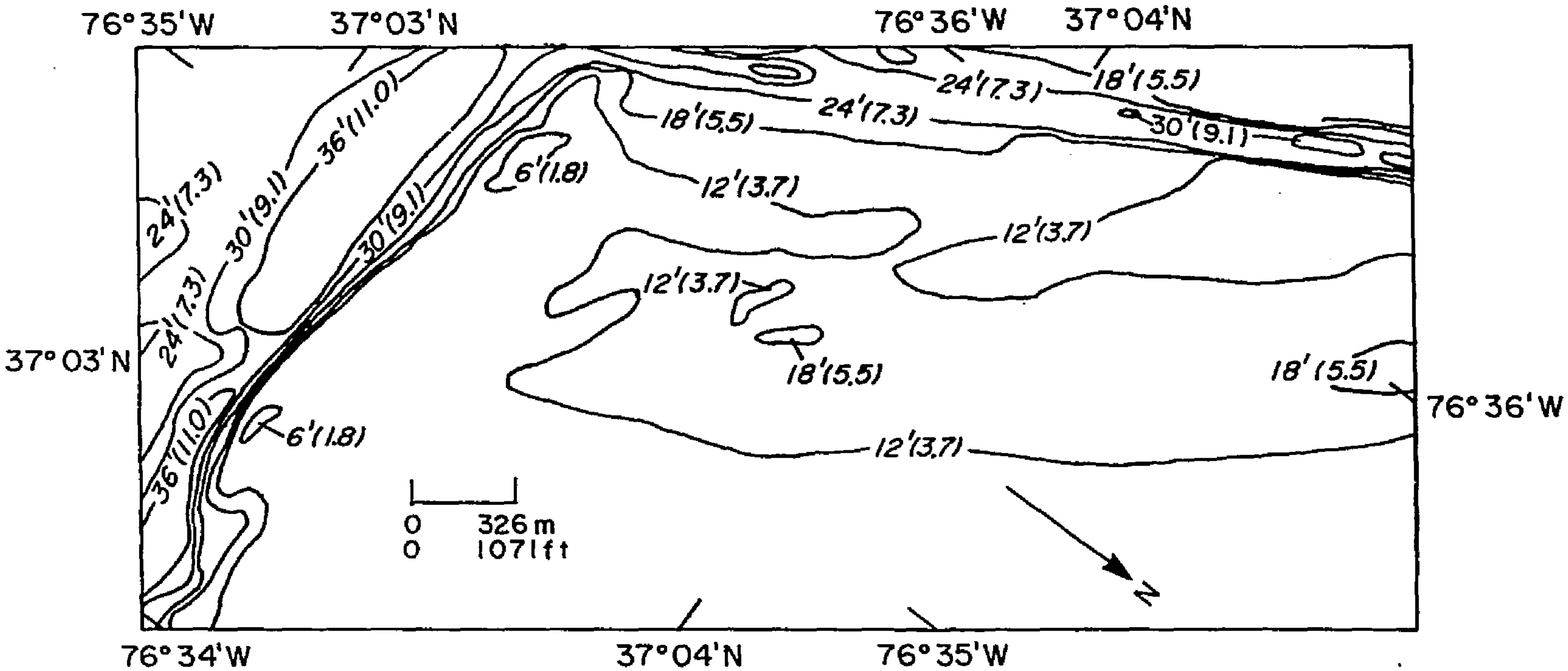
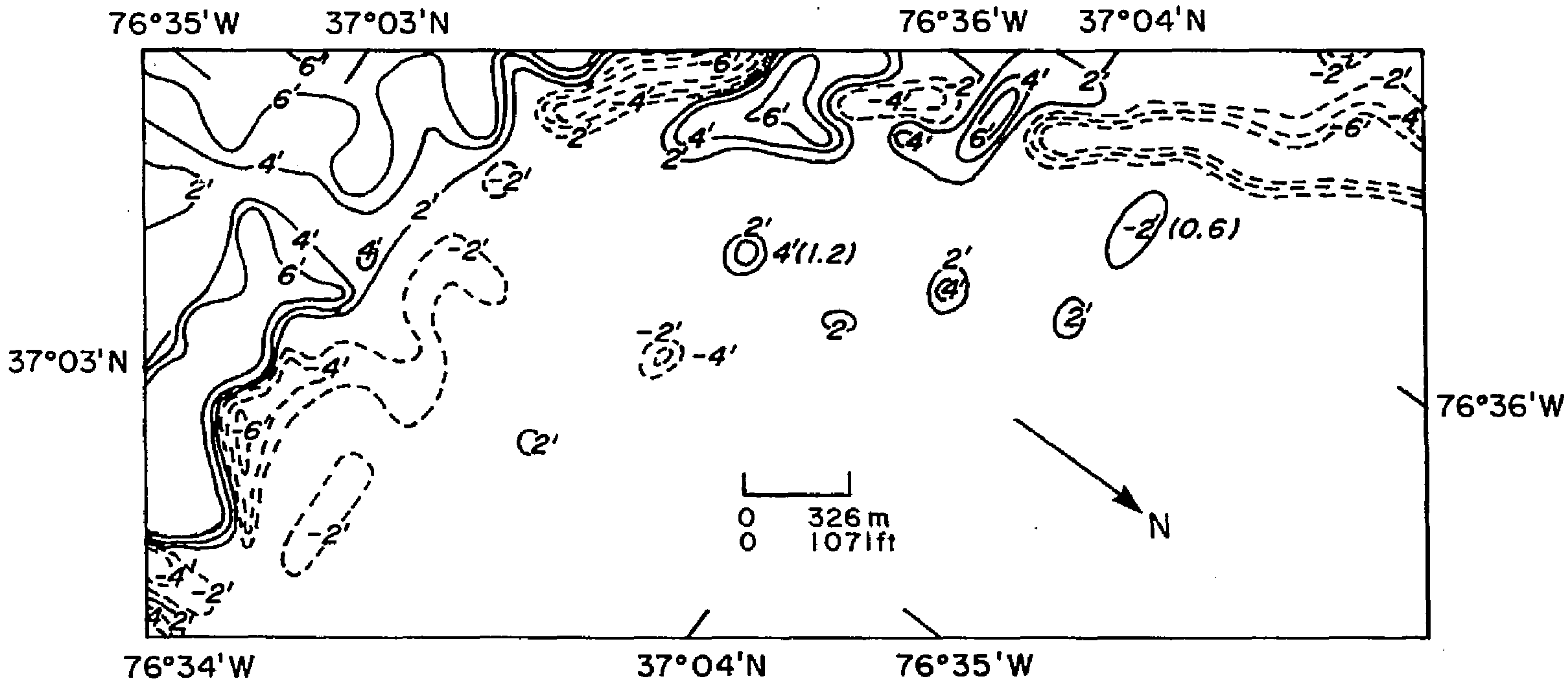


Figure 41

Wreck Shoal Study Area,
Bathymetric Comparison,
1871-1872 to 1946-1948

WRECK SHOAL STUDY AREA
BATHYMETRIC COMPARISON 1871-72 TO 1946-48
CONTOURS OF ACCRETION 2,4,6ft. (0.6,1.2,1.8m)
AND EROSION 2,4,6ft. (0.6,1.2,1.8m) BASED ON
U.S.C. & G.S., H-1179 AND H-7160



associated with the dredging of the channel in the 1930's. Over the remaining portion of the Wreck Shoal study area, the bottom was relatively stable. These trends are continued during the period from the 1940's to 1984 (Figure 42), including sedimentation in the main channel trough, loss of elevation along the crest of Wreck Shoal and the channel flank, and the bottom stability on the inshore portion of the study area.

Discussion

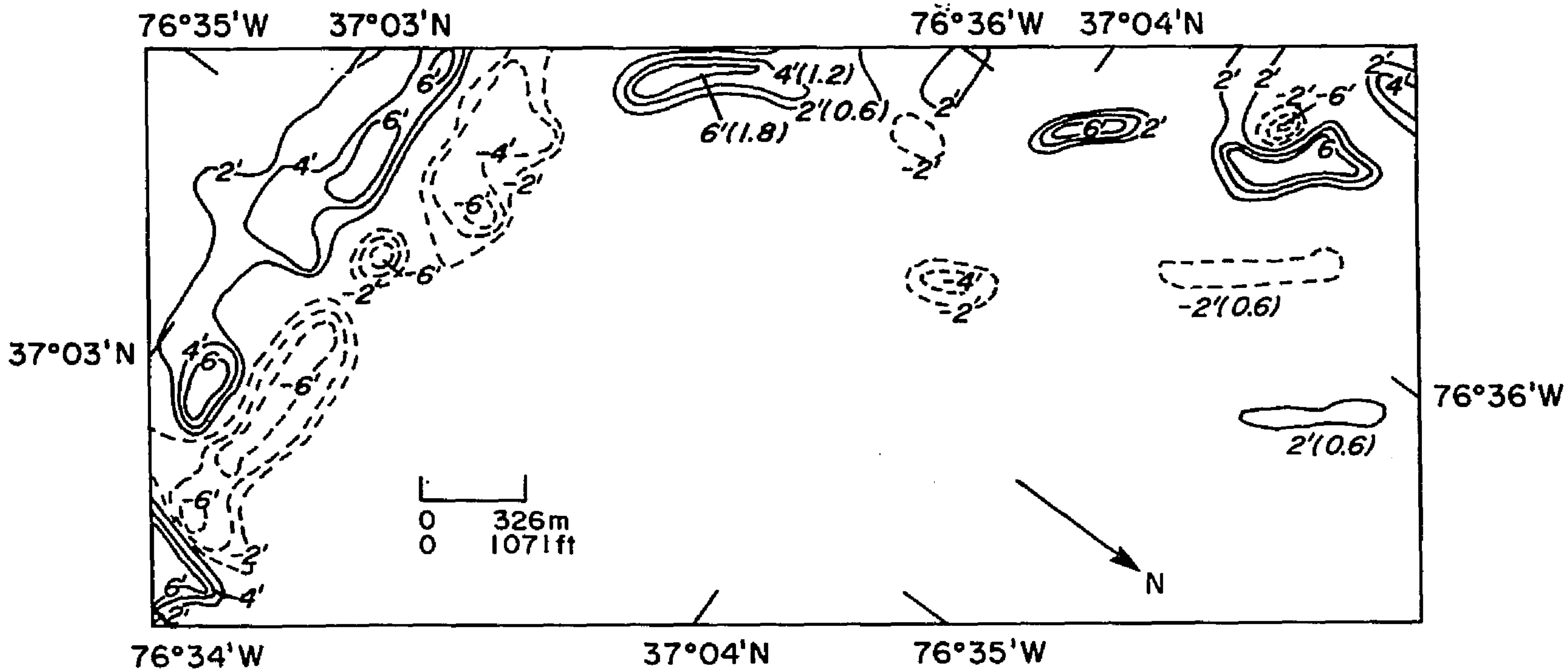
The specific objective of this part of the study was to investigate the recent geomorphic history of Wreck Shoal in order to understand the relationship between the contemporary reef morphology and the development of the oyster reef. To achieve this objective, bathymetry from the 1850's to present have been compared and interpreted. The results of that work are summarized in the sequel.

The Burwell Bay channel filled dramatically from the 1870's to the 1920's, prior to the dredging of Rocklanding Shoal Channel. There must have been either a significant increase to the sediment input of the river or a substantial change in the river circulation pattern to have caused this. Based on these analyses, sedimentation rates in the Burwell Bay portion of the James River were a maximum of 9 cm/year during the period from the 1870's to the 1940's and 3 cm per year during the period from the 1940's to 1985. These rates compare favorably with those of other investigators based on

Figure 42

Wreck Shoal Study Area,
Bathymetric Comparison
1946-1948 to 1984

WRECK SHOAL STUDY AREA
BATHYMETRIC COMPARISON 1946-48 TO 1984
CONTOURS OF ACCRETION 2,4,6ft. (0.6,1.2,1.8m)
AND EROSION 2,4,6ft. (0.6,1.2,1.8m) BASED ON
U.S.C.&G.S., H-7160 AND VIMS SURVEY, 1984



radionuclide analysis (Cutshall and others, 1981 and Wong and May, 1984).

The Point of Shoals area has also experienced dramatic changes during the last 130 years. The 1870's bathymetric charts for the area indicate more than 6 km of intertidal oyster reefs. These reefs were oriented transverse to the main channel axis, and certainly presented a significant obstruction to tidal flow over the shoal, restricting it to the main channel. The next complete bathymetric survey of the area was conducted in the 1940's, those charts do not indicate intertidal reefs. The reefs lost elevation due to a slowly rising sea level, and probably also due to harvesting by oystermen. At the present time, water depths over most of the former intertidal reefs are greater than 1 m, at MLW.

With respect to the Wreck Shoal study area, there are several trends in bottom change that must be noted. The trough area of the natural main channel has filled dramatically from the 1870's to present. The shallowest portions of the Wreck Shoal oyster reef have lost at least 1.2 to 1.8 m (4-6 feet) of elevation over the last 130 years. There has also been some loss of elevation along the upper portion of the main channel flank adjacent to the shallow oyster reef. Over the major inshore portion of the Wreck Shoal study area, the bottom has been very stable over the last 130 years. This observation of neither significant erosion or accretion also agrees with the results of other investigators regarding the sedimentation rates on Wreck Shoal based on radionuclide analysis.

There can be no doubt that there have been significant changes in the physiography of the James River in the vicinity of Wreck Shoal during the last 130 years. Man has played an important role in these changes by dredging Rocklanding Shoal Channel in the early 1930's, over-harvesting the intertidal oyster reefs thereby removing the transverse barriers to tidal flow over the shallow shoals, and dumping dredge spoil in the deep hole of the natural channel below Wreck Shoal. These activities have probably resulted in dramatic changes in the river circulation followed by changes in the estuarine sedimentation processes. Wreck Shoal and Point of Shoal have experienced little or no fine sediment accumulation during the last 130 years. In contrast, the Burwell Bay Channel has experienced rapid sedimentation, dramatically reducing the channel cross-sectional area. The difference in the sedimentation rates in Burwell Bay and on Wreck Shoal is accounted for based on both differences in the strength of tidal currents on the two areas and in the concentration of suspended sediments. Maximum tidal currents in Burwell Bay channel are 50 to 70 percent less than the currents over Point of Shoals or Wreck Shoal. In the mid-estuary region of the James River, the concentration of suspended sediments in water depths of 15 m varies from less than 15 mg/l near the surface to more than 80 mg/l near the bottom (Nichols, 1972). Wreck Shoal and Point of Shoals being very shallow, relative to the Burwell Bay channel, are not exposed to the higher concentrations of suspended sediments found in deeper water required to sustain a rapid sedimentation rate.

Holocene Evolution of the Wreck Shoal Oyster Reef and the Adjacent Areas of the James River

Sub-Bottom Profiler Survey

The results and analysis of the sub-bottom profiler surveys conducted in July 1985 are presented in this section. A total of eight transects were made during a two day period across the Wreck Shoal-Burwell Bay region, five in the east-west direction, and three in the north-south direction (Figure 6).

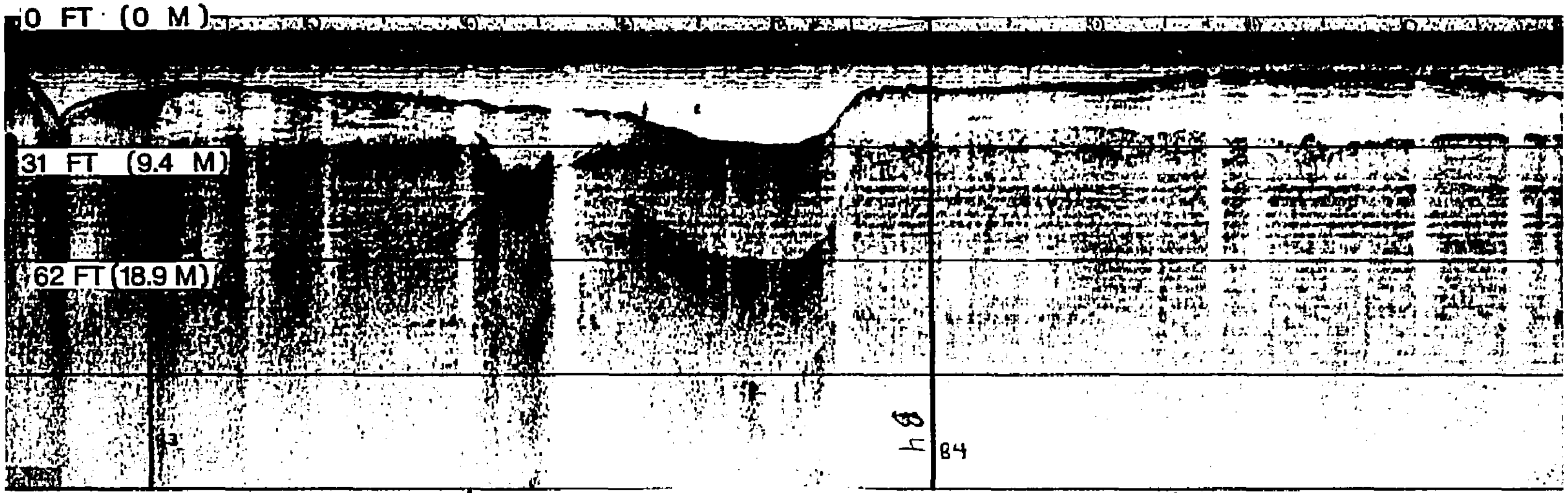
The success of the sub-bottom data collection was limited by the geological conditions of the region. In the Burwell Bay area, the bottom is composed of soft organic mud. The muds are characterized by the presence of gases produced by the anaerobic decomposition of organic material in the sediments. These gases act as a reflector of the acoustic signal, thereby limiting the penetration of the signal and resulting in multiple reflections on the record. Over the hard oyster reefs in the Point of Shoals and Wreck Shoal areas, the relatively high density oyster reef sediments strongly reflect the acoustic signal, limit penetration and also result in multiple reflections on the record.

Sections of records from transects B′ and D′ oriented in the north-south direction along longitudes 76°36.0′ W and 76°35.0′ W are shown in Figure 43. The illustrated portion of transect B′ is centered on the Rocklanding Shoal dredged channel. To the left of the channel are shallow reefs of Point of Shoals and to the right of the channel is the northern portion of Wreck Shoal. A strong reflector is visible in the record at a depth of 9-10 m and this reflector intersects the dredged Rocklanding Shoal channel. The illustrated portion of transect D′ begins at the natural channel at the southern end of Wreck Shoal and continues over the shallow portions of Wreck Shoal. Over the deep channel and the crest of Wreck Shoal, only multiple reflections are observed. Immediately north of the oyster reef crest is the reflector at 9-10 m depth, noted previously. Below that layer is the outline of a buried channel and channel flank that reached a maximum depth of about 25 m.

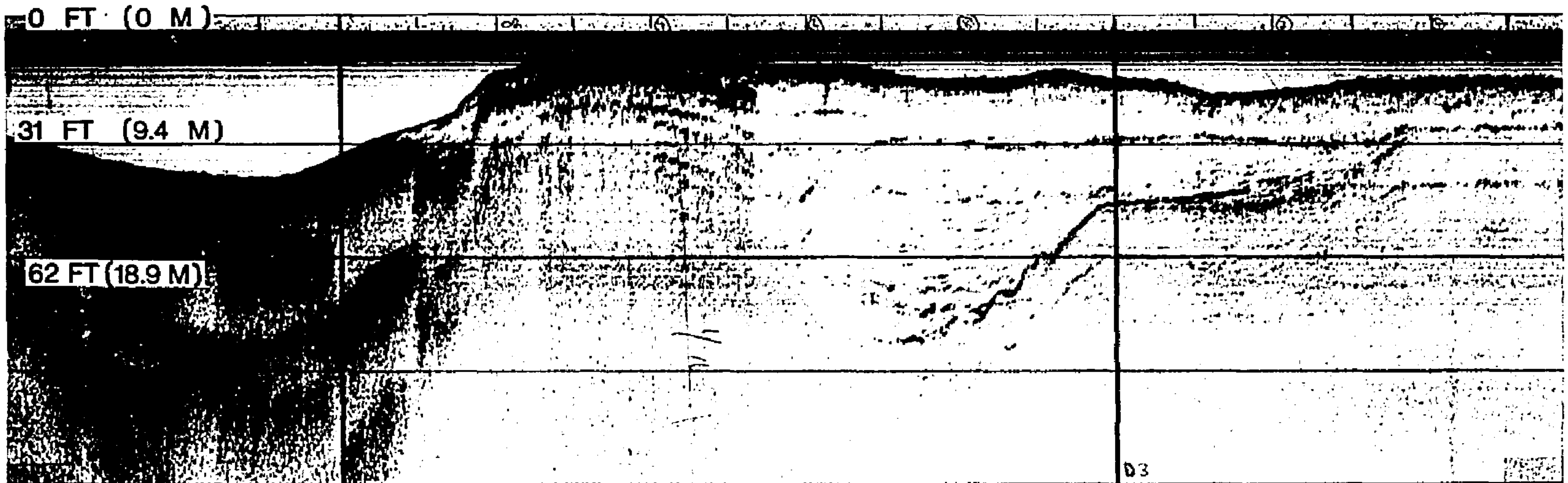
Sections of the record from transect B oriented east-west along latitude 37°03.5′ N are shown in Figure 44. The upper portion of the illustration is the record taken across the Point of Shoals oyster reef, the lower portion of the illustration is the record taken across the Rocklanding Shoal dredged channel and Wreck Shoal oyster reef. Over the Point of Shoals area, the bottom is at depths of 1-3 m. The patchy strong reflectors and the multiple reflections below them, are associated with oyster reefs. In the subsurface

Figure 43

Burwell Bay-Wreck Shoal Study Region,
Sub-Bottom Profiles, Transects B′ and D′,
12 July 1985



TRANSECT B′ 12 JULY 1985 76°36.0′W

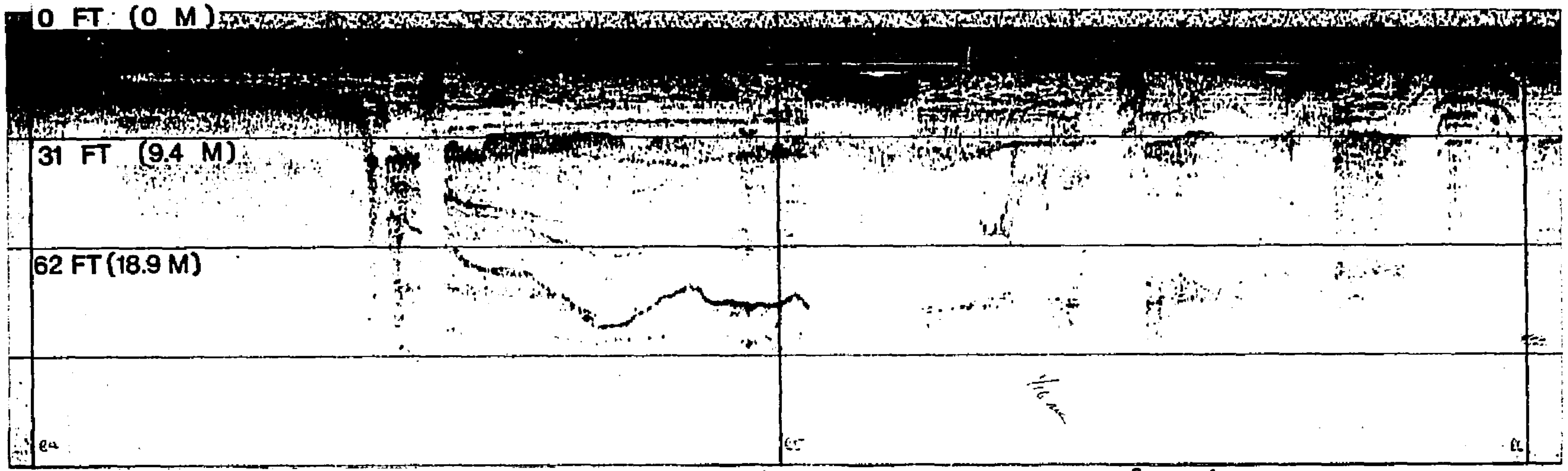


TRANSECT D′ 12 JULY 1985 76°35.0′W

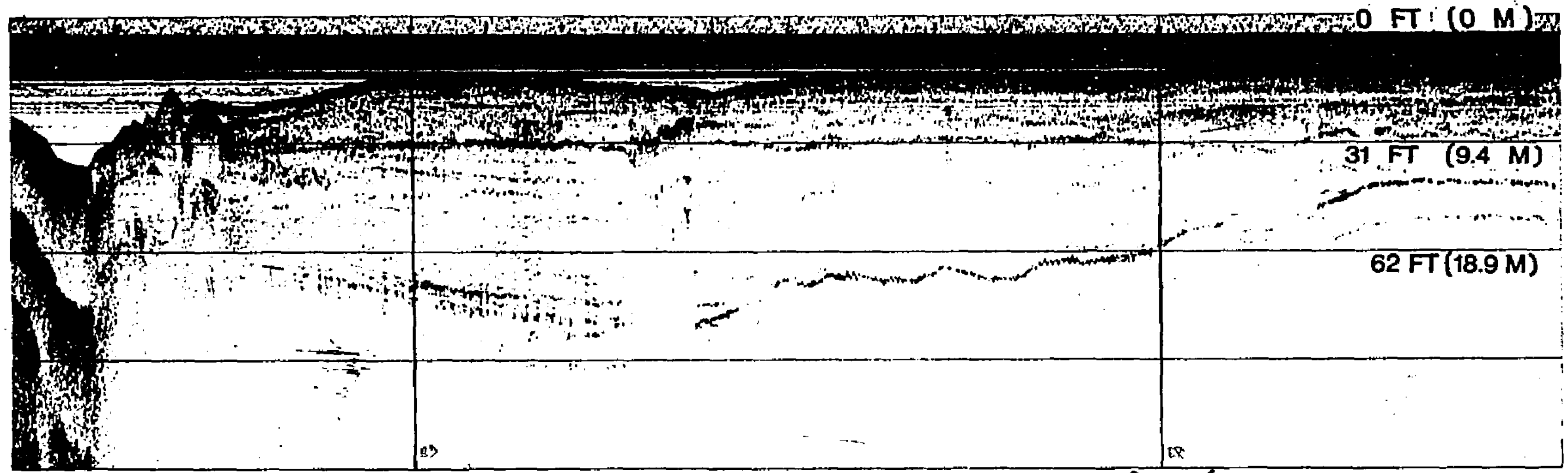
BURWELL BAY WRECK SHOAL STUDY REGION

Figure 44

Burwell Bay-Wreck Shoal Study Region,
Sub-Bottom Profiles, Transect B,
11 July 1985



TRANSECT B 11 JULY 1985 37°03.5'N



TRANSECT B 11 JULY 1985 37°03.5'N

BURWELL BAY WRECK SHOAL STUDY REGION

stratigraphy a nearly continuous reflector is observed at the 9-1Ø m depth. Another strong reflector is observed at the 25 m depth. Over the Wreck Shoal areas, the bottom is observed at depth of 2 to 4 m. Two strong sub-bottom reflectors are also observed at 9-1Ø m and 2Ø to 25 m.

The interpretation of sub-bottom profile data is difficult without the assistance of ground-truth data from borings along the profile lines. In this project, it was not possible to obtain the localized boring data, but other data was available.

Discrete sampling by dredge and tongs of the bottom sediments in the Rocklanding Shoal channel indicates the bottom to be composed of boulders, gravels, oyster shells and other coarse sediments. Assuming that these sediments were exposed by dredging, they are indicative of the strong acoustic reflector at 9-1Ø m. It is then reasonable to conclude that underlying the shallow Point of Shoals and Wreck Shoal oyster reefs is a coarse lag deposit. This deposit is probably of mid to late Plestocene age, corresponding to the transgressive-regressive sequences described by Pebbles (1984). The relatively deep buried channel at 2Ø-25 m, underlying most of the Point of Shoals-Wreck Shoal region is probably related to the ancestral James River, and has not played a role in the recent geomorphic development of the James River. Johnson (1976) analyzing the results of the James River Bridge borings, identified the top of the Yorktown Formation at a maximum depth of 38 m, with a wide buried channel at depths of 20-35 m. The buried channel underlying Point of Shoals and Wreck Shoal is probably related to that channel.

Two additional shallow borings were found in archived U.S. Army, Corps of Engineers data files (Table 9). Boring number one was taken from the southwest corner of Wreck Shoal oyster reef. Boring number two was taken from the northern tip of the White Shoal, immediately below the Wreck Shoal deep channel.

This boring data suggests that the Wreck Shoal oyster reef is limited to the 6.3 m depth and below that is a layer of crushed shells and fine sand. Unfortunately neither of these borings are sufficiently deep to penetrate the strong acoustic reflector identified at the 9-10 m depth.

To determine the age of the oyster shells forming the hard rock crest or ridge of the Wreck Shoal oyster reef, two samples of oyster shells were taken for radiocarbon dating. The locations of the sample sites were 37°03.25'N, 76°34.45'W and 37°03.38'N, 76°35.15'W. At both sample sites, the water depths were 3.1 m (10 ft), and the samples were from 0.3 m (1 ft) below the present reef surface. The oyster shells were excavated from a shell-mud matrix, articulated and in the growth position. The shells were analyzed by Beta Analytic, Inc., Coral Gables, FL, and were dated at 420, ±60 years and 430, ±70 years B.P. These results indicate that the Wreck Shoal oyster reef is a relatively young reef of Holocene age.

Table 9

U.S.A., CORPS OF ENGINEERS, BORING LOGS
WRECK SHOAL, WHITE SHOAL

Boring Number 1 - SW Corner Wreck Shoal Oyster Reef
(N - 268,600′ and E - 2,557,050′)

Depth m	Depth ft	Sediment Type
3.6	11.9	river bottom
		oyster shells
4.6	15.2	
		75% soft mud, 25% oyster shells
5.9	19.5	
		75% oyster shells, 25% mud
6.3	20.8	
		crushed shells and fine sand
8.7	28.5	

Boring Number 2 - Northern Tip White Shoal
(N - 267,400′ and E - 2,563,300′)

Depth m	Depth ft	Sediment Type
4.9	16.1	river bottom
		soft mud and shells
5.9	19.4	
		decayed wood and mud
6.3	20.5	
		coarse sand and few pebbles
8.8	29.0	

Discussion

The purpose of this part of the study was to investigate the Holocene evolution of the James River estuary, particularly in the region of Wreck Shoal, so as to understand the relationship between the long-term development of the river, the estuary, and the contemporary oyster reef morphology. The Pliestocene-Holocene geologic history of the lower James River is characterized by a series of transgressions and regressions of the sea, with alternating periods of erosion and deposition, resulting in fluvial, estuarine, and marine stratigraphic sequences. During the early and middle Pliestocene, a series of erosion, deposition cycles occurred in the ancestral James River. During this period, the deep buried channel (20-25 m depth) identified in the sub-bottom records, was probably cut into the marine sediments of the Yorktown Formation. Later in the Sangamonian Interglaciation, this channel was filled. In subsequent transgression, associated with oscillations in sea level, a coarse lag deposit was formed at the 9-10 m depth. At the end of that period and extending into the beginning of the Wisconsinan Glaciation, as sea level receded, the present James River developed, and point-bars were formed opposite the meanders. The ridge and trough topography of the point-bar complex associated with Wreck Shoal, Point of Shoals, and Mulberry Island were probably formed during this period. During the late

Wisconsinan Glaciation, the erosion of the James River deep channel valley probably occurred.

As sea level rose during the late Pliestocene and Holocene, the James River valley was flooded, and the estuary developed. As the estuary developed, conditions at the Wreck Shoal, Point of Shoals point-bar complex became favorable for the growth of oysters about 1,ØØØ years B.P. Oyster reefs initially developed on the ridges or topographic highs of the point-bar complex about 6 m (19.3 ft) below present sea level or about 1.5 m (5 ft) below sea level at that time. As sea level rose, the oyster reefs developed vertically. Approximately 425 years B.P., the crest of the Wreck Shoal oyster reef was 3.4 m (11 ft) below present sea level or 1.5 m (5 ft) below sea level at that time. From approximately 1ØØØ B.P. to 425 B.P., the reef developed vertically about 3 m or 5Ø cm per 1ØØ years.

SUMMARY AND CONCLUSIONS

Wreck Shoal is a subtidal oyster reef, located in the middle estuary region of the James River, Virginia. Two types of oyster reefs, with significantly different geomorphic characteristics, were identified on Wreck Shoal. The hard-rock oyster reefs are characterized by a relatively thick oyster shell layer, higher densities of live oysters, coarser interstitial sediment, and negligible sediment cover. In contrast, the mud-shell oyster reefs are characterized by a very thin oyster shell layer, finer interstitial sediments, and 1-2 cm layer of very fine sediments covering the reef.

The contemporary sedimentation processes operating on the Wreck Shoal oyster reefs are complex. Yet there are basic differences in these processes that account for the differences between the hard-rock and mud-shell oyster reefs. The fundamental observation is that the hard-rock oyster reefs do not accumulate fine sediments and the mud-shell reefs do accumulate fine sediments. On Wreck Shoal, the hard-rock reefs are in shallower water and the mud-shell reefs are in deeper water. Bottom currents are stronger on the hard-rock reefs and weaker on the mud-shell reefs, but the difference in the current strength is caused by local spatial variations in the current that are inversely related to water depth. The hard-rock oyster reef is hydraulically rougher than the mud-shell oyster reef. The sedimentary environment is related to the bottom shear stress, which is related to the square of the magnitude of the bottom current, the water density, and the bottom roughness coefficient. Thus given the differences in the bottom current and bottom roughness on the hard-rock and mud-shell oyster reefs, the differences in the observed sedimentary environments are fully explainable.

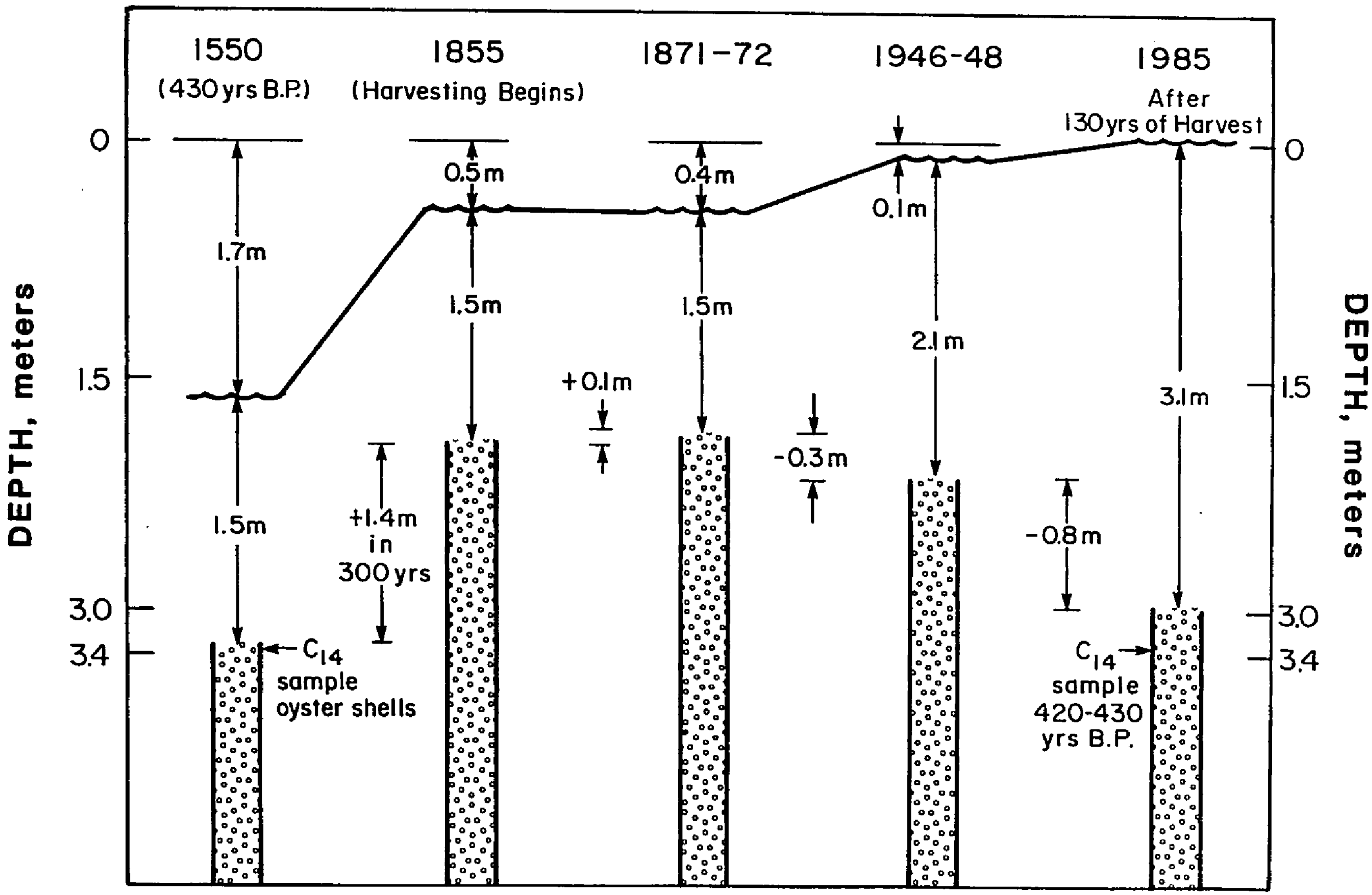
The Coastal Plain part of the ancestral James River developed during the early to middle Pliestocene Epoch. A series of transgresions and regressions of the sea alternately filled and eroded deep channels in the river valley. The buried channel, found in the sub-bottom profile records at depths of 20-25 m is related to these processes. The coarse lag deposit observed in bottom samples from the Rocklanding Shoal dredged channel, and found in the sub-bottom profile records at depths of 9-10 m is probably related to a series of late Pliestocene oscillations in sea level. During the Wisconsinan Glaciation, the present James River channel was incised into the coastal plain sediments. During that time, the river channel meandered and the point-bars were formed.

As sea level rose during the Holocene Epoch, the James River stream valley flooded, and the estuarine zone progressively moved upstream. As this flooding proceeded, that narrow portion of the estuary that is favorable for oyster growth also continuously moved upstream (Figures 2, 3, and 4). At the present time the Wreck Shoal oyster reef is about mid-way through this zone, and it is reasonable to assume that about 1000 B.P. it was on the upstream boundary of that zone. At that time sea level was about 2.5 m below its present level. The Wreck Shoal hard-rock oyster reefs probably initially formed on the shallow sandy shoals of the point-bar. Then as sea level slowly rose, the reefs developed vertically maintaining their relative position with respect to sea level. The mud-shell oyster reefs probably formed in the topographic lows of the point-bar ridge and swale topography. These reefs have been marginal in their productivity since their inception because of their relative deep water, slow currents, and high sedimentation rates.

The recent evolution of the Wreck Shoal oyster reef has been documented in this study and is summarized in Figure 45. The oldest data on the reef is the radiocarbon dates of the oyster shells, indicating that the surface of the reef was about 3.4 m below present sea level in 1550. Sea level at that time was about 1.7 m below the present sea level. The first bathymetric data concerning Wreck Shoal was taken in 1855, and it indicates a depth of 1.5 m to the oyster reef but sea level was also 0.5 m lower than at present. This indicates that the oyster reef developed vertically 1.4 m in the 300 year interval between 1550 and 1850. By early 1870, the reefs developed another 0.1 m, and at this

Figure 45

Recent Geomorphic Evolution,
Wreck Shoal Oyster Reef



1550
(430 yrs B.P.)
1855
(Harvesting Begins)
1871-72
1946-48
1985
After
130 yrs of Harvest
DEPTH, meters
0
1.5
3.0
3.4
1.7m
1.5m
0.5m
1.5m
0.4m
1.5m
0.1m
2.1m
3.1m
+1.4m
in
300 yrs
+0.1m
-0.3m
-0.8m
C_{14}
sample
oyster shells
C_{14}
sample
420-430
yrs B.P.
DEPTH, meters

point, active offshore harvesting began. In the mid 1940's, the water depth over the reef was 2.1 m, and after accounting for sea level rise, the oyster reef lost 0.3 m of elevation. In 1985, the water depth over the reef was 3.1 m and again after accounting for sea level rise, the oyster reef lost another 0.8 m for a total loss in elevation of more than 1 m in 100 years of harvesting activity.

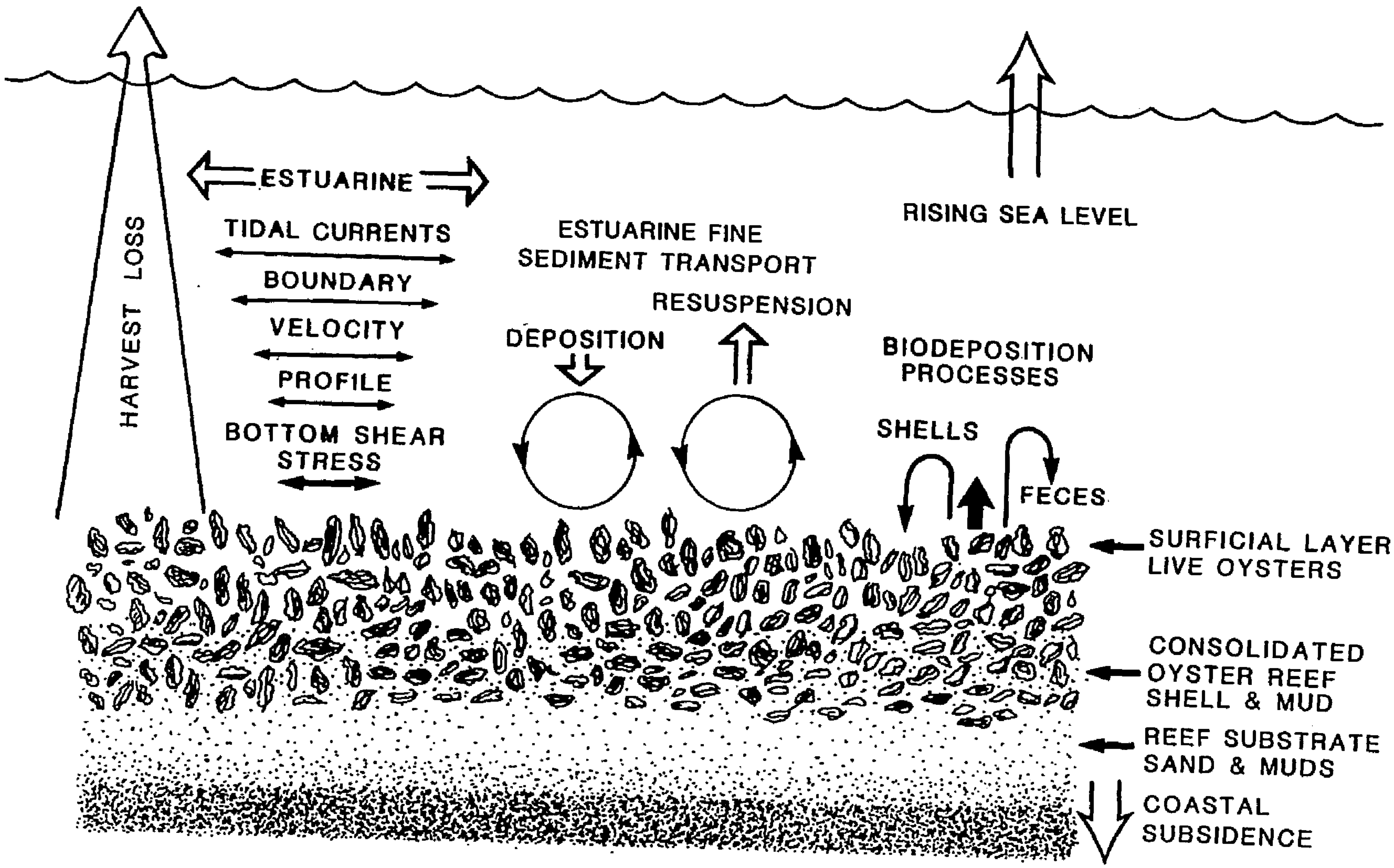
During the period from 1550 to 1855, the Wreck Shoal oyster reef developed vertically at a rate of 0.5 m per 100 years, and this agrees with the rate of reef growth proposed in the model of biodeposition processes presented previously. During the period from 1870 to 1985, the Wreck Shoal oyster reef lost more than 1 m of elevation, the equivalent of 200 years of natural vertical growth, undoubtably due to harvesting activity. It appears that on the Wreck Shoal oyster reef, siltation is not a problem, but harvesting is.

During the period from the 1870's to the 1980's, there have been substantial changes in the morphology of the James River in the vicinity of Wreck Shoal. The 6 km of intertidal oyster reef that traversed the Point of Shoals area have disappeared. The former main channel of the river, meandering around the Point of Shoals-Wreck Shoal point-bar, has filled dramatically, with the cross sectional area decreasing more than 50 percent. A deep hole, 48.8 m, in the natural channel below Wreck Shoal, has filled to 16.8 m. A navigation channel (8 m) was dredged across the point-bar separating Point of Shoals and Wreck Shoal in the early 1930's. These changes in the morphology of the river have probably influenced estuarine circulation and sedimentation processes.

Integrating all aspects of this study into a conceptual model, it appears that there exist complex interdependencies between the productivity of the oyster reefs, the contemporary hydraulic and sedimentation processes and historical geomorphology of the shoal (Figure 46). The local physiography of the shoal is a very important factor related to the sedimentary processes. Given a sufficient bottom shear stress, fine estuarine sediments do not accumulate on the oyster reef and the reef flourishes, indicated by a thicker shell layer and higher densities of live oysters that contribute to the bottom roughness. The thickening shell layer decreases the local water depths, increasing the magnitude of the bottom current. Given the appropriate set of initial conditions, the process of oyster reef growth is self-perpetuating. Further complicating the problem, however, is the rise in sea level, and the effect of man's harvesting both tending to reduce the thickness of the shell layer, and thus increasing the local water depth, decreasing bottom current and bottom shear stress, resulting in increased sedimentation, and decreased oyster productivity.

Figure 46

Model of Subtidal Oyster Reef Dynamics


HARVEST LOSS
ESTUARINE
TIDAL CURRENTS
BOUNDARY
VELOCITY
PROFILE
BOTTOM SHEAR STRESS
ESTUARINE FINE SEDIMENT TRANSPORT
DEPOSITION
RESUSPENSION
RISING SEA LEVEL
BIODEPOSITION PROCESSES
SHELLS
FECES
SURFICIAL LAYER LIVE OYSTERS
CONSOLIDATED OYSTER REEF SHELL & MUD
REEF SUBSTRATE SAND & MUDS
COASTAL SUBSIDENCE

MANAGEMENT IMPLICATIONS OF THIS STUDY

Reef Damage by Vessel Traffic

Based on the results of the side scan sonar study, it is clear that the passage of large commercial vessels over Wreck Shoal is adversely effecting the oyster reef. The damage is unnecessary, if the large commercial vessels would remain in the marked navigation channels, and not travel over the shoals, even though the water is sufficiently deep not to run aground. Therefore, it is recommended that the resource management agencies act to prohibit this activity by requiring that commercial vessels remain in the marked navigation channels.

Present Status of the Wreck Shoal Oyster Population

As a result of the 1984 subenvironment description, the standing crop of oysters on Wreck Shoal was determined for the three subenvironments. This data was averaged and is expressed in terms of density (oysters per square meter, or bushels per acre). It is of interest to compare these to previous data available for the same area:

Date	No. per m^2	Bushel/Acre	Source
1984	71	386	This study
1979	19	186	Haven, and others, 1981
1973-75	22	158	Loesch, and others, 1975
1910	49	308	Moore, 1910

Review of the 1984 data indicates abnormally high counts for the sand-shell subenvironment due to a good spatfall the previous year (the ratio of small to large oysters was 2Ø:1), and this certainly biases the results. However, regardless of this, it is clear that in 1984 the density of oysters on Wreck Shoal was as good as has ever been documented, if not improved. It should also be noted here that there is a paucity of good quantitative density data (individuals or volume of oysters per unit area of bottom) for the oyster reefs of Virginia. Comparisons based on volume of dredged bottom material, while better than nothing, do not provide the basis for accurate, sound management decisions. It would seem logical for VIMS and the VMRC to develop and implement a systematic, repeatable experimental design for the collection of oyster density data on the public bottoms of the Commonwealth of Virginia. This would allow for the real-time monitoring of oyster reef standing-crop, harvest, recruitment, box mortality, and for the cross-comparison of data. This should be included in the proposed Fisheries Management Plan for the oyster resource of the Commonwealth.

Effectiveness of the Cull Law

The results of the historical bathymetric chart comparisons, indicate significant losses in bottom elevation on the oyster reefs of Wreck Shoal and Point of Shoals. On Point of Shoals the intertidal reefs of the 187Ø's have become subtidal, and on Wreck Shoal the bottom elevation losses are greater than 1 m in the crest of the reef.

From an oyster resource management perspective, it would appear that the present "cull law" as enforced (separation of market and seed oysters from cultch, and the return of cultch to the bottom) is not serving to maintain the Wreck Shoal oyster reef. The continued loss of elevation on Wreck Shoal will eventually deplete the fossil reef shell stock. In addition, other aspects of this study suggest that a loss of elevation results in diminished local bottom currents over the bed, and this may lead to increased siltation and decreased productivity. The stricter enforcement of the existing "cull law" or implementation of a new "cull law" may only serve to decrease the efficiency of harvesting activity and drive the price of seed and market oysters upward, reducing demand. An alternative approach would be to balance the harvesting loss of cultch with sparsely planted fresh shell stock. This shell could be "sprinkle planted" over the most productive reef areas at rates of 300 bushels per acre (43 shells per square meter), based on 600 shells per bushel. A sparse planting of shell would not bury the existing reef or live oysters, but only supplement the annual loss of cultch due to harvesting.

Cultch Condition and Spatfall

The shell-shale spatfall experiments conducted on Wreck Shoal as an ancillary part of this project provide an interesting quantitative comparison between the spat catching ability of fresh planted shell and natural bottom cultch, although it has been known for years that fresh planted shell is superior to natural bottom (Ziegler, Haven and DeAlteris, 1985). In the late fall of 1984, on adjacent experimental plots, planted shell collected approximately 2160 spat per square meter or 200 spat per square foot in contrast to natural bottom collecting 21.6 spat per square meter (2 spat per square foot), a performance difference of two orders of magnitude. Again, the implications of these results are clear, fresh planted shell is vastly superior to natural bottom cultch in its ability to catch spat. This further reinforces the previous recommendation for "sprinkle planting" shell over the most productive reef areas.

A logical extension of the initial James River Seed Oyster Bed Studies would be to propose and conduct several limited field experiments on Wreck Shoal in an attempt to increase the natural spatfall on Wreck Shoal, and thus increase the productivity of the oyster reef. The first of these experiments might be the "sprinkle planting" of a five acre experimental plot on the reef. With appropriate experimental design and monitoring, this would clearly demonstrate the effectiveness of the method when compared to an adjacent control area. A second experiment might be the cultivation of the existing natural bottom cultch with a modified dredge. Again, a five acre experimental plot, accurately monitored and compared to a control plot, would provide convincing data on the usefulness of this technique.

LITERATURE CITED

Andrews, J.P., 1962, Oyster mortality studies in Virginia IV, MSX in James River public seed beds: Proc. Natl. Shellfish Assoc., v. 53, p. 65-84.

Ariathurai, R., and Krone, R.B., 1976, Finite element model for cohesive sediment transport: Jour. of the Hydraulic Div., Amer. Soc. of Civil Engineers, v. 102, p. 323-328.

Bagnold, R.A., 1963, Mechanics of marine sedimentation: in The Sea, Hill, P., (Ed.), v. 3, Interscience Pub., New York, NY, p. 507-528.

Bagnold, R.A., 1966, An approach to the sediment transport problem from general physics: U.S. Geological Survey Prof. Paper 422-I, 37 p.

Bahr, L.M., 1974, Aspects of the structure and function of the intertidal oyster reef community in Georgia: Ph.D. dissertation, University of Georgia, Athens, GA.

Bahr, L.M., and Lanier, W.P., 1981, The ecology of oyster reefs of the South Atlantic Coast, a community profile: U.S. Fish and Wildlife Service Report, OBS-81/15, 105 p.

Bloomfield, P., 1976, Fourier analysis of time series, an introduction: Interscience Pub., New York, NY, 355 p.

Bouma, A.H., 1976, Subbottom characteristics of San Antonio Bay: in Shell Dredging and Its Influence on Gulf Coast Environments, Bouma, A.H., (Ed.), Gulf Pub., Houston, TX, p. 132-148.

Boon, J.D., 1973, Sediment transport processes in a salt marsh drainage system: Ph.D. dissertation, College of William and Mary, Williamsburg, VA, 238 p.

Byrne, R.J., and Boon, J.D., 1973, An inexpensive fast response current speed indicator: Chesapeake Science, v. 14, p. 217-218.

Byrne, R.J., Hobbs, C.H., and Carron, M.J., 1982, Baseline sediment studies to determine distribution, physical properties, sedimentation budgets, and rates in the Virginia portion of the Chesapeake Bay: EPA Report, Virginia Institute of Marine Science, 155 p.

Cameron, W.M., and Pritchard, D.W., 1963, Estuaries: in The Sea, Hill, P., (Ed.), v. 2, Interscience Pub., New York, NY, p. 306-324.

Carver, R.E., 1971, Procedures in Sedimentary Petrology: John Wiley and Sons, New York, NY, 653 p.

Chen, H.S., Lukens, R.J., and Fang, C.S., 1979, A Two-Dimensional Hydrodynamic and Biogeochemical Water Quality Model and its Application to the Lower James River: Virginia Institute of Marine Science, S.R.A.M.S.O.E., no. 183.

Churchill, E.P., 1920, The oyster and the oyster industry of the Atlantic and Gulf Coasts: Bureau of Fisheries Document No. 890, 51 p.

Comstock, J.P., 1967, Principles of naval architecture: Soc. Naval Arch. and Marine Engineers, New York, NY, 827 p.

Crisp, D.J., and Meadows, P.S., 1963, Absorbed layer, the stimulus to settlement in barnacles: Proc. Royal Soc. Biol., v. 158, p. 364-387.

Cutshall, N.H., Larsen, I.L., and Nichols, M.M., 1981, Man-made radionuclides confirm rapid burial of Kepone in James River sediments: Science, v. 213, p. 440-442.

DeAlteris, J., Carr, C., Roney, J., and Stahl, L., 1975, A Sediment transport study, offshore New Jersey: Civil Engineering in the Oceans III, Newark, DE, A.S.C.E., p. 225-244.

DeAlteris, J.T., 1985, The role of bottom currents and the geomorphology of the estuary on the sedimentation processes and productivity of Wreck Shoal, an oyster reef in the James River, Virginia: in press.

Dean, R.G., 1966, Tides and harmonic analysis: in Estuary and Coastline Hydrodynamics, Ippen, A.T., (Ed.), McGraw-Hill, New York, NY, p. 197-230.

Diaz, R., Schaffner, L.C., Byrne, R.J., and Gammish, R.A., 1985, Baltimore Harbor and Channels Aquatic Benthos Investigations: Final Technical Report to U.S. Army Corps of Engineers, Virginia Institute of Marine Science.

Dronkers, J.J., 1964, Tidal computations in rivers and coastal waters: North-Holland Pub., Amsterdam, 518 p.

Dyer, K.R., 1973, Estuaries: a physical introduction: Wiley and Sons, New York, NY, 248 p.

Emery, K.O., 1967, Estuaries and lagoons in relation to continental shelves: in Estuaries, Lauff, G.H. (Ed.), Amer. Assoc. Adv. of Sci., Pub. 83, Washington, DC, pp. 9-11.

Feuillet, J.P., and Fleischer, P., 1979, Estuarine circulation: controlling factor of clay mineral distribution in the James River estuary, Virginia: Jour. of Sed. Pet., v. 5Ø, no. 1, p. 267-279.

Folk, R.L., 1974, Petrology of Sedimentary Rocks: Hemphill Publishing Co., Austin, TX, 182 p.

Galtsoff, P.S., 1964, The American oyster, Crassostera virginica, Gmelin: U.S. Fish and Wildlife Service, Fishery Bulletin, v. 64, 48Ø p.

Graf, W.H., 1971, Hydraulics of sediment transport: McGraw Hill Book Company, New York, NY, 513 p.

Grant, W.D., Williams, A.J., Glenn, S.M., Cacchione, D.A., and Drake, D., 1983, High frequency bottom stress variability and its prediction in the CODE region: W.H.O.I. Tech. Rept., no. 83-19, 71 p.

Grave, C., 19Ø5, Investigation for the promotion of the oyster industry of North Carolina: Report U.S. Commission of Fish and Fisheries for 19Ø3, p. 247-341.

Grinnell, R.S., 1971, Structure and development of oyster reefs on the Suwannee River Delta, Florida, Ph.D. dissertation, State University of New York, New York, NY, p. 186.

Gross, F.G., and Smyth, J.C., 1946, The decline of oyster populations: Nature, v. 157, p. 54Ø-546.

Gucinski, H., 1978, Sediment suspension and resuspension from small craft induced turbulence, Anne Arundel Community College, Maryland, 61 p.

Guy, H.R., Simons, D.B., and Richardson, E.V., 1966, Summary of alluvial channel data from flume experiments, 1956-1961: U.S. Geological Survey Prof. Paper 462-I, 69 p.

Hargis, W.J., 1966, Operation James River (final report): Virginia Institute of Marine Science, S.R.A.M.S.O.E., no. 7, 5Ø p.

Haven, D.S., Hargis, W.J., and Kendall, P.C., 1978, The oyster industry of Virginia: its status, problems, and promise, Virginia Institute of Marine Science, Special Paper Marine Science, no. 4, 1024 p.

Haven, D.S., and Morales-Almo, R., 1966, Use of flourescent particles to trace oyster biodeposits in marine sediments: Council Permanent Internat. Explor. Mar. Jour., v. 30, p. 267-269.

Haven, D.S., and Morales-Almo, R., 1967, Aspects of biodeposition by oysters and other invertebrate filter feeders: Limnol. Oceanography, v. 11, p. 478-498.

Haven, D.S., and Morales-Almo, R., 1968, Occurrence and transport of fecal pellets in suspension: Sedimentary Geology, v. 2, p. 141-151.

Haven, D.S., and Morales-Almo, R., 1972, Biodeposition as a factor in sedimentation of fine suspended solids in estuaries: Geol. Soc. of Amer., Memior No. 133, p. 121-130.

Haven, D.S., Whitcomb, J.P., and Kendall, P.C., 1981, The present and potential productivity of the Baylor grounds of Virginia, V. II: Virginia Institute of Marine Science, Spec. Rept. No. 243, 134 p.

Haven, D.S., and Whitcomb, S.P., 1983, The origin and extent of the oyster reefs in the James River, Virginia: Jour. Shellfish Res., v. 3, no. 2, p. 141-151.

Henderson, F.M., 1966, Open channel flow: MacMillan Company, New York, NY, 522 p.

Hindu, H. and Haskins, H., 1971, Setting of the American oyster related to environmental factors and larval behavior: Proc. Natl. Shellfish Assoc., v. 61, p. 35-50.

Holdahl, S.R., and Morrison, N.L., 1974, Regional investigations of vertical crustal movements in the U.S., using precise releveling and mareographic data: Tectophysics, v. 23, p. 373-390.

Inman, D.L., 1949, Sorting of sediments in the light of fluid mechanics: Jour. of Sed. Pet., v. 19, p. 51-70.

Inman, D.L., 1963, Sediment: physical properties and mechanics of sedimentation: in Submarine Geology, Shepard, F.A., Harper and Row, New York, NY, p. 1Ø1-151.

Ito, S., and Imal, T., 1955, Ecology of oyster bed I, on the decline of productivity due to repeated cultures: Tohoku Journal of Agricultural Research, v. 5, no. 4, p. 251-268.

Jenkins, G.M., and Watts, P.G., 1968, Spectral analysis and its applications: Holden-Day, Inc., San Francisco, CA.

Johnson, G.H., 1976, Geology of the Mulberry Islands, Newport News and North Hampton Quadrangles, VA: Virginia Division of Mineral Resources, Charlottesville, VA, 62 p.

Johnson, G.H., and Peebles, P.C., 1985, Late Cenozoic Geology of southeastern Virginia: Chesapeake Bay Symposium Guidebook, Williamsburg, VA, p. 48.

Kachel, N.B., and Sternberg, R.W., 1971, Transport of bed load as ripples during an ebb current: Marine Geol., v. 1Ø, p. 229-244.

Krone, R.B., 1962, Flume studies of the sediment transport in estuarial shoaling processes: Hydraulic Engineering Laboratory, Final Report, University of California, Berkeley, CA, 11Ø p.

Krone, R.B., 1978, Aggregation of suspended particles in estuaries: in Estuarine Transport Processes, Kjerfve, B. (Ed.), The Belle W. Baruch Library of Marine Science, Number 7, University of South Carolina Press, Columbia, SC, p. 171-19Ø.

Larsen, P.F., 1974, Quantitative studies of the macrofauna associated with the mesohaline oyster reefs of the James River, Virginia: Ph.D. dissertation, College of William and Mary, Williamsburg, VA, 183 p.

Liou, Y.C., and Herbich, J.B., 1976, Sediment movement induced by ships in restricted waterways: TAMU-SG-76-2Ø9, 85 p.

Loesch, J.G., Haven, D.S., and Whitcomb, J.P., 1975, Investigation of the seed oyster reserves in Virginia and testing and modifying of gear to harvest oysters: Final Report Contract No. 3-193-R, Virginia Institute of Marine Science, Gloucester Point, VA.

Loosanoff, V.L., 1965, The American or eastern oyster: U.S. Fish and Wildlife Service Circ. No. 2Ø5, p. 36.

Lund, E.J., 1957 a, Self-silting by the oyster and its significance for sedimentation geology: Pub. Institute of Marine Science, University of Texas, v. 4, no. 2, p. 320-327.

Lund, E.J., 1957 b, Quantitative study of clearance of a turbid medium and feeding by the oyster: Pub. Institute of Marine Science, University of Texas, v. 4, no. 2, p. 296-312.

Lund, E.J., 1957 c, Self-silting survival of the oyster as a closed system, and reducing tendencies of the environment of the oyster: Pub. Institute of Marine Science, University of Texas, v. 4, no. 2, p. 313-319.

Lynch, M.P., and Harrison, W., 1970, Sedimentation caused by a tube building amphipod: Jour. of Sed. Pet., v. 40, p. 434-436.

MacKenzie, C.L., 1983, To increase oyster production in northeastern United States: Marine Fisheries Review, v. 45, no. 3, p. 1-22.

Marshall, N., 1954, Changes in the physiography of oyster bars in the James River, Virginia: Virginia Jour. of Science, v. 5, no. 3, p. 173-181.

McDonnell, D.M., and O'Conner, R.A., 1977, Hydraulic Behavior of Estuaries: John Wiley, New York, NY, p. 292.

McHugh, J.L., 1967, Estuarine Nekton: in Estuaries, Lauff, G.H., (Ed.), Amer. Assoc. Adv. of Sci., Washington, DC, p. 581-620.

Meade, R.H., 1969, Landward transport of bottom sediments in estuaries of the Atlantic Coastal Plain: Jour. of Sed. Pet., v.39, p. 222-234.

Meade, R.H., 1972, Transport and deposition of sediments in estuaries: in Geol. Soc. of Amer., Memoir No. 133, p. 173-181.

Mehta, A.J., 1973, Depositional behavior of cohesive sediments: Ph.D. dissertation, University of Florida, Gainsville, FL.

Mehta, A.J. (in preparation), Characterization of cohesive sediments properties and transport processes in estuaries: 36 p.

Moncure, R., and Nichols, M.M., 1968, Characteristics of the sediments in the James River estuary: Virginia Institute of Marine Science, Special Science Report No. 53, 40 p.

Moore, H.F., 1910, Condition and extent of the oyster beds of the James River: U.S. Bureau of Fisheries, Doc. No. 729, Washington, DC, 83 p. plus charts.

Morisawa, M., 1968, Streams, their dynamics and morphology: McGraw Hill, New York, NY, 173 p.

Nichols, M.M., and Poor, G., 1967, Sediment Transport in a coastal plain estuary: Amer. Soc. of Civil Eng., Jour. Waterways and Harbors Div., v.93, no. WW4, p. 83-95.

Nichols, M.M., 1972 a, Sediments of the James River estuary, Virginia: in Geol. Soc. of Amer., Memoir No. 133, p. 160-212.

Nichols, M.M., 1972 b, Effect of increasing depth on salinity in the James River, estuary, Virginia: in Geol. Soc. of Amer., Memoir No. 133, p. 571-588.

Nichols, M.M., and Biggs, R.B., 1984, Estuaries: in Coastal Sedimentary Environments, Davis, R.A., (Ed.), Springer-Verlag Publisher, p. 76-180.

Nikuradse, J., 1933, Laws of Flow in Rough Pipes: Natl. Advisory Comm., Aeronautics Tech. Mem. 1292 (translation from German, 1950).

Norris, R.M., 1953, Buried oyster reefs in some Texas bays: Jour. of Paleontology, v. 27, no. 4, p. 569-576.

Nowell, A.R., Jumars, P.A., and Eckman, J.E., 1981, Effects of biological activity on the entrainment of marine sediments: Marine Geol., v. 42, p. 133-153.

Oaks, R.Q., and Coch, N.K., 1973, Post-Miocene stratigraphy and morphology, southeastern Virginia: Virginia Division of Mineral Resources Bulletin, v. 82, 135 p.

Officer, C.B., and Nichols, M.M., 1980, Box model application to a study of suspended sediment distribution and fluxes in partially mixed estuaries: in Estuarine Perspectives, Kennedy, V., (Ed.), Academic Press, New York, NY, p. 329-340.

Onuschak, E., 1973, Pliestocene-Holocene environmental geology: in Geologic Studies Coastal Plain of Virginia, Virginia Division of Mineral Resources Bulletin No. 83, v. 3, p. 103-153.

Parchure, T.M., and Mehta, A.J., 1983, Erosion strength of soft muddy deposits: Proceeding of the Second Indian Conference in Ocean Engineering, Poona, India, p. 871-884.

Partheniades, E., 1962, A study of erosion and deposition of cohesive soils in salt water: Ph.D. dissertation, University of California, Berkeley, CA.

Partheniades, E., 1971, Erosion and deposition of cohesive materials: in River Mechanics, Volume II, Shen, H.W., (Ed.), Fort Collins, CO.

Peebles, P.C., 1984, Late cenozoic landform, stratigraphy, and history of sea-level oscillations of Southeastern Virginia and Northeastern North Carolina: Ph.D. dissertation, College of William and Mary, Williamsburg, VA.

Peebles, P.C., Johnson, G.H., and Berquist, C.R., 1984, The middle and late Plistocene stratigraphy of the outer coastal plain: Virginia Minerals, v. 30, no. 2, p. 13-22.

Price, W.A., 1954, Oyster reefs of the Gulf: in The Gulf of Mexico, Its Origin, Waters and Marine Life. U.S. Fish and Wildlife Service, Fishery Bulletin, v. 55, no. 89, 491 p.

Price, W.A., 1968, Oyster Reefs: in The Encyclopedia of Geomorphology, Fairbridge, R.W., (Ed.), Reinhold Book Corp., New York, NY, p. 799-803.

Pritchard, D.W., 1952, Salinity distribution and circulation in Chesapeake Bay estuary system: Jour. of Marine Research, v. 11, p. 106-123.

Pritchard, D.W., 1954, A study of salt balance in a coastal plain estuary: Jour. of Marine Research, v. 13, p. 133-144.

Pritchard, D.W., 1955, Estuarine circulation patterns: Amer. Soc. Civil Eng. Proc., v. 81, p. 1-11.

Pritchard, D.W., 1956, The dynamic structure of a coastal plain estuary: Jour. of Marine Research, v. 15, p. 33-42.

Pritchard, D.W., 1967a, Observations of circulation of coastal plain estuaries: in Estuaries, Lauff, G.H., (Ed.), Amer. Assoc. Adv. of Sci., Pub. No. 83, Washington, DC, p. 37-44.

Pritchard, D.W., 1967b, What is an estuary: a physical viewpoint: in Estuaries, Lauff, G.H., (Ed.), Amer. Assoc. Adv. of Sci., Pub. No. 83, Washington, DC, p. 3-5.

Pritchard, D.W., and Kent, R.E., 1953, The reduction and analysis of data from the James River, Operation Oyster Spot: Tech. Report VI, Ref. 53-12, CBI, Johns Hopkins University.

Pritchard, D.W., and Carter, H.H., 1971a, Estuarine circulation patterns: in The Estuarine Environment, Amer. Geological Institute, Washington, DC, p. II-9 to II-110.

Pritchard, D.W., and Carter, H.H., 1971b, Estuarine circulation patterns: in The Estuarine Environment, Amer. Geological Institute, Washington, DC, p. IV-1 to IV-17.

Sallenger, A.H., Goldsmith, V., and Sutton, C.H., 1975, Bathymetric comparisons, a manual of methodology, error criteria and techniques, Virginia Institute of Marine Science, S.R.A.M.S.O.E., no. 66, 34 p.

Schubel, J.R., 1971a, Estuarine circulation and sedimentation: in The Estuarine Environment, Amer. Geological Institute, p. VI-1 to VI-17.

Schubel, J.R., 1971b, Sources of Sediments to Estuaries: in The Estuarine Environment, Amer. Geological Institute, Washington, DC, p. V-1 to V-19.

Sheldon, R.W., Loring, D.H., and Delen, S., 1969, Physiographic changes in Malpegue Bay, Prince Edward Island, between 1845 and 1955, and the possible effects on oyster production: Jour. Fish. Res. Bd. Canada, v. 26, p. 171-175.

Shidler, J., and MacIntyre, W., 1967, Hydrographic data collection for Operation James River, 1964: Virginia Institute of Marine Science, Data Report No. 5, 145 p.

Soulsby, R.L., 1983, The bottom boundary layer of shelf seas: in The Physical Oceanography of Coastal and Shelf Seas, Johns, B., (Ed.), Elsevier, New York, NY, p. 189-266.

Soulsby, R.L., and Dyer, K.R., 1981, The form of the near-bed velocity profile in a tidally accelerating flow: Jour. of Geophysical Research, v. 86, no. C9, p. 8067-8074.

Steele, R.G., and Torrie, J.H., 1960, Principles and procedures of statistics: McGraw Hill, New York, NY, 479 p.

Stenzel, H.B., 1971, Oysters: in Treatise on Invertebrate Paleontology, Moore, K.C., (Ed.), Part N, v. 3, Geol. Soc. of Amer., p. N953-N1224.

Sternberg, R.W., 1967, Measurements of sediment movement and ripple migration in a shallow marine environment: Marine Geol., v. 5, p. 195-205.

Sternberg, R.W., 1968, Friction factors in tidal channels with differing bed roughness: Marine Geol., v. 6, p. 243-260.

Sternberg, R.W., 1972, Predicting initiation motion and bed load transport of sediment particles in the shallow marine environment: in Shelf Sediment Transport, Swift, D., Duane, D., and, Pilkey, O. (Eds.), Dowden, Hutchinson, and Ross, PA, p. 61-82.

Vanomi, V.A., 1952, Some effects of suspended sediment on flow characteristics: Proc. Fifth Hydraulic Conference, Bull. 34, State University of Iowa, Iowa City, IO.

Verwey, J., 1952, On the ecology of distribution of cockle and mussel in the Dutch Waddensea, their role in sedimentation, with a short review of the feeding behavior of bivalve mollusks: Arch. Nerrl. Zool., v. 10, p. 172-239.

Wilson, W.B., 1950a, The effects of dredging on oysters in Capono Bay, Texas: in Annual Report of the Laboratory of Texas Game Fish and Oyster Commission for 1948-1949, 150 p.

Wilson, W.B., 1950b, The effects of sedimentation due to dredging operations on oyster in Capono Bay: MS thesis, A and M College of Texas, 128 p.

Wong, G.T., and May, C.S., 1984, Cesium 137, Metals and organic carbon in the sediments of the James River Estuary, Virginia: Estuarine, Coastal and Shelf Science, v. 18, p. 37-49.

Yonge, C.M., 1960, Oysters: Willmer Brothers and Haram, Ltd., London, England, p. 209.

Ziegler, J.M., Haven, D.S. and DeAlteris, J.T., 1985, Oyster spatfall on slate planted in the James River, Atlantic Estuarine Research Society, Annual Meeting, Abs.

APPENDIX A

ANALYSIS OF THE CAUSE OF THE BOTTOM SCARS ON THE WRECK SHOAL OYSTER REEF

There are several possible explanations for the scars or tracks on Wreck Shoal. Perhaps the most plausible would be an anchor or dredge dragging across the bottom, or possibly the keel of a boat. The width of the tracks or scars (5-10 m) was directly measured from the side scan sonar record. The precision fathometer records the vertical dimension of the scars or tracks when they pass directly under the survey vessel. The depth of the track varies from 0-1 m (0 to 3 ft). Water depth in the areas of the scar ranges from 2.7 to 5.5 m (9 to 18 ft), Reference MLW. Thus, because of the width and depth of the bottom scars and the water depth it appears doubtful that any of the above explanations reasonably account for these marks. An alternative explanation is that the marks have been caused by the propellor wash of large commercial vessels operating out of the navigation channel, crossing Wreck Shoals.

Liou and Herbich (1976) investigated the sediment movement by ships in restricted waterways, Specifically, their study used the momentum theory of propellor action to estimate the jet of water generated by a ship's propellor. The velocity distribution of that jet downstream of the propellor was simulated by a Gaussian normal distribution function. The shear velocity and shear stresses were also determined using Sternberg's formulas. Based on their development of the problem, a computer program was written to determine the velocity and shear stress at the bed, given the ship's speed, depth of the waterway, propellor RPM's and diameter, and the ship's draft. Their case studies dealt with the Corpus Christi ship channel, with a water depth of 13.7 m, ship's drafts of about 10.7 m, and propellor diameters of about 6.7 m. Based on their analysis, a typical ship had a maximum prop wash exit velocity of 12.8 m/sec and induced maximum bottom velocities of 5.7 m/sec. The largest, deepest draft vessel induced maximum bottom velocities of 9.8 m/sec.

In contrast to the numerical modelling approach of Liou and Herbich (1976), Gucinski (1978) working in the shallow waters of Chesapeake Bay, investigated the effects of the operation of small craft on the turbidity of the water. The results of this study found that the effects of the propellor wash of small boats on the bottom causing resuspension of fine sediments and thus increasing turbidity, is restricted to very shallow water, no more than twice the vessels draft. For the small vessels used in that study, the effects were limited to water depths of 2.5 m.

Vessel traffic in the James River ranges from the small pleasure craft to large ships. The Port of Richmond serves ships in the 100 m range. These vessels draw 5.5 to 6.7 m of water and have propellors 3.7 to 4.6 m in diameter. There is also a large number of tug boats and barges traveling the river. A typical tugboat may handle 2-12 barges. These vessels draw 2.1 to 2.4 m of water, have 1000-1200 H.P. engines, use a propellor 1.8 m in diameter with a shaft RPM of 360, and travel the river at a speed of 2.6 m/sec, (Mr. H. Moss, Port Captain, Lone Star Industries, personal communication). Other large vessels operating on the river include the U.S. Army Landing Craft and Amphibious Vehicles, and large oyster buy boats. At times, all of these vessels have been observed to be outside the marked navigation channel. U.S. Army Landing Craft regularly cross Wreck Shoal. In August of 1984, a mothballed ship under tow by two commercial tugs was observed run hard aground on the flank of the natural channel adjacent to Wreck Shoal. Commercial tugs with barges have been observed at night crossing Wreck Shoal.

An adaptation of the numerical program developed by Liou and Herbich (1976) was written for a microcomputer to investigate the propellor wash exit velocity, the velocity distribution of the jet downstream of the propellor, and the velocities one meter above the bed for varying depths of water. The momentum theory of screw propellor action was utilized realizing that this would provide a conservative estimate of the propellor wash exit velocity. This theory only considers the axial velocity downstream of the propellor, and the rotational effects are neglected. The theory states that the propellor may be replaced by a disc that simply imparts momentum to the water within its cross-section. More sophisticated theories account for the propellor's actual thrust and consider the aerodynamic aspects of propellor action (Comstock, 1967). Using input criteria of the typical James River tugboat, and varying water depths of 3.1, 4.3 and 5.5 m, the propellor exit velocity, the maximum bottom velocities were determined. In all three cases, the propellor exit velocity was 10.7 m/sec. The maximum bottom velocities were 10.7, 3.4 and 2.0 m/sec, for the 3.1, 4.3 and 5.5 m water depth cases, respectively. These bottom velocities are certainly capable of scouring the bottom, and creating the wide trench in the bottom observed on both the side scan sonar and the fathometer records. Thus, based on this analysis it appears that the propellor wash hypothesis is the most plausible explanation for the bottom scars.

It is the longevity of these tracks or scars on the bottom that is of interest, with respect to sediment transport processes on Wreck Shoal. The side scan sonar indicated no observable change in the majority of the bottom scars between the two surveys, a period of nine months. The implications of this are that there is certainly not a significant amount of active sediment transport occurring on Wreck Shoal, otherwise these trenches would have filled and become unrecognizable. Future resurveys of Wreck Shoal will be able to determine exactly how long these features remain.

Both the E.G. & G. side scan sonar surveys identified about 19+ km of bottom scars with the width of the scars about 10 m including the adjacent banks. Therefore the resulting area impacted is 2×10^5 m^2 or about fifty acres. In terms of the total acreage of the Wreck Shoal oyster reef (about 2000 acres), the area affected by the bottom scars is about two percent.

APPENDIX B

DISCRETE SAMPLE DATA STATION LOCATIONS, SEDIMENT AND OYSTER REEF CHARACTERISTICS

SAMPLE STATION LOCATIONS
WRECK SHOAL STUDY AREA

Station	Latitude N	Longitude W
WS 1	37-Ø4.35	76-36.15
WS 2	37-Ø4.5Ø	76-35.93
WS 3	37-Ø4.64	76-35.66
WS 4	37-Ø4.25	76-35.3Ø
WS 5	37-Ø4.1Ø	76-35.55
WS 6	37-Ø3.97	76-35.8Ø
WS 7	37-Ø3.7Ø	76-35.15
WS 8	37-Ø3.85	76-34.9Ø
WS 9	37-Ø3.27	76-35.14
WS 1Ø	37-Ø3.12	76-34.36
WS 11	37-Ø3.3Ø	76-34.38

SAMPLE STATION LOCATIONS
HARD-ROCK SUBENVIRONMENT

Station Number	Latitude N	Longitude W
HR 1	37-Ø3.45	76-34.85
HR 2	37-Ø3.47	76-34.82
HR 3	37-Ø3.49	76-34.78
HR 4	37-Ø3.51	76-34.75
HR 5	37-Ø3.53	76-34.72
HR 6	37-Ø3.42	76-34.83
HR 7	37-Ø3.45	76-34.79
HR 8	37-Ø3.47	76-34.76
HR 9	37-Ø3.49	76-34.73
HR 1Ø	37-Ø3.51	76-34.69
HR 11	37-Ø3.4Ø	76-34.8Ø
HR 12	37-Ø3.42	76-34.77
HR 13	37-Ø3.44	76-34.73
HR 14	37-Ø3.46	76-34.7Ø
HR 15	37-Ø3.48	76-34.67
HR 16	37-Ø3.37	76-34.7Ø
HR 17	37-Ø3.39	76-34.74
HR 18	37-Ø3.41	76-34.71
HR 19	37-Ø3.43	76-34.67
HR 2Ø	37-Ø3.5Ø	76-34.64
HR 21	37-Ø3.35	76-34.75
HR 22	37-Ø3.38	76-34.71
HR 23	37-Ø3.39	76-34.67
HR 24	37-Ø3.4Ø	76-34.65
HR 25	37-Ø3.42	76-34.62

SAMPLE STATION LOCATIONS
SAND-SHELL SUBENVIRONMENT

Station Number	Latitude N	Longitude W
SS 1	37-03.67	76-34.62
SS 2	37-03.69	76-34.59
SS 3	37-03.71	76-34.55
SS 4	37-03.73	76-34.52
SS 5	37-03.75	76-34.49
SS 6	37-03.65	76-34.59
SS 7	37-03.67	76-34.56
SS 8	37-03.69	76-34.53
SS 9	37-03.71	76-34.49
SS 10	37-03.72	76-34.46
SS 11	37-03.62	76-34.57
SS 12	37-03.64	76-34.54
SS 13	37-03.66	76-34.50
SS 14	37-03.68	76-34.47
SS 15	37-03.70	76-34.44
SS 16	37-03.59	76-34.54
SS 17	37-03.61	76-34.51
SS 18	37-03.63	76-34.47
SS 19	37-03.65	76-34.44
SS 20	37-03.70	76-34.41
SS 21	37-03.57	76-34.51
SS 22	37-03.59	76-34.48
SS 23	37-03.61	76-34.45
SS 24	37-03.63	76-34.42
SS 25	37-03.65	76-34.38

SAMPLE STATION LOCATIONS
MUD-SHELL SUBENVIRONMENT

Station Number	Latitude N	Longitude W
SM 1	37-03.67	76-35.39
SM 2	37-03.68	76-35.35
SM 3	37-03.70	76-35.32
SM 4	37-03.72	76-35.28
SM 5	37-03.74	76-35.24
SM 6	37-03.64	76-35.36
SM 7	37-03.66	76-35.33
SM 8	37-03.68	76-35.29
SM 9	37-03.69	76-35.25
SM 10	37-03.71	76-35.22
SM 11	37-03.61	76-35.34
SM 12	37-03.63	76-35.30
SM 13	37-03.65	76-35.27
SM 14	37-03.67	76-35.23
SM 15	37-03.68	76-35.20
SM 16	37-03.58	76-35.31
SM 17	37-03.64	76-35.21
SM 18	37-03.62	76-35.24
SM 19	37-03.60	76-35.28
SM 20	37-03.65	76-35.17
SM 21	37-03.56	76-35.29
SM 22	37-03.58	76-35.26
SM 23	37-03.59	76-35.23
SM 24	37-03.61	76-35.19
SM 25	37-03.63	76-35.15

OYSTER REEF SAMPLE DATA
WRECK SHOAL STUDY AREA

Station	Water Depth (Feet)	Volume Exposed Cultch (Qts.)	Total Number Live Oysters	Volume Live Oysters (Qts.)	Number Oysters Boxes
WS 1	15	2	1Ø4	4	5
WS 2	18+	Ø.5	1Ø9	2	1
WS 3	12.5	1	31	2	5
WS 4	13	Ø.6	36	1	1
WS 5	16	1	23	2	4
WS 6	14	Ø.4	12	1	1
WS 7	18+	4	4Ø	3	5
WS 8	12	1.2	77	4	3
WS 9	13	1Ø	76	9	11
WS 1Ø	11.5	5.6	94	9	19
WS 11	13.5	5.6	48	4	8

OYSTER REEF SAMPLE DATA
HARD-ROCK SUBENVIRONMENT

Station	Water Depth (Feet)	Volume Exposed Cultch (Qts.)	Total Number Live Oysters	Volume Live Oysters (Qts.)	Number Oyster Boxes
HR 1	10	12	90	5	8
HR 2	13	7.2	65	6	8
HR 3	13	4.8	74	6	17
HR 4	14	4.2	53	6	5
HR 5	12	1.8	85	3	1
HR 6	12	2	62	4	4
HR 7	13	3.5	39	3	4
HR 8	13	4.6	54	6	6
HR 9	13	3.0	36	3	5
HR 10	10.5	2.5	85	5	9
HR 11	12	4.5	67	5	14
HR 12	12	4.5	108	7	10
HR 13	12	7.5	84	6	4
HR 14	12	3.0	50	4	3
HR 15	11	2.0	109	7	10
HR 16	11	6	116	8	18
HR 17	11	7.5	93	7	9
HR 18	12	3.6	59	4	11
HR 19	12	5.0	61	4	5
HR 20	11	1.4	71	5	6
HR 21	12	3.5	42	4	3
HR 22	11	8	111	6	11
HR 23	12	7.5	84	6	13
HR 24	12	11.2	84	6	9
HR 25	12	3.2	77	6	15

OYSTER REEF SAMPLE DATA
SAND-SHELL SUBENVIRONMENT

Station	Water Depth (Feet)	Volume Exposed Cultch (Qts.)	Total Number Live Oysters	Volume Live Oysters (Qts.)	Number Oyster Boxes
SS 1	12	1.2	79	4	2
SS 2	13	2.0	103	5	6
SS 3	13	1.2	26	2	5
SS 4	12	1.6	107	5	6
SS 5	12	1.2	43	3	9
SS 6	12	2.5	80	5	4
SS 7	12	2.0	45	3	11
SS 8	13	1.8	97	5	10
SS 9	12	3.0	86	6	10
SS 10	12	1.5	128	5	3
SS 11	11.5	1.0	105	6	6
SS 12	12	1.2	78	5	1
SS 13	12	1.8	169	7	1
SS 14	12	1.8	104	6	13
SS 15	11.5	1.6	131	6	9
SS 16	11.5	1.0	86	5	0
SS 17	12	2.0	80	5	5
SS 18	12	2.4	95	4	6
SS 19	11	2.0	104	4	4
SS 20	12	0.8	68	4	6
SS 21	11	2.0	77	5	9
SS 22	12	6.8	95	6	12
SS 23	11	3.0	92	8	10
SS 24	11	1.5	65	4	8
SS 25	11	2.4	129	6	7

OYSTER REEF SAMPLE DATA
MUD-SHELL SUBENVIRONMENT

Station	Water Depth (Feet)	Volume Exposed Cultch (Qts.)	Total Number Live Oysters	Volume Live Oysters (Qts.)	Number Oyster Boxes
SM 1	14	1.2	8	1	3
SM 2	16	2.4	32	3	3
SM 3	18+	1.5	19	2	3
SM 4	18+	1.2	34	3	5
SM 5	18+	2.4	33	3	1
SM 6	14	2.2	17	2	1
SM 7	16	1.8	26	4	6
SM 8	18+	Ø	1	Ø	Ø
SM 9	18+	2.7	36	4	8
SM 1Ø	18+	1.2	28	3	5
SM 11	15	2.Ø	12	1	3
SM 12	17	3.6	23	3	8
SM 13	19	Ø.5	6	4	1
SM 14	18+	1.6	7	5	1
SM 15	17	4.Ø	49	4	4
SM 16	15	1.8	7	1	1
SM 17	17	4.8	34	5	8
SM 18	15	5.6	36	5	12
SM 19	18	1.6	35	4	2
SM 2Ø	17	5.5	45	4	1Ø
SM 21	15	3.Ø	23	3	7
SM 22	16	2.4	33	3	4
SM 23	18+	2.4	3Ø	4	4
SM 24	18	3.3	22	4	6
SM 25	15	3.Ø	27	3	4

SEDIMENT SAMPLE PERCENTAGES
WRECK SHOAL STUDY AREA

Station	Gravel	Sand	Silt	Clay	Water
MS 1	21.4	21.3	19.Ø	38.4	44.6
MS 2	24.6	25.7	13.5	36.2	47.6
MS 3	5Ø.1	3Ø.4	14.5	5.Ø	33.4
MS 4	1.4	46.3	17.8	34.5	46.5
MS 5	13.6	3Ø.2	15.1	41.Ø	44.8
MS 6	2.2	16.6	23.2	58.1	51.4
MS 7	7.8	23.9	23.Ø	45.4	52.6
MS 8	23.8	47.4	9.8	18.9	33.Ø
MS 9	28.5	49.7	7.4	14.4	29.Ø
MS 1Ø	35.4	41.2	8.4	15.Ø	25.9
MS 11	25.7	45.3	1Ø.9	18.Ø	31.3

SEDIMENT SAMPLE PERCENTAGES
HARD-ROCK SUBENVIRONMENT

Station	Gravel	Sand	Silt	Clay	Water	Carbonate
HR 1	41.2	37.8	Ø.6	2Ø.3	36.8	
HR 2	32.1	37.Ø	5.7	24.9	33.7	
HR 3	38.4	25.8	11.Ø	24.6	28.8	
HR 4	38.1	33.6	3.2	24.9	36.8	
HR 5	35.3	45.8	2.5	16.1	28.5	
HR 6	39.8	37.5	2.2	2Ø.3	33.4	
HR 7	34.5	42.Ø	2.4	21.Ø	31.5	
HR 8	37.3	32.7	12.2	17.6	31.8	5Ø.Ø
HR 9	42.9	34.6	2.2	2Ø.2	33.3	
HR 1Ø	35.4	42.4	1.8	2Ø.3	34.4	
HR 11	33.4	44.2	2.3	19.9	33.9	
HR 12	3Ø.9	38.5	13.Ø	17.4	31.5	59.4
HR 13	44.4	3Ø.9	9.7	14.9	33.4	53.6
HR 14	4Ø.9	31.4	1Ø.9	16.6	32.2	56.6
HR 15	41.Ø	38.1	1.9	18.8	29.4	
HR 16	34.5	3Ø.8	3.6	3Ø.8	28.5	
HR 17	35.5	42.5	2.7	19.1	31.8	
HR 18	36.Ø	39.1	1Ø.2	14.4	28.7	59.3
HR 19	53.4	25.3	2.2	19.Ø	32.4	
HR 2Ø	31.7	47.2	3.Ø	17.9	28.5	
HR 21	42.1	39.3	1.7	16.7	28.6	
HR 22	35.4	49.2	2.Ø	13.3	26.5	
HR 23	5Ø.6	32.Ø	1.7	15.5	3Ø.4	
HR 24	42.5	39.1	2.2	16.Ø	3Ø.9	
HR 25	42.4	37.4	2.Ø	18.Ø	31.Ø	

SEDIMENT SAMPLE PERCENTAGES
SAND-SHELL SUBENVIRONMENT

Station	Gravel	Sand	Silt	Clay	Water	Carbonate
SS 1	42.Ø	38.3	7.8	11.7	31.7	
SS 2	3Ø.1	43.2	11.2	15.3	29.Ø	
SS 3	29.2	47.3	1Ø.4	12.9	26.2	
SS 4	42.3	38.6	7.6	11.4	26.7	
SS 5	25.Ø	49.9	8.9	16.1	3Ø.7	
SS 6	32.2	4Ø.Ø	11.Ø	16.6	32.4	
SS 7	36.2	35.9	11.Ø	16.7	32.3	
SS 8	24.2	44.8	15.8	15.Ø	29.6	4Ø.3
SS 9	22.3	43.1	9.2	13.Ø	3Ø.2	
SS 1Ø	11.3	5Ø.7	6.6	12.2	28.6	
SS 11	39.5	38.4	9.5	12.4	27.7	
SS 12	34.1	38.9	1Ø.7	16.2	28.2	53.6
SS 13	37.1	32.4	1Ø.7	19.6	33.1	46.7
SS 14	21.4	51.7	11.2	15.5	27.5	4Ø.3
SS 15	22.6	56.8	8.1	12.3	26.9	
SS 16	33.3	41.4	1Ø.1	15.Ø	27.1	
SS 17	51.7	3Ø.8	9.Ø	8.4	29.6	
SS 18	37.6	39.5	9.3	13.5	29.4	63.8
SS 19	36.6	42.7	8.7	11.8	28.2	
SS 2Ø	23.4	54.4	8.5	13.5	26.4	
SS 21	37.6	35.5	16.6	1Ø.1	3Ø.9	
SS 22	45.1	38.8	9.7	13.1	31.5	
SS 23	33.3	43.7	9.4	13.5	2Ø.4	
SS 24	31.Ø	49.6	7.8	11.4	25.6	
SS 25	3Ø.Ø	24.7	26.3	18.8	28.1	

SEDIMENT SAMPLE PERCENTAGES
MUD-SHELL SUBENVIRONMENT

Station	Gravel	Sand	Silt	Clay	Water	Carbonate
SM 1	1.1	19.5	21.8	57.6	49.4	
SM 2	3.6	25.0	26.8	44.5	56.6	
SM 3	2.7	23.4	23.9	50.0	55.1	
SM 4	7.8	23.5	22.1	46.6	51.4	
SM 5	4.2	37.6	19.6	38.6	47.5	
SM 6	1.3	26.5	25.3	47.0	50.7	
SM 7	-	-	-	-	-	
SM 8	0.1	36.4	13.7	49.7	42.2	5.8
SM 9	-	-	-	-	-	
SM 10	1.6	42.9	20.7	34.8	45.4	
SM 11	2.4	24.8	24.9	47.9	51.7	
SM 12	5.1	17.2	18.5	59.1	54.3	13.5
SM 13	0.5	20.9	14.6	63.8	47.9	
SM 14	10.1	17.3	15.9	56.5	52.0	14.6
SM 15	12.5	23.5	22.1	42.0	53.1	
SM 16	12.9	25.0	21.4	40.6	47.5	
SM 17	10.0	22.4	23.1	44.5	38.7	
SM 18	16.3	18.0	12.9	52.6	47.7	38.3
SM 19	3.3	26.0	23.5	47.2	51.2	
SM 20	31.8	19.6	17.9	30.7	47.1	
SM 21	4.4	27.1	23.1	45.4	52.2	
SM 22	4.7	23.0	23.5	48.7	53.0	
SM 23	7.2	23.4	22.2	47.1	50.4	
SM 24	30.0	14.7	20.1	35.1	46.8	
SM 25	-	-	-	-	-	

SEDIMENT SAMPLE STATISTICS-MOMENT MEASURES
HARD-ROCK, SAND-SHELL, MUD-SHELL SUBENVIRONMENTS

Station	First Momemt	Second Moment	Skewness	Kurtosis
HR 8	1.7	14.4	Ø.9	2.8
HR 12	2.1	15.Ø	Ø.9	2.7
HR 13	1.2	13.9	1.1	3.1
HR 14	1.4	15.2	1.1	2.9
HR 18	1.7	13.3	Ø.9	3.Ø
SS 8	2.4	12.1	Ø.8	2.9
SS 12	1.7	13.1	1.Ø	3.2
SS 13	1.8	17.1	1.Ø	2.7
SS 14	2.5	11.9	Ø.9	3.2
SS 18	1.5	12.9	1.1	3.2
SM 8	3.9	1Ø.8	1.7	3.2
SM 12	3.4	13.5	1.4	2.9
SM 13	3.6	12.6	1.7	3.1
SM 14	3.3	16.7	1.1	2.4
SM 18	2.7	18.2	1.1	2.4

VITA

Joseph T. DeAlteris

Born in New York, New York, 4 December 1946. Graduated from Henry Hudson Regional High School in 1964. Earned a B.A. in Biological Sciences (marine ecology) from Rutgers the State University in 1968. Served as an officer on submarines in the U.S. Navy Reserve on active duty from 1969 to 1972. Received a M.A. in Marine Science (coastal processes) from the College of William and Mary in 1973. Employed as Project Oceanographer at Dames and Moore, 1974-1975, and as Senior Oceanographer at Pandullo Quirk Associates, 1976-1977. Self-employed oceanographic consultant, DeAlteris Associates, 1977-1983. Joined the faculty of the University of Rhode Island as Assistant Professor of Fisheries and Aquaculture in 1983. Entered the doctoral program in the College of William and Mary, School of Marine Science in 1983.

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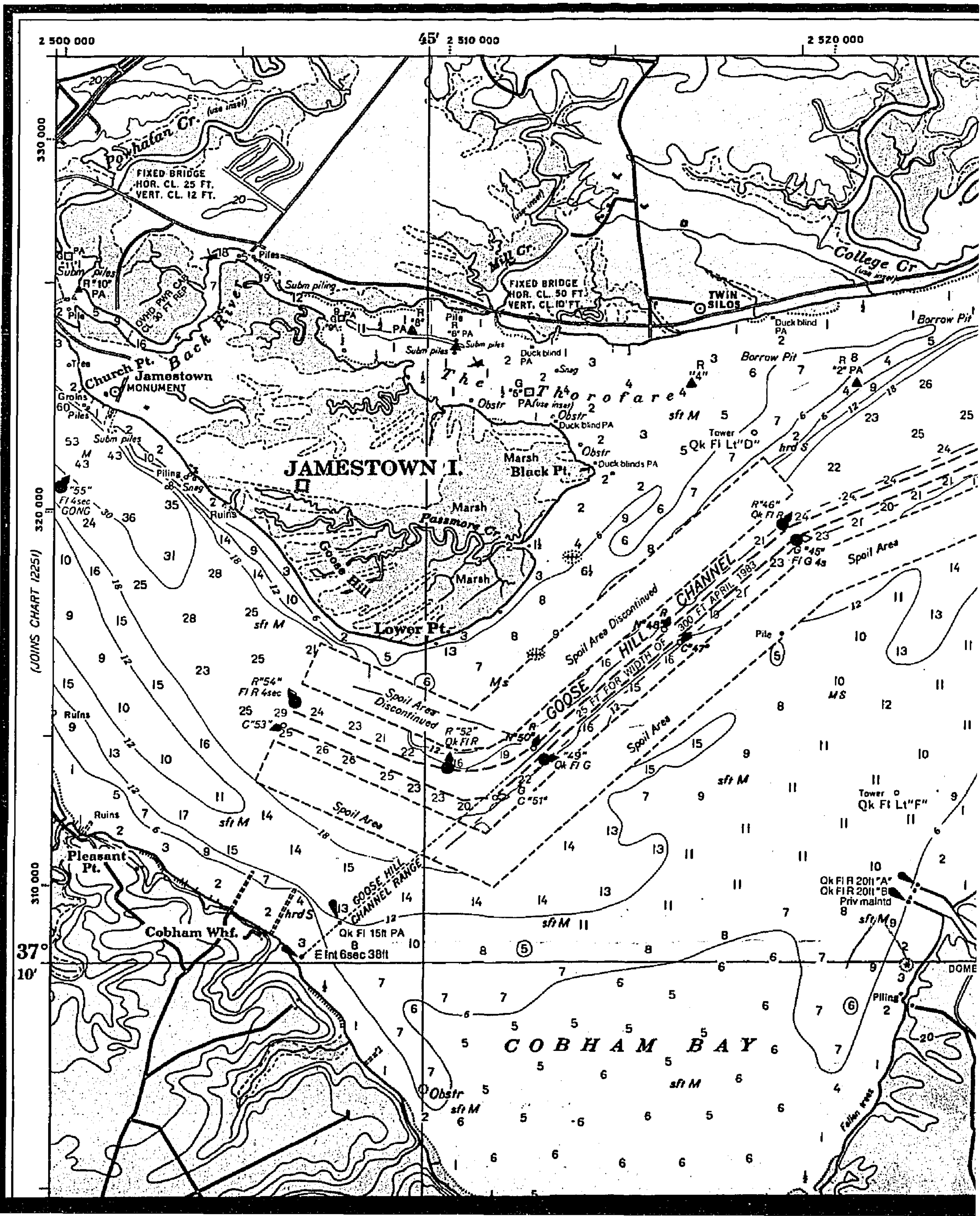
This nautical chart has been designed to promote safe navigation. The National Ocean Service encourages users to submit corrections, additions, or comments for improving this chart to the Director, Charting and Geodetic Services (N/CG22), National Ocean Service, NOAA, Rockville, Maryland 20852.

LOGARITHMI

1 2 3 4 5 6 7

To find SPEED, place one point of dividers on distance run (in any u
right point on 60 and left point will then indicate speed in units per hour



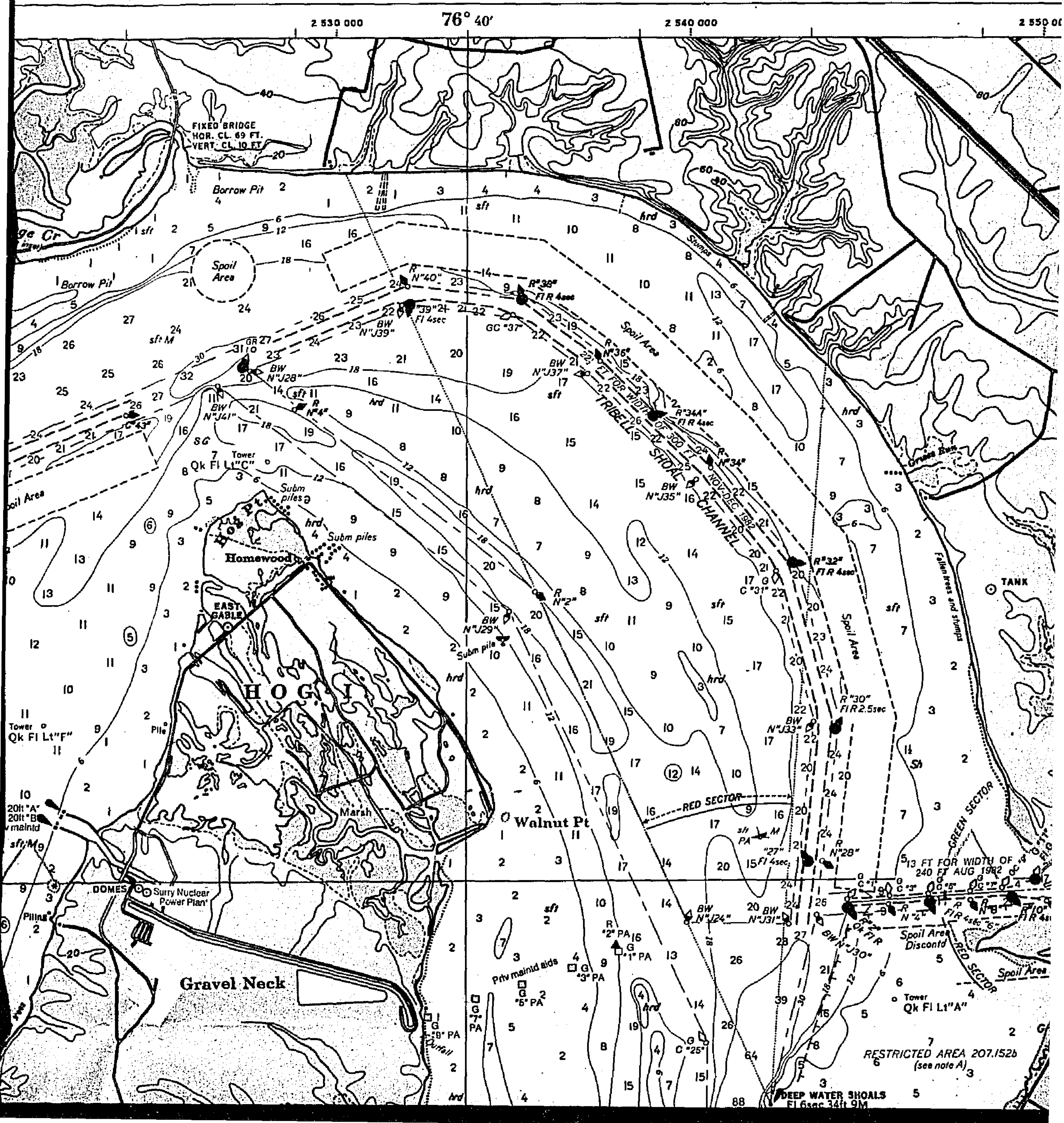
LOGARITHMIC SPEED SCALE

5 6 7 8 9 10 15 20 25 30 40 50 60

…distance run (in any unit) and the other on minutes run. Without changing divider spread, place …speed in units per hour. Example: with 4.0 nautical miles run in 15 minutes, the speed is 16.0 knots

CAUTION
CHANGES in BUOYAGE

Mariners are advised that authorized aids to navigation are being changed to conform to maritime standards of the International Association of Lighthouse Authorities Maritime Buoyage System, Region B. Significant changes are: black port hand buoys to green; black and white vertically striped buoys to red and white vertically striped buoys; and lateral lights from white to red or green as appropriate. Changes to aids to navigation will be announced in the Defense Mapping Agency Hydrographic/Topographic Center weekly Notice to Mariners and the U.S. Coast Guard Local Notice to Mariners.



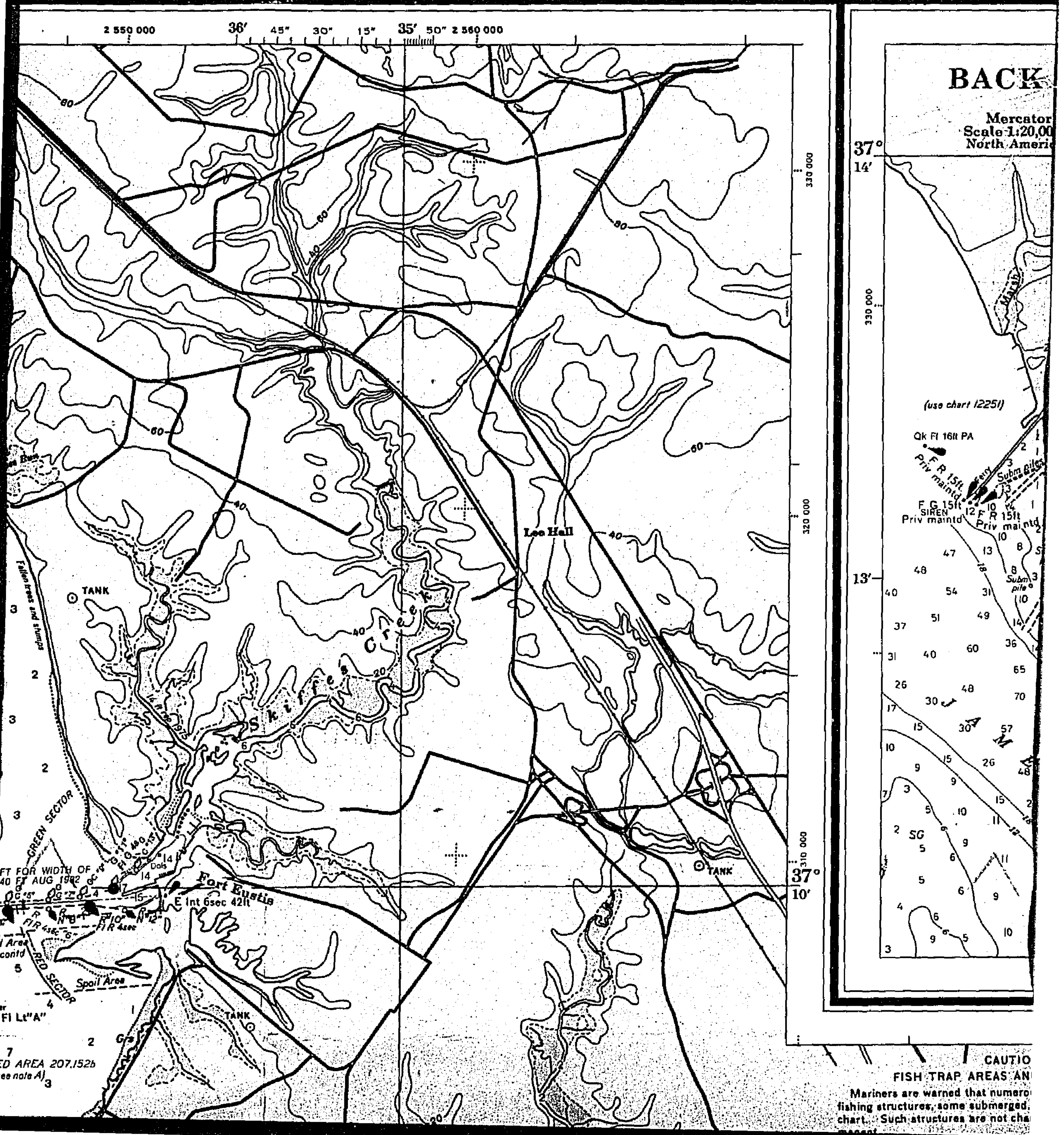
being changed to
on of Lighthouse
anges are: black
s to red and white
n as appropriate.
Mapping Agency
nd the U.S. Coast

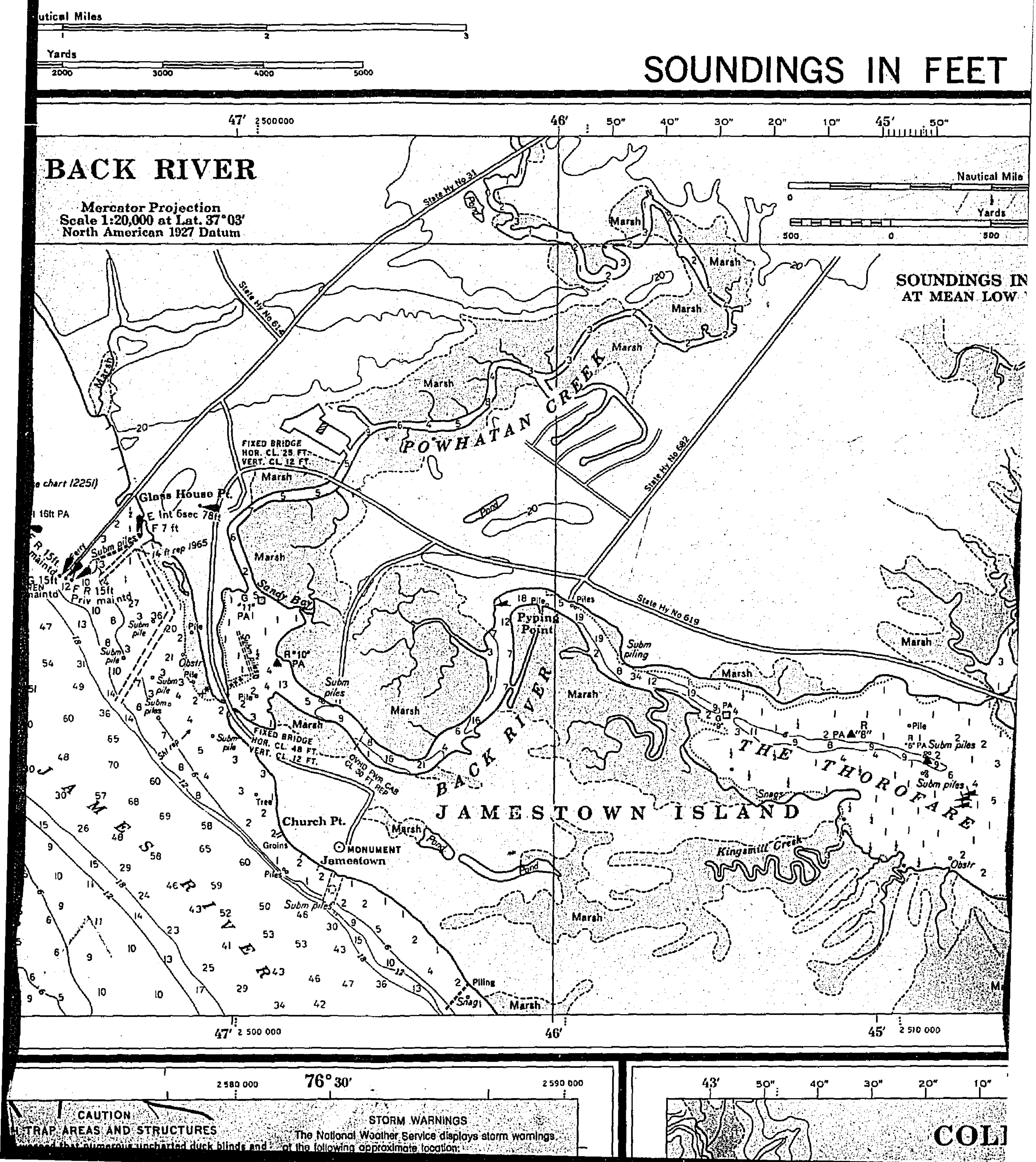
Nautical Miles

Yards

1000 0 1000 2000

Formerly C&GS 529, 1st Ed., Jan. 1912 G-1952-795

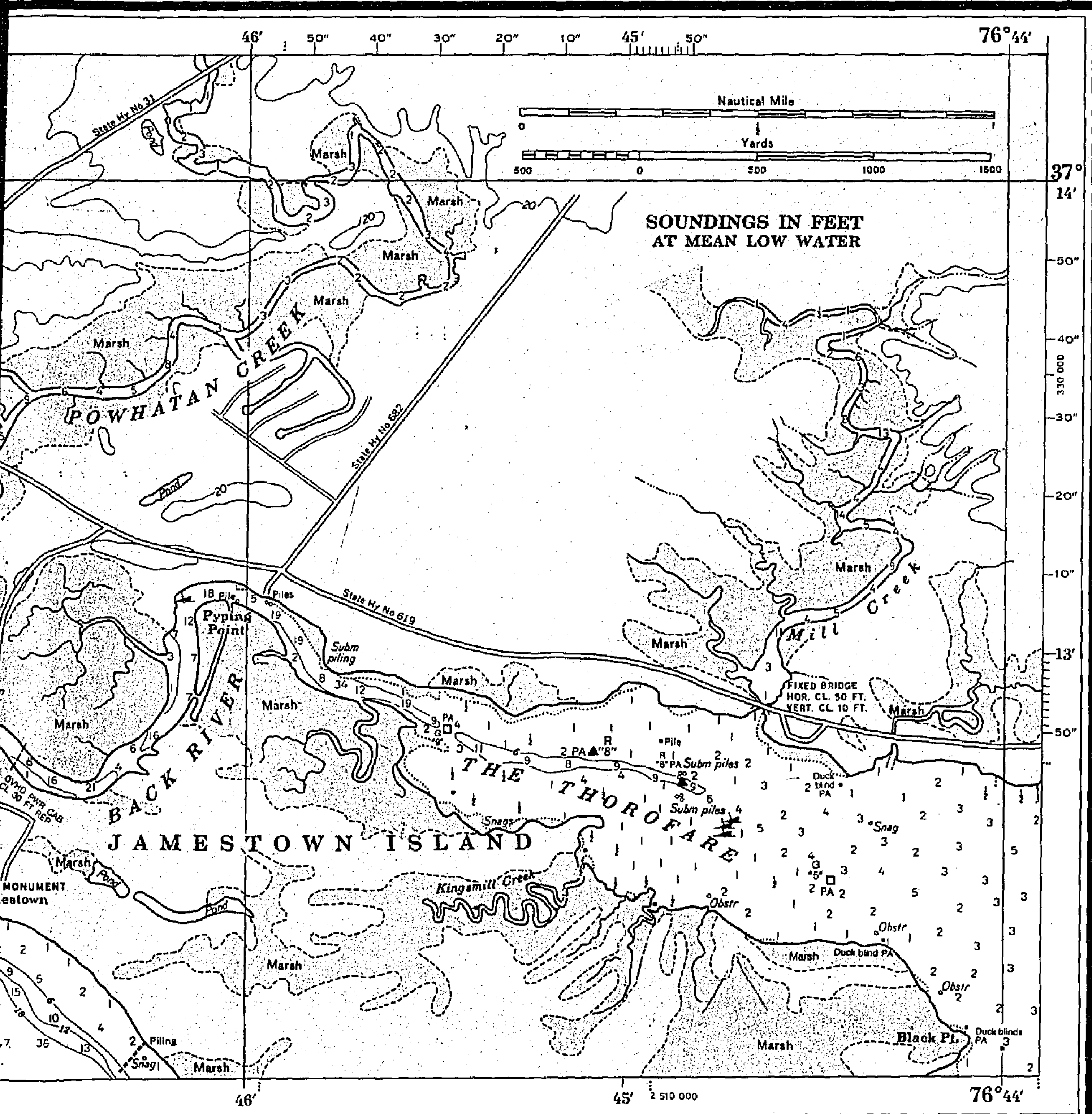



Nautical Miles
Yards
SOUNDINGS IN FEET
BACK RIVER
Mercator Projection
Scale 1:20,000 at Lat. 37°03'
North American 1927 Datum
Nautical Mile
Yards
SOUNDINGS IN
AT MEAN LOW
State Hy No 31
State Hy No 614
State Hy No 682
State Hy No 619
POWHATAN CREEK
FIXED BRIDGE
HOR. CL. 25 FT.
VERT. CL. 12 FT.
Glass House Pt.
E Int 6sec 78ft
F 7 ft
Subm piles
14 ft rep 1965
Priv maintd
Sandy Bay
Pyping Point
Subm piling
Marsh
Pond
BACK RIVER
THE THOROFARE
FIXED BRIDGE
HOR. CL. 48 FT.
VERT. CL. 12 FT.
OVHD PWR CAB
CL 30 FT REP
JAMESTOWN ISLAND
Church Pt.
MONUMENT
Jamestown
Kingsmill Creek
Snags
Obstr
Groins
Piling
JAMES RIVER
STORM WARNINGS
The National Weather Service displays storm warnings at the following approximate location:
CAUTION
TRAP AREAS AND STRUCTURES

SOUNDINGS IN FEET

Nautical Chart Catalog No. 1, Panel D

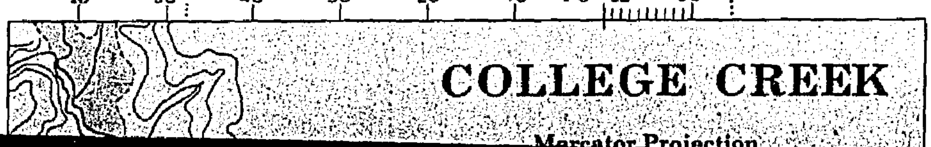
12248



5°30′ 2 590 000

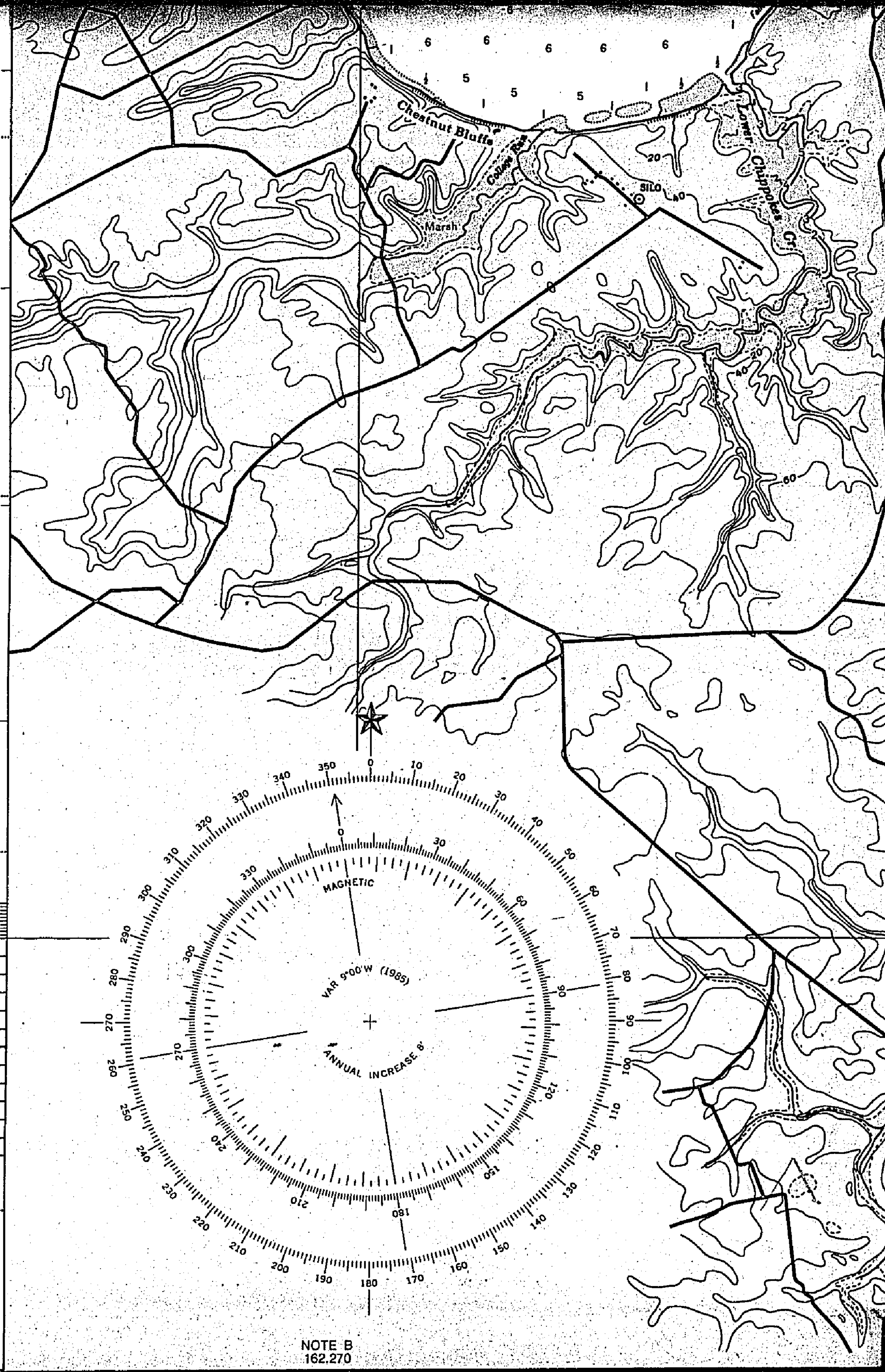
STORM WARNINGS

[N]ational Weather Service displays storm warnings [at the fo]llowing approximate location:

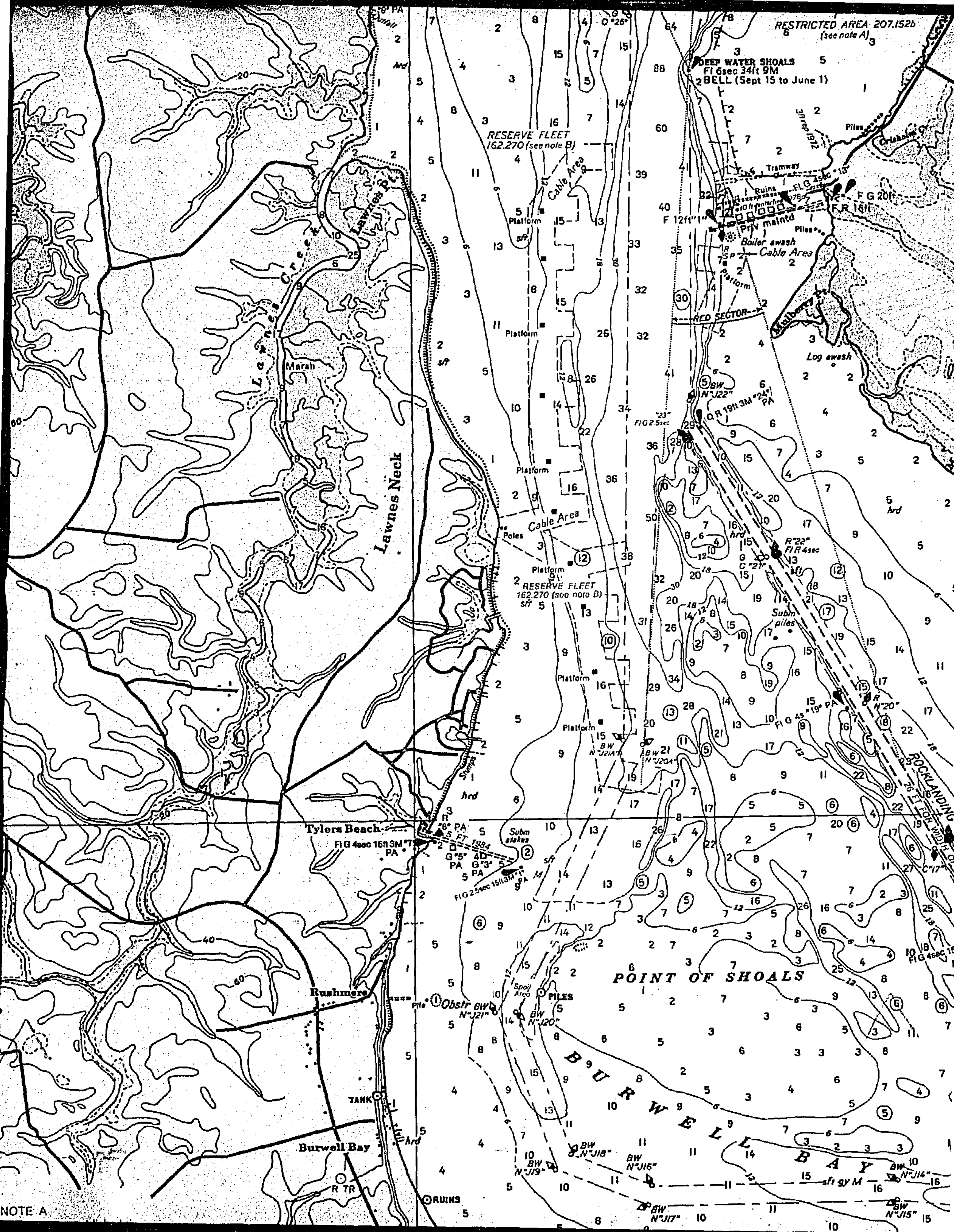


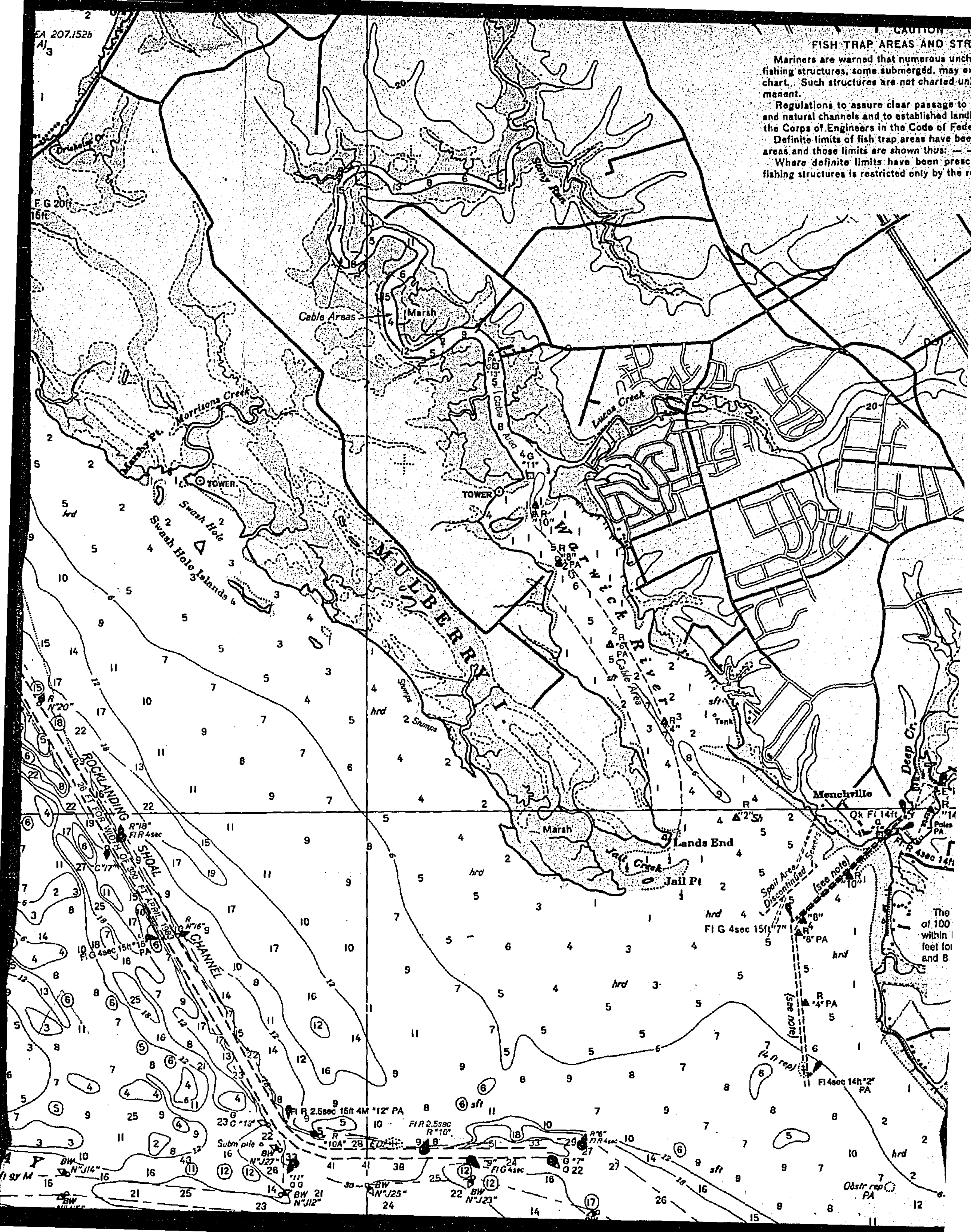
COLLEGE CREEK

Mercator Projection



NOTE B
162,270


RESTRICTED AREA 207.152b
(see note A)
DEEP WATER SHOALS
Fl 6sec 34ft 9M
BELL (Sept 15 to June 1)
RESERVE FLEET
162.270 (see note B)
Cable Area
Tramway
Ruins
Priv maintd
Boiler awash
Platform
RED SECTOR
Mulberry Pt
Log awash
Lawnes Creek
Lawnes Pt
Marsh
Lawnes Neck
Poles
Subm piles
ROCKLANDING
Tylers Beach
Subm stakes
POINT OF SHOALS
Spoil Area
PILES
Obstr
Rushmere
BURWELL BAY
TANK
Burwell Bay
R TR
RUINS
NOTE A


CAUTION
FISH TRAP AREAS AND STRU
Mariners are warned that numerous uncha
fishing structures, some submerged, may exi
chart. Such structures are not charted unle
manent.
Regulations to assure clear passage to a
and natural channels and to established landi
the Corps of Engineers in the Code of Fede
Definite limits of fish trap areas have bee
areas and those limits are shown thus:
Where definite limits have been prescr
fishing structures is restricted only by the re
Stony Run
Cable Areas
Marsh
Morrisons Creek
Lucas Creek
Menchville
Deep Cr.
TOWER
Swash Hole
Swash Hole Islands
MULBERRY I.
Warwick River
Cable Area
Stumps
2 Stumps
Tank
Lands End
Jail Creek
Jail Pt
Spoil Area, Discontinued
Sewers
(see note)
ROCKLANDING SHOAL CHANNEL
26 FT FOR WIDTH OF 300 FT APRIL 1983
Fl R 4sec
Fl G 4sec 15ft "7"
Fl G 4sec 15ft "15" PA
Qk Fl 14ft
Fl 4sec 14ft "2" PA
Fl R 2.5sec 15ft 4M "12" PA
Fl R 2.5sec R "10"
Subm pile
Obstr rep PA
(4 ft rep)
hrd
sft

UTION

S AND STRUCTURES

umerous uncharted duck blinds and erged, may exist in the area of this ot charted unless known to be per-

r passage to and through dredged tablished landings are prescribed by Code of Federal Regulations. reas have been established in some wn thus: — —— — —— — e been prescribed the location of only by the regulations.

STORM WARNINGS

The National Weather Service displays storm warnings at the following approximate location:

Fort Eustis (37°10.0'-76°36.5')

PLANE COORDINATE GRID

Virginia State Grid, south zone, is indicated by dotted ticks at 10,000 foot intervals.

CAUTION

Improved channels shown by broken lines are subject to shoaling, particularly at the edges.

CAUTION

Only marine radiobeacons have been calibrated for surface use. Limitations on the use of certain other radio signals as aids to marine navigation can be found in the U.S. Coast Guard Light Lists and Defense Mapping Agency Hydrographic/Topographic Center Publication 117 (A & B).

Radio direction-finder bearings to commercial broadcasting stations are subject to error and should be used with caution.

Station positions are shown thus:

⊙(Accurate location) o(Approximate location)

CAUTION

Temporary changes or defects in aids to navigation are not indicated on this chart. See Notice to Mariners.

SUPPLEMENTAL INFORMATION

Consult U.S. Coast Pilot 3 for important supplemental information.

NOAA VHF-FM WEATHER BROADCASTS

The National Weather Service station listed below provides continuous marine weather broadcasts. The range of reception is variable, but for most stations is usually 20 to 40 miles from the antenna site.

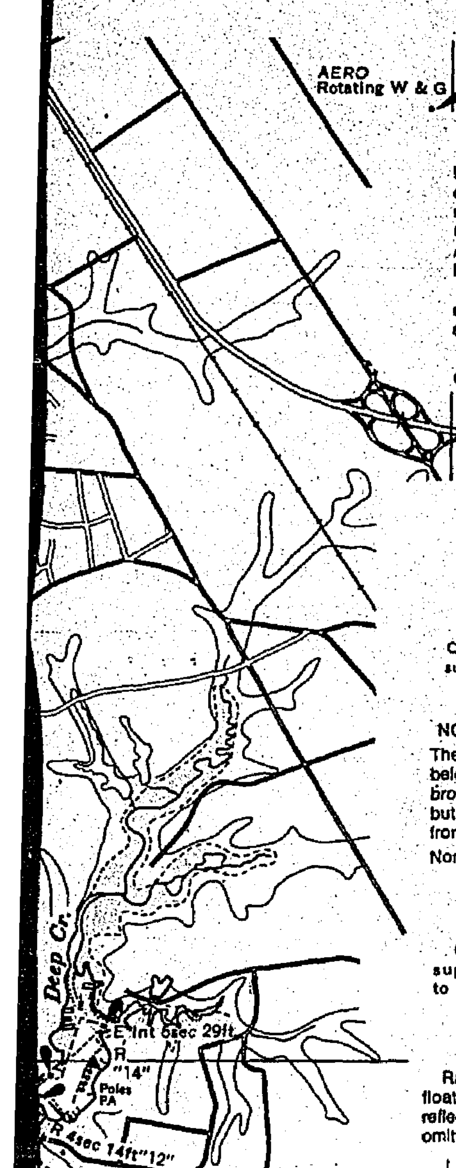
Norfolk, Va. KHB-37 162.55 MHz

AIDS TO NAVIGATION

Consult U.S. Coast Guard Light List for supplemental information concerning aids to navigation.

RADAR REFLECTORS

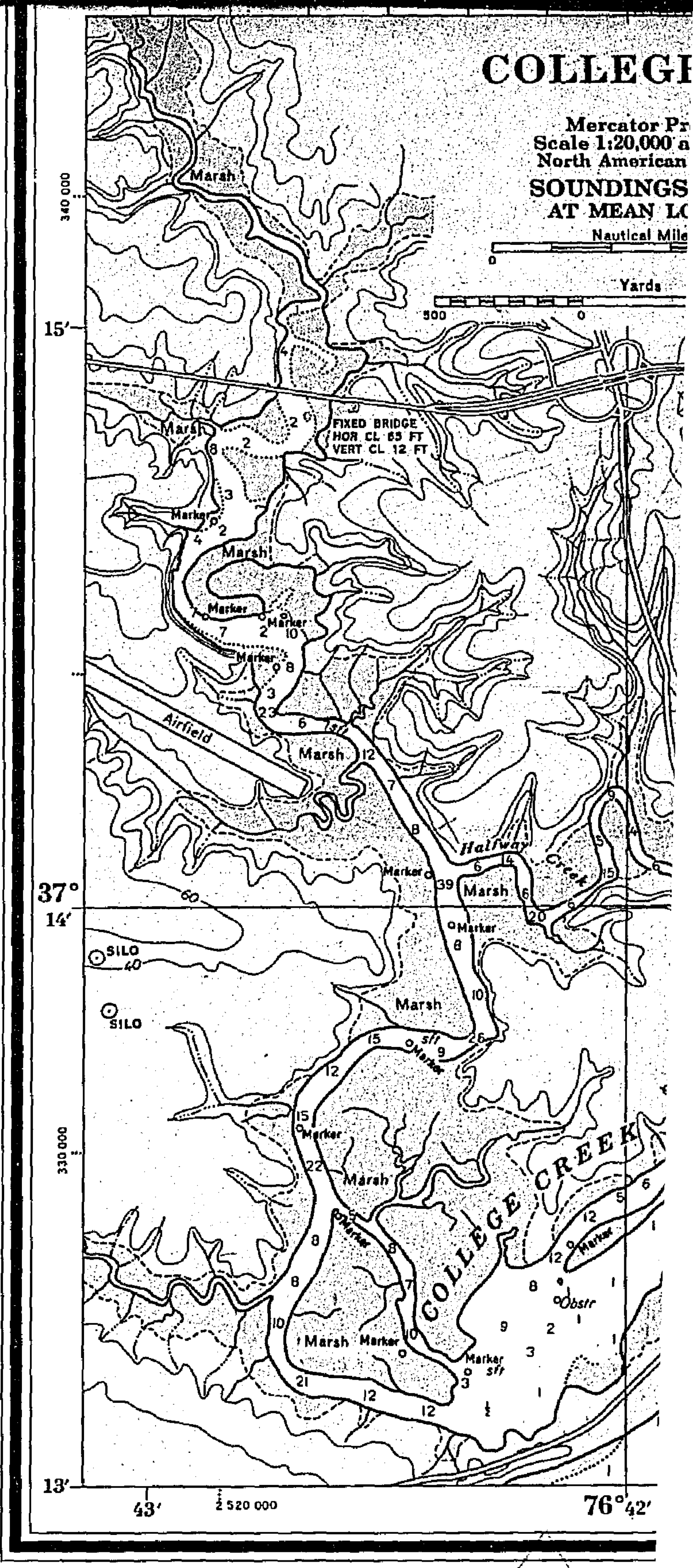
Radar reflectors have been placed on many floating aids to navigation. Individual radar reflector identification on these aids has been omitted from this chart.



DEEP CREEK

The controlling depth was 8 feet for a width of 100 feet from the channel entrance to a point within 800 feet of the turning basin; thence 8 feet for a width of 60 feet to the turning basin; and 8 feet in the basin.

NOV 1979-JAN 1980



...RM WARNINGS
...er Service displays storm warnings
...ximate location:
...s (37°10.0'-76°36.5')

...PLANE COORDINATE GRID
... State Grid, south zone, is indicated
...d ticks at 10,000 foot intervals.

CAUTION

...channels shown by broken lines are
...oaling, particularly at the edges.

CAUTION

...ne radiobeacons have been cali-
...rface use. Limitations on the use of
... radio signals as aids to marine
...an be found in the U.S. Coast
...t Lists and Defense Mapping
...drographic/Topographic Center
...17 (A & B).
...ction-finder bearings to commer-
...sting stations are subject to error
...e used with caution.
...sitions are shown thus:
...location) o(Approximate location)

CAUTION

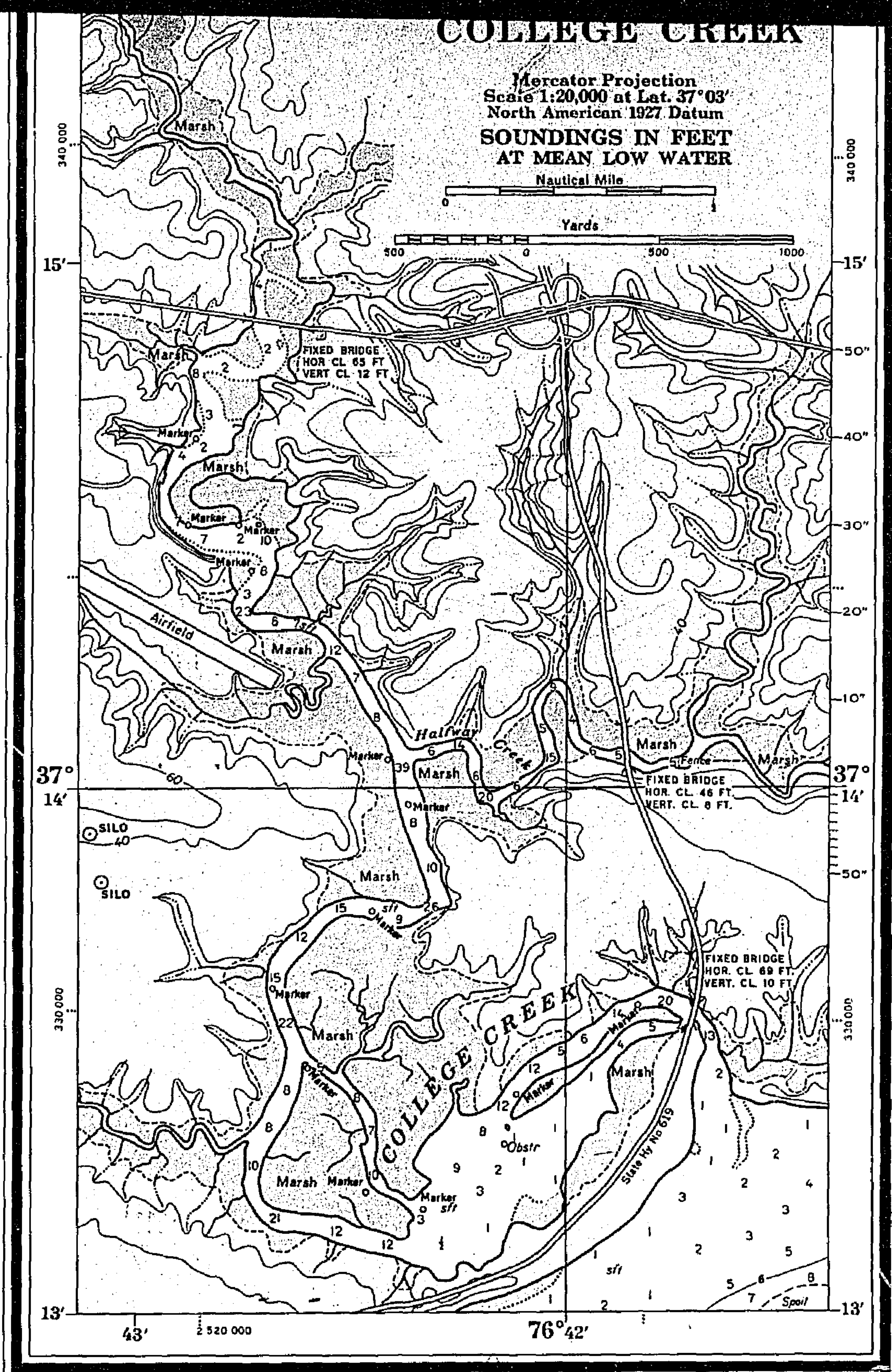
...y changes or defects in aids to
...re not indicated on this chart.
...o Mariners.

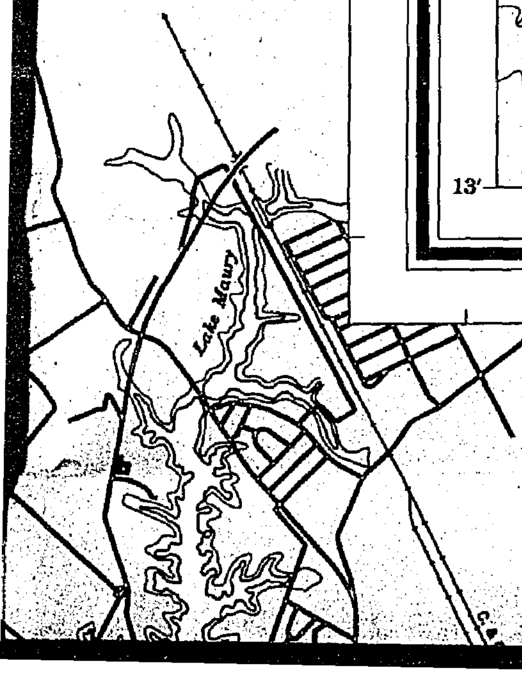
...MENTAL INFORMATION
... Coast Pilot 3 for important
...nformation.

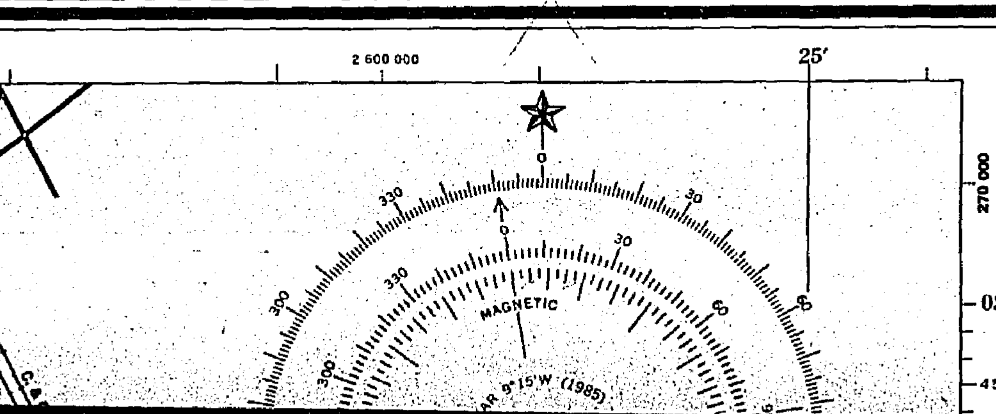
...M WEATHER BROADCASTS
...Weather Service station listed
...s continuous marine weather
...e range of reception is variable,
...ations is usually 20 to 40 miles
...na site.
... KHB-37 162.55 MHz

...S TO NAVIGATION
...S. Coast Guard Light List for
...l information concerning aids

...DAR REFLECTORS
...tors have been placed on many
...o navigation. Individual radar
...ication on these aids has been
...is chart.







NOTE B
162.270

Maritime Administration James River Reserve Fleet

No vessels or other watercraft, except those owned or controlled by the U.S. Government, shall cruise or anchor between Reserve Fleet units; within 500 feet of the end vessels in each unit, or within 500 feet of the extreme units of the fleet, unless specific permission to do so has first been granted in each case by the enforcing agency.

ANCHORAGE AREAS

110.168 (see note A)

Limits and designation of anchorage areas are shown in color.

(F) EXPLOSIVE ANCHORAGE

ALL OTHER ANCHORAGES ARE FOR GENERAL USE

NOTE A

Navigation regulations are publis Chapter 2, U.S. Coast Pilot 3, or Notice to Mariners which include new vised regulations. Information con the regulations may be obtained at the of the District Engineer, Corps of Eng in Baltimore, Md.

Anchorage regulations may be obta the Office of the Commander, 5th Guard District in Portsmount, Va.

Refer to section numbers shown wi designation.

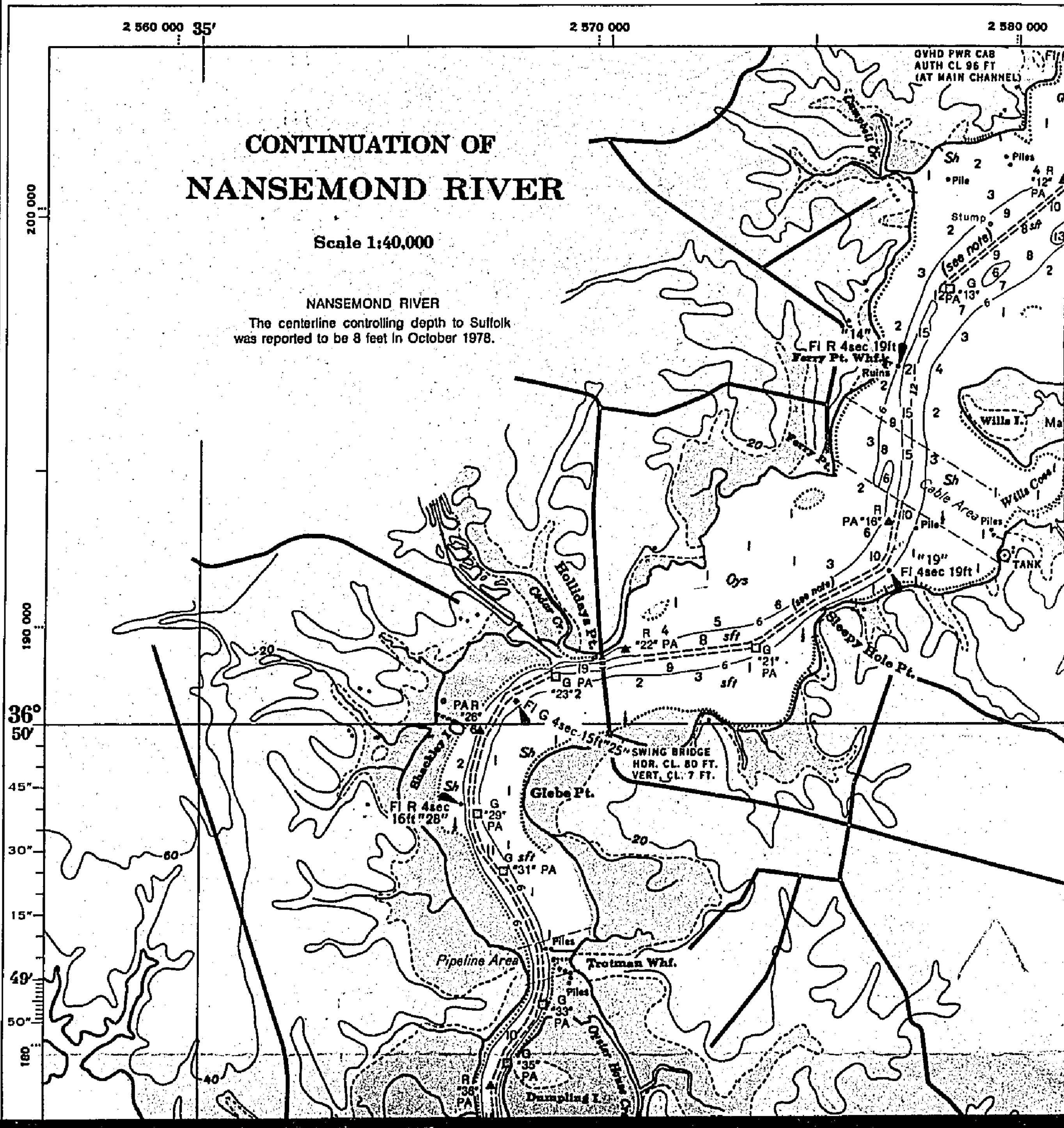
2 510 000 45′ 2 520 000 250 000

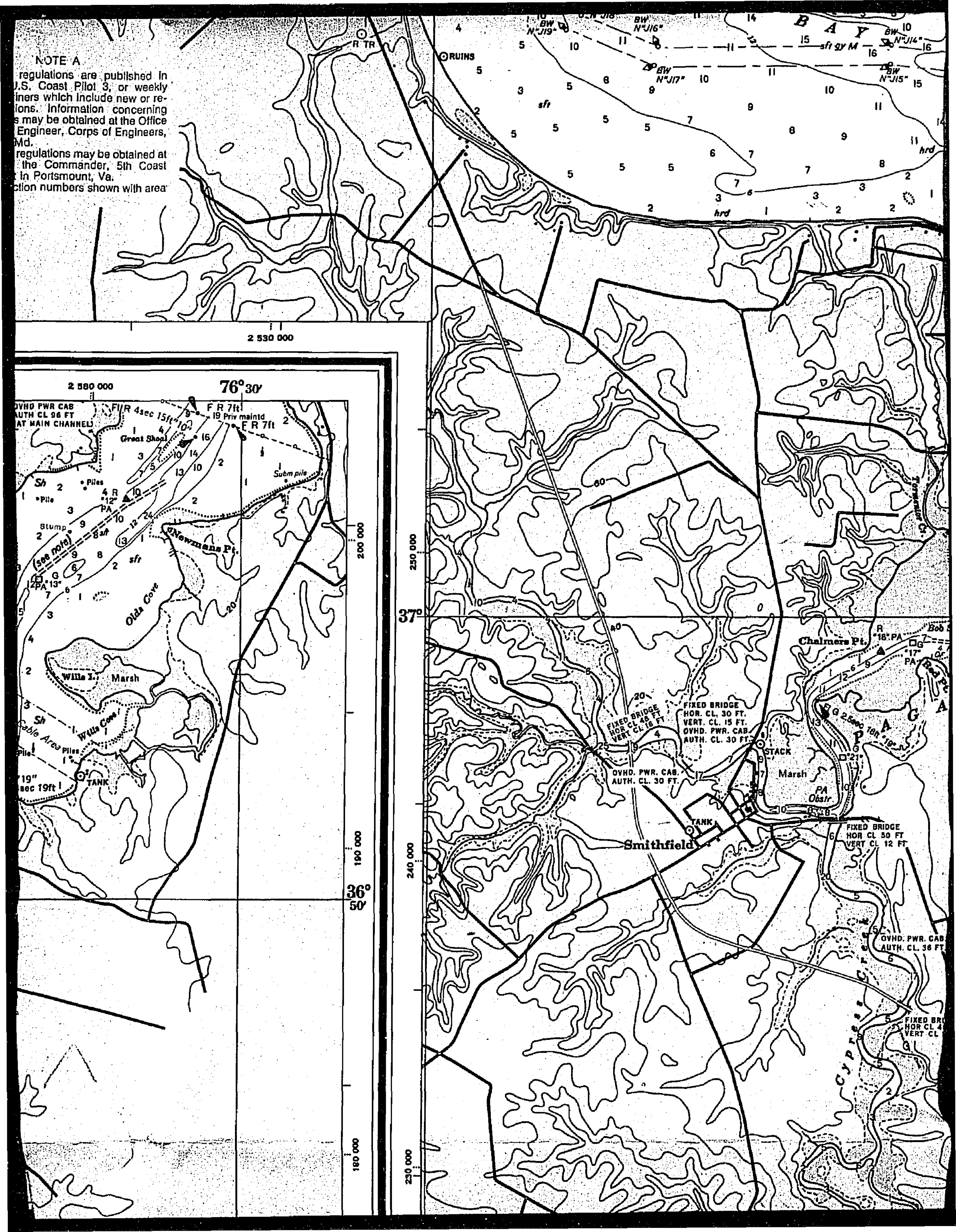
CONTINUATION OF NANSEMOND RIVER

Scale 1:40,000

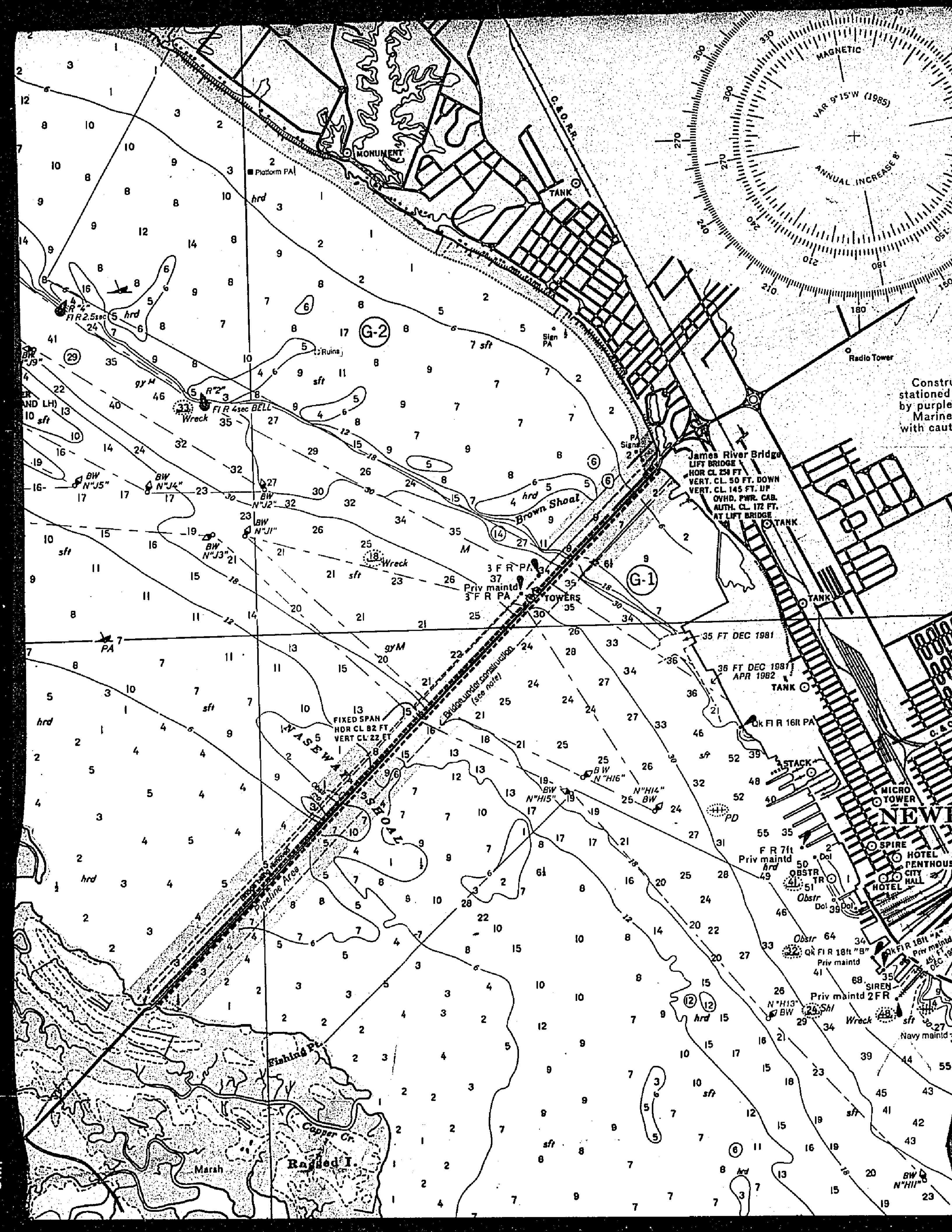
NANSEMOND RIVER

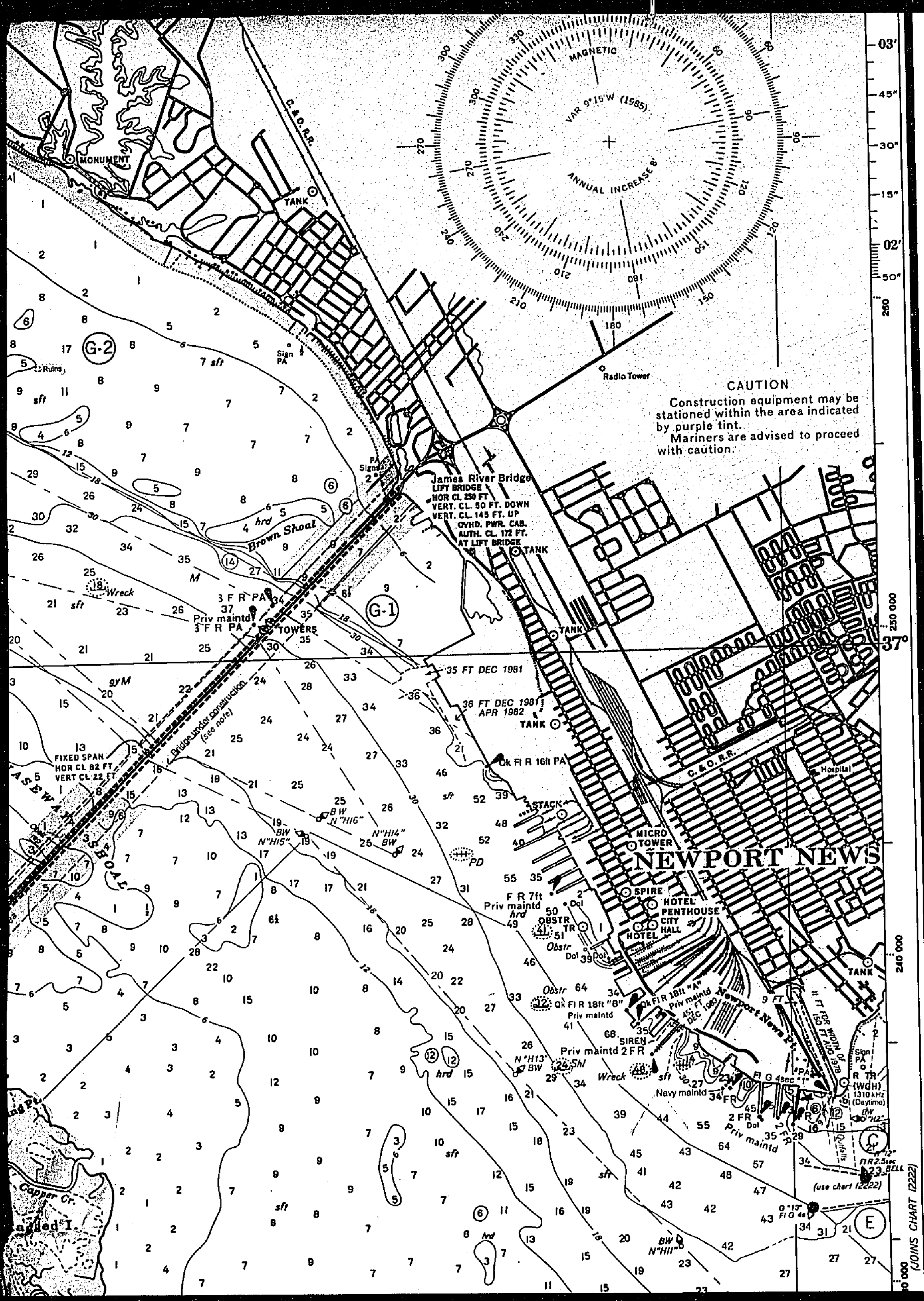
The centerline controlling depth to Suffolk was reported to be 8 feet in October 1978.



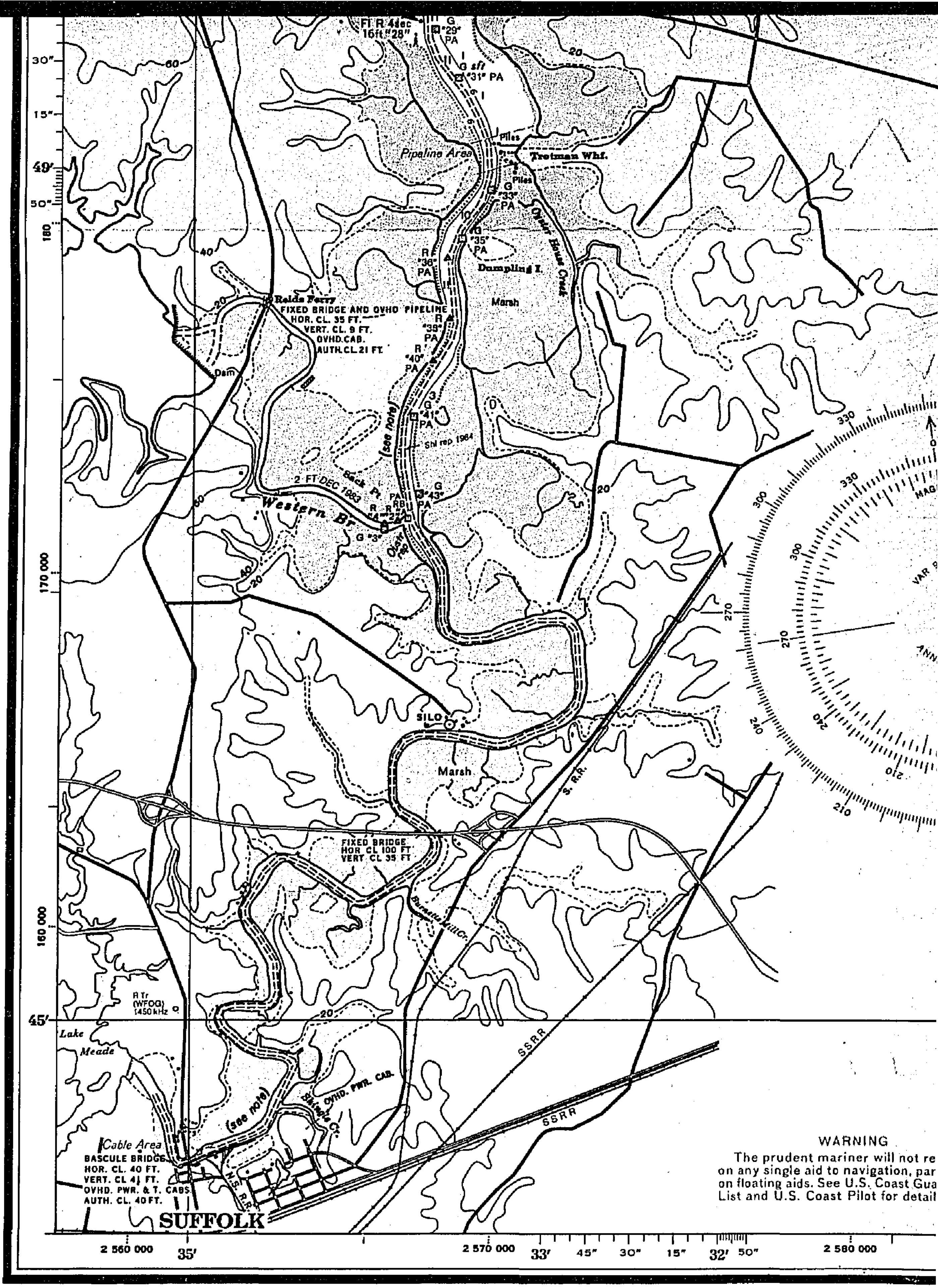

NOTE A
regulations are published in
U.S. Coast Pilot 3, or weekly
iners which include new or re-
ions. Information concerning
s may be obtained at the Office
Engineer, Corps of Engineers,
Md.
regulations may be obtained at
the Commander, 5th Coast
in Portsmount, Va.
ction numbers shown with area
RUINS
B A Y
2 530 000
2 580 000
76°30′
OVHD PWR CAB
AUTH CL 96 FT
(AT MAIN CHANNEL)
Great Shoal
Subm pile
Newmans Pt.
Olds Cove
Wills I.
Marsh
Wills Cove
TANK
36°50′
37°
Chalmers Pt.
FIXED BRIDGE
HOR CL 48 FT
VERT CL 18 FT
FIXED BRIDGE
HOR. CL. 30 FT.
VERT. CL. 15 FT.
OVHD. PWR. CAB.
AUTH. CL. 30 FT.
OVHD. PWR. CAB.
AUTH. CL. 30 FT.
STACK
Marsh
PA Obstr
TANK
Smithfield
FIXED BRIDGE
HOR CL 50 FT
VERT CL 12 FT
OVHD. PWR. CAB
AUTH. CL. 36 FT
Cypress Cr.
200 000
190 000
180 000
250 000
240 000
230 000


Days Pt.
Rainbow Farm Pt
WHITE SHOAL
TOWER (ABAND LH)
Oyster Rock
Bob Shoal
Battery Park
Rescue
Marsh
Williams Cr.
Beatty Cr.
Moon Cr.
Jones Cr.
Titus Cr.
Red Pt.
R I V E R
6 FT FOR WIDTH OF 80 FT OCT 1955-MAR 1969
4 FT FOR WIDTH OF 60 FT JUNE 1971
FIXED BRIDGE HOR CL 30 FT VERT CL 8 FT REP
OVHD PWR CAB AUTH CL 32 FT
FIXED BRIDGE HOR. CL. 40 FT. VERT. CL. 7 FT.
FIXED BRIDGE HOR CL 50 FT VERT. CL 12 FT
OVHD. PWR. CAB. AUTH. CL. 36 FT.
FIXED BRIDGE HOR CL 46 FT VERT CL 16 FT
Obstr rep PA
I Qk Fl 15ft PA
Fl R 4sec 14ft "8"
Fl G 2.5sec 15ft
Fl R 2.5sec 14ft "12"
Fl G 4sec "13"
Fl R 6sec 14ft "16"
R TR


MONUMENT
Platform PA
C.&O.R.R.
TANK
MAGNETIC
VAR 9°15'W (1985)
ANNUAL INCREASE 8'
Radio Tower
Constru
stationed
by purple
Marine
with caut
Sign PA
Ruins
G-2
G-1
R "4" Fl R 2.5sec
R "2" Fl R 4sec BELL
Wreck
BW "J9"
BW N"J5"
BW N"J4"
BW N"J2"
BW N"J1"
BW N"J3"
Brown Shoal
James River Bridge
LIFT BRIDGE
HOR CL 250 FT
VERT. CL. 50 FT. DOWN
VERT. CL. 145 FT. UP
OVHD. PWR. CAB.
AUTH. CL. 172 FT.
AT LIFT BRIDGE
3 F R PA
Priv maintd
3 F R PA
TOWERS
35 FT DEC 1981
36 FT DEC 1981
APR 1982
TANK
Qk Fl R 16ft PA
FIXED SPAN
HOR CL 82 FT
VERT CL 22 FT
Bridge under construction (see note)
NASEWAYS SHOAL
Pipeline Area
BW N"H16"
BW N"H15"
N"H14" BW
STACK
MICRO TOWER
NEWP
SPIRE
HOTEL
PENTHOUSE
CITY HALL
HOTEL
F R 7ft Priv maintd
OBSTR
Obstr
Dol
Qk Fl R 18ft "B" Priv maintd
Qk Fl R 18ft "A" Priv maintd
SIREN
Priv maintd 2 F R
N"H13" BW
Shl
Wreck
Navy maintd
BW N"H11"
PD
Fishing Pt.
Copper Cr.
Ragged I.
Marsh
hrd
sft
gy M



MAGNETIC
VAR 9°15'W (1985)
ANNUAL INCREASE 8'
C. & O. R.R.
MONUMENT
TANK
Radio Tower
CAUTION
Construction equipment may be stationed within the area indicated by purple tint.
Mariners are advised to proceed with caution.
James River Bridge
LIFT BRIDGE
HOR CL 250 FT
VERT. CL. 50 FT. DOWN
VERT. CL. 145 FT. UP
OVHD. PWR. CAB.
AUTH. CL. 172 FT.
AT LIFT BRIDGE
Brown Shoal
Wreck
TOWERS
Priv maintd
35 FT DEC 1981
36 FT DEC 1981
APR 1982
FIXED SPAN
HOR CL 82 FT
VERT CL 22 FT
Bridge under construction (see note)
Qk Fl R 16ft PA
STACK
MICRO TOWER
NEWPORT NEWS
SPIRE
HOTEL PENTHOUSE
CITY HALL
HOTEL
Hospital
OBSTR
Obstr
Qk Fl R 18ft "B"
Qk Fl R 18ft "A"
Newport News Pt.
SIREN
Navy maintd
Fl G 4sec "1"
R TR (WDH) 1310 kHz (Daytime)
Fl R 2.5sec
BELL
(use chart 12222)
Copper Cr.
Ragged I.
Outfalls
250 000
240 000
37°
03'
02'
(JOINS CHART 12222)



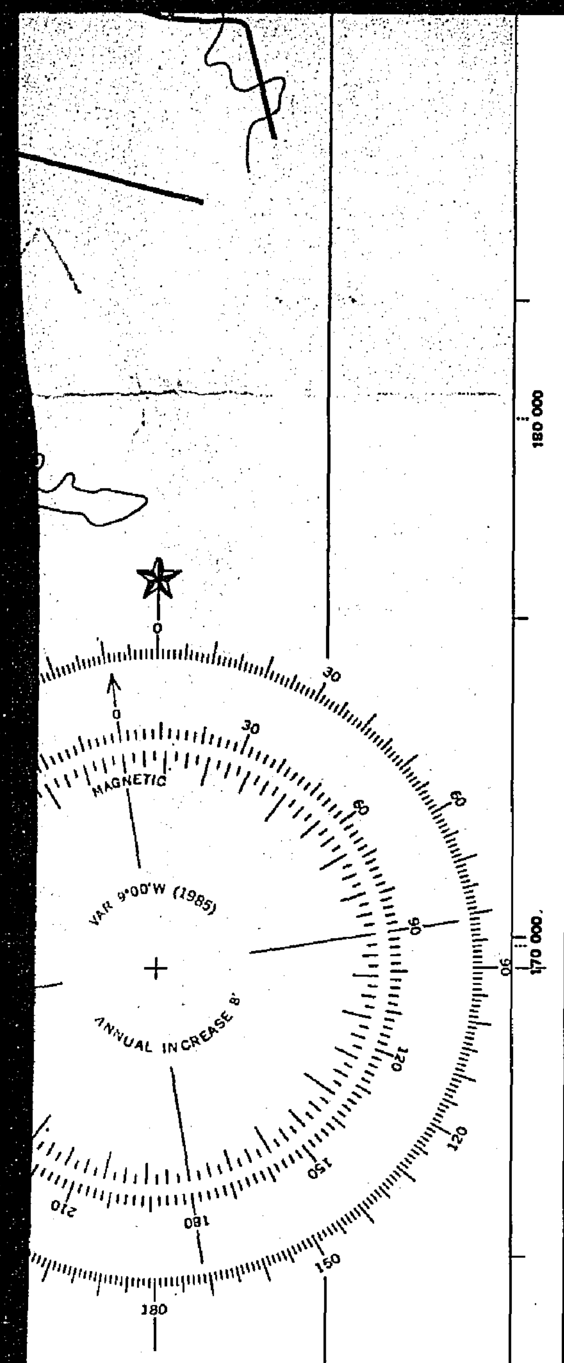
28th Ed.,June 29/85 ■

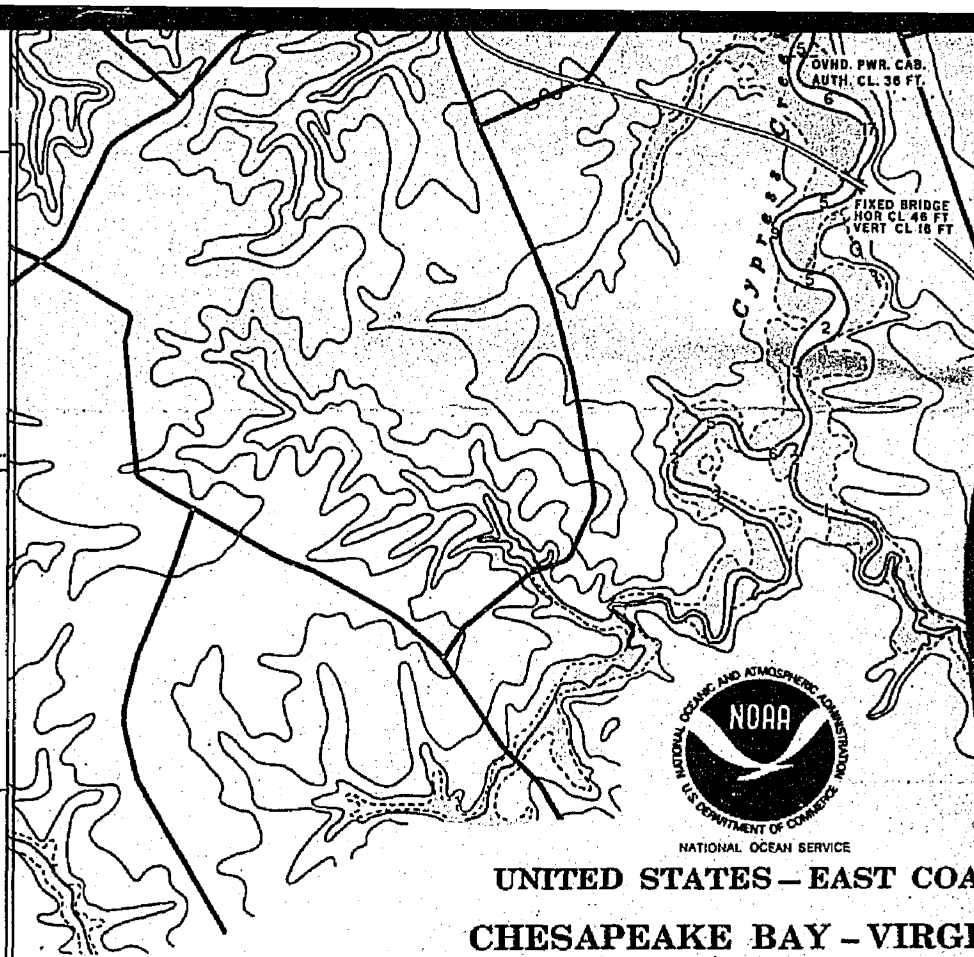
12248

CAUTION

This chart has been corrected from the Notice to Mariners published weekly by the Defense Mapping Agency Hydrographic/Topographic Center and the Local Notice to Mariners issued periodically by each U.S. Coast Guard district to the print date shown in the lower left hand corner.

SOUNI





UNITED STATES – EAST COA

CHESAPEAKE BAY – VIRGI

JAMES RIVER

NEWPORT NEWS TO JAMEST(

Mercator Projection
Scale 1:40,000 at Lat. 37°03′
North American 1927 Datum

SOUNDINGS IN FEET
AT MEAN LOW WATER

220 000

36° 55′

210 000

TIDAL INFORMATION

Place	Height referred to datum of soundings (MLW)		
	Mean High Water	Mean Tide Level	Mean Low Water
	feet	feet	feet
Newport News	2.6	1.3	0.0
Suffolk	3.8	1.9	0.0
Menchville	2.6	1.3	0.0
Burwell Bay	2.4	1.2	0.0
Hog Point	2.1	1.0	0.0

(1184)

ABBREVIATIONS (

H

Hydrography
Charting and Ge
Engineers, Geol

-45′

ING
er will not rely solely
vigation, particularly
S. Coast Guard Light
ilot for details.

Nautical Miles

1 0

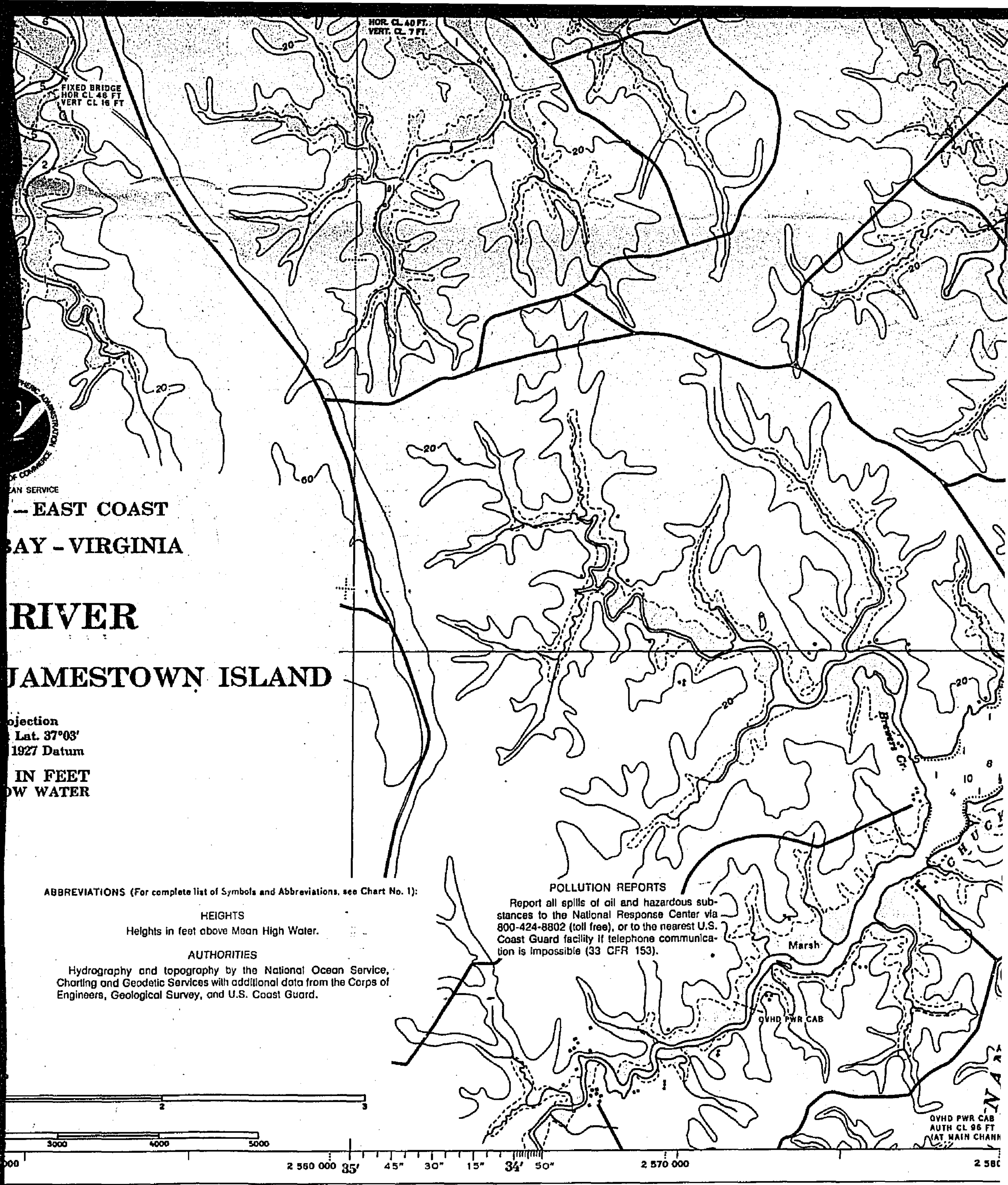
Yards

1000 0 1000 2000 3000

000 76° 30′ 40′ 2 540 000 2 550 000

OUNDINGS IN FEET

U.S. D
NATIONAL OCEA



ABBREVIATIONS (For complete list of Symbols and Abbreviations, see Chart No. 1):

HEIGHTS

Heights in feet above Mean High Water.

AUTHORITIES

Hydrography and topography by the National Ocean Service, Charting and Geodetic Services with additional data from the Corps of Engineers, Geological Survey, and U.S. Coast Guard.

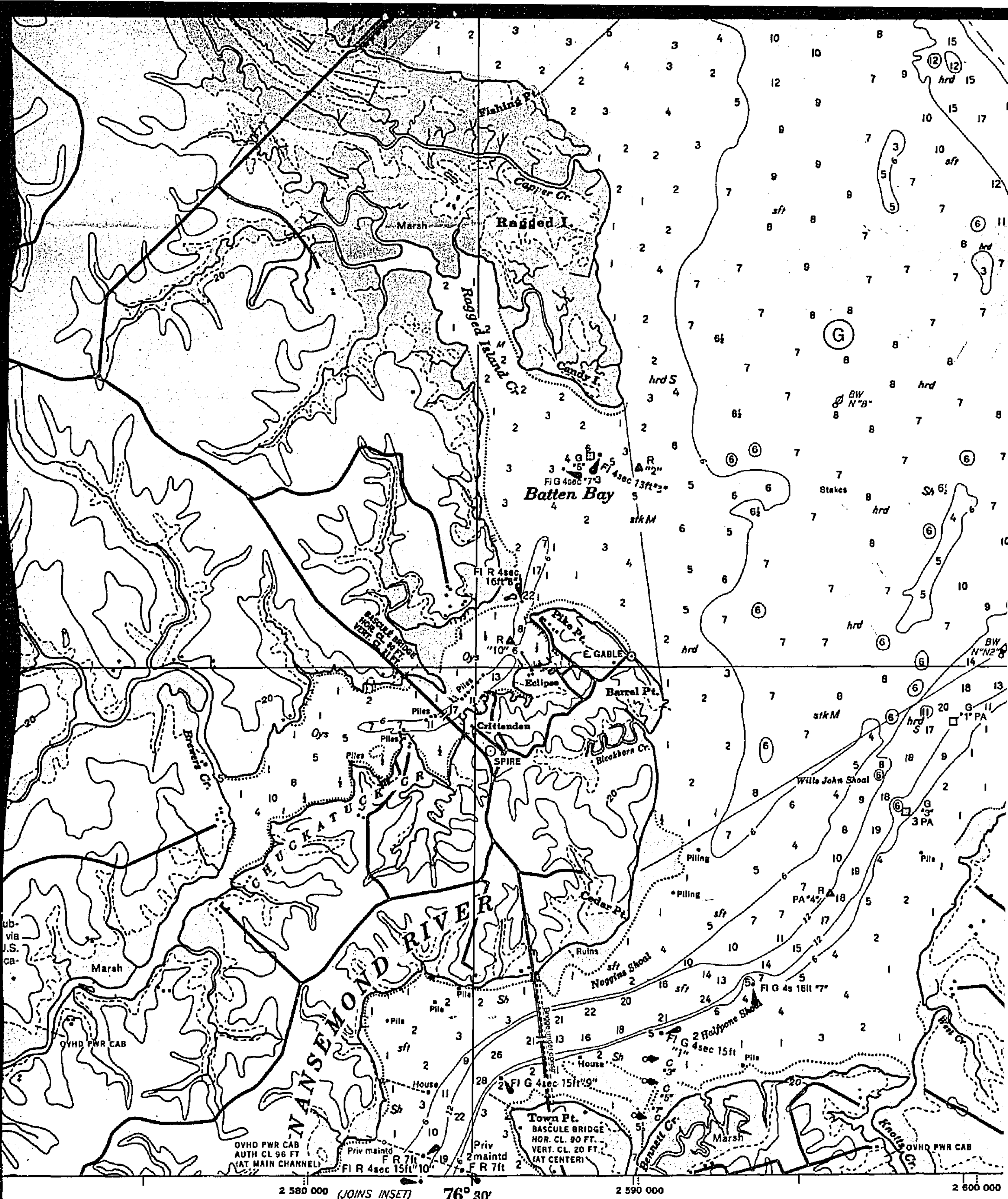
POLLUTION REPORTS

Report all spills of oil and hazardous substances to the National Response Center via 800-424-8802 (toll free), or to the nearest U.S. Coast Guard facility if telephone communication is impossible (33 CFR 153).

Published at Washington, D.C.
U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL OCEAN SERVICE

FATHOMS	1	2	3	4	5	6	7	8	9
FEET	6	12	18	24	30	36	42	48	54

METERS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1

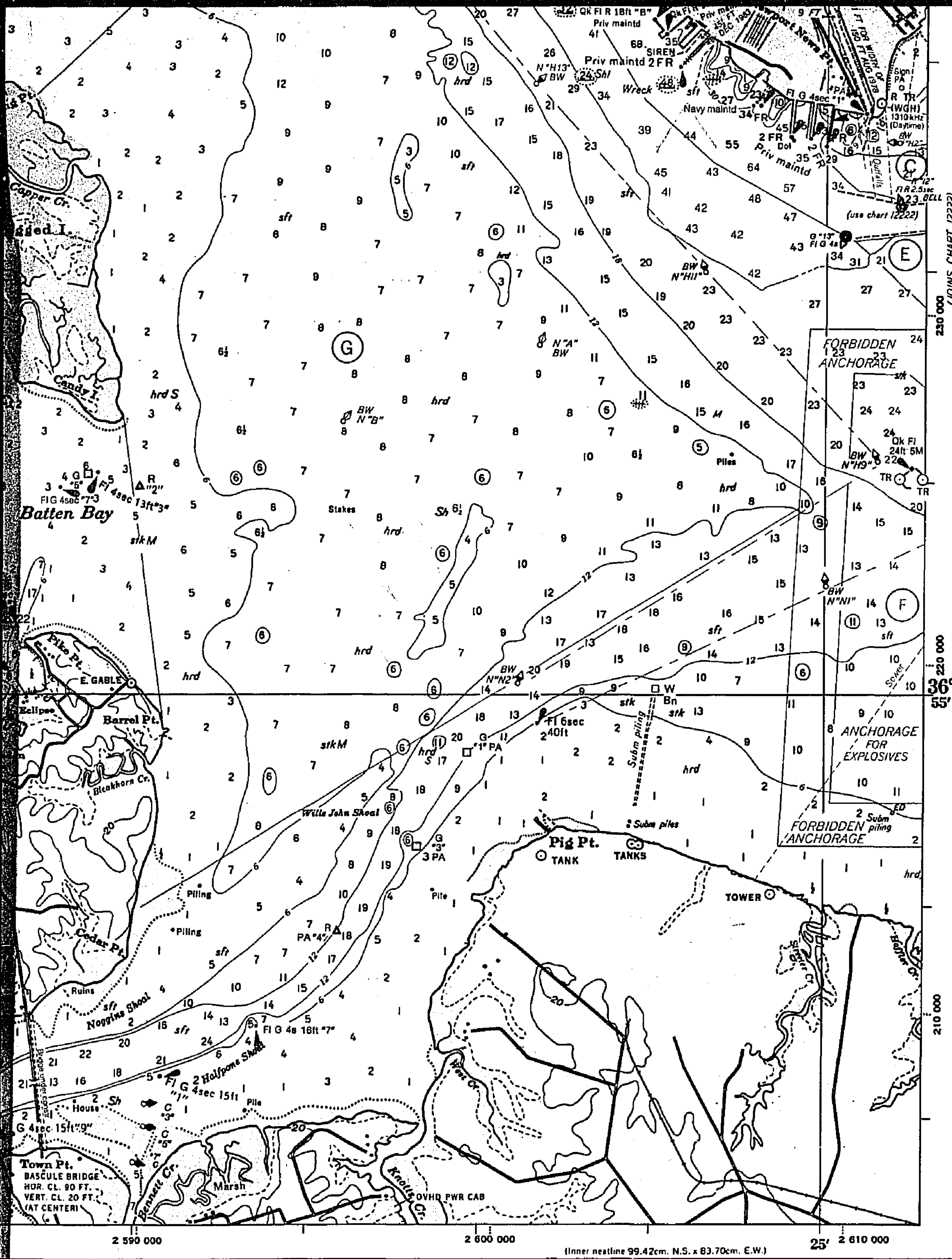


FATHOMS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
FEET	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102

METERS 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

(James River, Newport News to Jan

SOUNDINGS IN FEET - SCALE 1:40,000



DMA STOCK NO. 12AHA12248

(James River, Newport News to Jamestown Island) **12248**

SOUNDINGS IN FEET - SCALE 1:40,000