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The Recent History of Wachapreague Inlet, Virginia

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THE RECENT HISTORY OF
WACHAPREAGUE INLET, VIRGINIA

A Thesis
Presented to
Virginia Institute of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
of the Requirements for a Degree of
Master of Arts in Marine Science

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by

Joseph Thomas DeAlteris

1973

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirement for the degree of
Master of Arts in Marine Science

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ABSTRACT

The purpose of this study was to trace the recent morphometric history of the Wachapreague Inlet Complex and to determine what geological and sedimentological controls, if any, have influenced its stability and evolution.

The configuration of Wachapreague Inlet has been traced since 1852 to the present from bathymetric surveys and aerial photographs. During the last 120 years this offset tidal inlet has migrated to the south at a rate of 1 meter per year. A cyclic growth and decay of the lateral ramp margin shoals has been documented over the last 24 years. These variations were not likely due to variations in littoral drift along the adjacent islands. A study of the net long-term sand volume changes on the ebb tidal delta has shown no significant long-term change in the storage of sand.

The mobile sediment distribution of the inlet was investigated with respect to spatial variations over the entire inlet complex and temporal variations in the deep inlet throat. The sediment distribution correlated well with the various depositional environments ranging from gravels in the deep inlet throat to silty sands on the flood tidal delta. Changes in the inlet throat sediment distribution were monitored over a 3-month period. Short-term fluctuations in the inlet cross-sectional area were correlated with overall changes in the bottom sediment characteristics in the inlet throat.

Investigation into the geology of the inlet orifice has shown the north flank to be a sandy spit extending south from the barrier island, while the south flank is a firm, cohesive lagoonal mud. Thus, as Wachapreague Inlet migrates south in response to a predominately southerly littoral drift, it leaves in its path a wedge of sand (the only sand sink in the system) and cuts into firm marine lagoonal deposits.

Crustal uplift on the order of 92 m (310') in the area of Wachapreague Inlet, Virginia, is proposed to account for radiocarbon dates of 18,750 and 19,600 years B.P. on lagoonal shell material in mint condition recovered from 15.0 m (46') and 20 m (62') below present MTL. According to accepted eustatic sea level curves, these shells should have been 110 m below present MTL 19,000 years ago.

INTRODUCTION AND BACKGROUND DISCUSSION

Introduction

Wachapreague Inlet, a natural tidal inlet located on the Eastern Shore of Virginia, is typical of several inlets with a similar bathymetric structure along a 60 km expanse of the southeastern Delmarva Peninsula coast (Fig. 1). Wachapreague Inlet is an "offset coastal inlet" similar to those described by Hayes, et al. (1971); it is offset to the downdrift side. The "Wachapreague Inlet Complex" is composed of the inlet channel, Parramore Island to the south, Cedar Island to the north, a crescentric ebb tidal delta to the east and finally a system of lagoons, and tidal channels to the west. The geometry of the inlet channel cross-section is unusual, in that the south flank has a maximum measured slope of 45° and has an average slope of 30° (Fig. 2). In contrast, the northern flank has a gradually sloping wall with an average inclination of 3.5°. These unusual characteristics motivated the study to trace the recent morphometric history of the inlet and to determine what geological and sedimentological controls have influenced its stability and evolution.

The work was divided into three distinct phases: 1) an investigation into the history of the inlet complex using available charts and photography as a data source,

2) a survey of the present configuration including bathymetry and mobile sediment distribution, and 3) an investigation into the geology of the area surrounding the inlet.

Regional Setting

Wachapreague Inlet, located on the Virginia coastline of the Delmarva Peninsula, is part of the Atlantic Coastal Plain lying between Delaware and Chesapeake bays. The tidal range varies from 1.0 to 1.5 m and the gradual slope of the continental shelf reduces wave action to moderately low levels.

Four geomorphically distinct zones can be recognized along the Atlantic coast of this peninsula. From Cape Henlopen in Delaware Bay to Ocean City, Maryland, a barrier beach impinges on the mainland. Bay mouth bars separate estuaries or bays associated with drowned fluvial systems from the Atlantic Ocean.

From Ocean City to Chincoteague Inlet a continuous barrier spit, Assateague Island, is separated from the Pleistocene mainland by a 10 to 13 km wide lagoon, Chincoteague Bay. Fishing Point, on the southern end of Assateague, is a pronounced recurved spit of relatively recent origin pointed toward Chincoteague Inlet and Island. From Chincoteague to Wachapreague inlets, the broken chain of barrier islands is markedly indented. Harrison (1971) speculated that this reentrant marks the path of a paleochannel across the Delmarva. The barrier islands along this section of coast have a shallow topographic relief, and lagoons separating the barriers from the mainland are considerably smaller.

The final sector begins at Parramore Island on the south flank of Wachapreague Inlet and continues south to Cape Charles. These barrier islands have noticeably greater relief than those immediately to the north. Between the barrier islands and the mainland lies a tidal flat complex of shallow bays, intertidal flats, marshes, and tidal channels that varies in width from 7 to 15 kilometers.

No major streams drain the eastern Delmarva Peninsula to supply sediments to the modern coast. Erosion of the headlands along the northern Delmarva provides sands for the beaches there and for the barrier spit extending to Chincoteague Inlet. In contrast, the thin, narrow beaches south of Chincoteague Inlet indicate that there is a short supply of sand there. The present beach sands are probably derived from reworked older sediments.

Regional Geology

The Holocene sediments of the eastern shore of the southern Delmarva Peninsula are restricted to the tidal flat lagoon complex and the protecting barrier islands. Harrison (1971) studied these sediments and their respective sedimentary processes. The sediment accumulating in the tidal flat complex is a silty clay. The inorganic portion of sediment is apparently derived from the erosion of the old marsh-peat on the seaward side of the complex. It enters the complex as individual grains or as agglomerates bound together with organic detritus. A significant portion of the sediment occurs as fine sand and coarse silt-sized fecal pellets which significantly alter the textural characteristics of the deposits. Newman and Munsart (1968) investigated the Holocene geology of Wachapreague lagoon, and, based on radiocarbon dates of basal peats from the base of the lagoonal sediments at depths ranging from 20 to 25 ft below M.H.W., they report the lagoon to have been in existence for at least 5,000 years B.P. Since the lagoon apparently requires barrier beaches for its development, the coastal barrier must have been in existence at least this long. Prior to about 1,000 years B.P., most of the Wachapreague lagoon consisted of open bays and tidal flats. This contention is supported in the Foraminifera contained in the lagoonal sediments. Thus, the extensive salt marsh that exists today began developing after 1,000 years B.P.

The Pleistocene geology of this Virginia section of the Delmarva has been extensively studied by Sinnott, et al. (1961). Four terraces were identified on the mainland of the Eastern Shore Peninsula. From youngest to oldest, there are the Chowan, Dismal Swamp, Princess Anne, Pre-Chowan and Wicomico, as defined by Wentworth (1930). The terraces are considered to be the emerged upper surfaces of these formations. The Columbia group of terrace formations of Pleistocene Age consist of a succession of thin, very gently sloping marine and estuarine formations that overlie the tertiary sedimentary rocks of the Virginia Coastal Plain.

As mentioned previously, Harrison (1971) alluded to the possibility of an early Pleistocene paleochannel across the Delmarva Peninsula. He found pebbles and cobbles along Metomkin beach "that could be definitely associated with formations west of Chesapeake Bay." Such gravels could only have been transported from the source rocks via a fluvial system. This system must pre-date the formation of the drowned valley, Chesapeake Bay, which now forms the western margin of the Delmarva Peninsula. Harrison (1971) goes on to suggest that the Potomac River, which crosses rock outcrops similar to those found along Metomkin beach, crossed the Delmarva and emerged at the indentation between Chincoteague Inlet and Wachapreague Inlet.

Local Geology

Several investigators have published papers based on research in the area of Wachapreague, Virginia. Most of this research is related to the marsh behind the barrier islands. The marsh, however, is important to the inlet configuration. That is, as the marsh area increases, lagoon areas decrease, consequently the tidal prism decreases. Based on M. P. O'Brien's (1969) graph describing a linear relationship between tidal prism and cross-sectional area of the estuary orifice, the smaller tidal prism will have an effect on the cross-sectional area of the inlet.

Newman and Rusnak (1965) and Newman and Munsart (1967) extensively studied the marshes behind Cedar and Parramore islands. Using a piston corer to the depth of refusal, they mapped a Holocene-Pleistocene contact surface. The results of their work have been mentioned previously.

DeVries (1970), working in the marsh behind Wachapreague Inlet, has drawn contours on a proposed Pleistocene surface at about 30 ft, and on the Miocene surface at about 75 ft in the area of Wachapreague Inlet. Both of these surfaces represent local topographic lows. The contour maps were drawn based on information gathered from 20 wash borings in both the marsh and the barrier islands.

More recently, Kremerer (1972) has investigated the stratigraphy of the marsh behind Cedar Island by means of jet washing. His study traces the transgression of Cedar Island over the marsh during the last 120 years. Callahan (1972) has measured the suspended sediment concentration in Gates Channel and Gates Bay. His research documents net suspended transport out of the marsh.

Harrison (1971) investigated the sediments and sedimentary processes of the Holocene tidal flat complex, Delmarva Peninsula, Virginia. In his dissertation, he briefly describes the bottom sediment of the entire Wachapreague Inlet Complex to be sand.

Donaldson and Morton (1972), again working in the marsh behind Wachapreague Inlet, using the jet wash technique, describe an unconformity between the Holocene and underlying Pleistocene sediments that exhibits 50 feet of topographic relief. Located in the marsh between Wachapreague, Virginia, and the barrier islands, they attribute this unconformity to a former Pleistocene stream valley.

Figure 3 summarizes the proposed geologic contact surfaces between the Holocene and Pleistocene, and between the Pleistocene and Miocene. Perhaps the most significant point in this section is the lack of agreement among the previous investigators as to where exactly these surfaces exist and their nature.

Previous Investigations in Tidal Inlets

There are no recently published papers specifically describing the inlets of the Eastern Shore of Virginia. However, there is a great deal of literature addressed to the general topics of inlets on sandy coasts. Wachapreague Inlet is on a sandy coast, and for this reason a review of some of the more significant classical papers is included.

Brown (1928) investigated inlets on the east coast of the United States. His paper stresses the strong interaction between the action of the tidal currents tending to scour the inlet and littoral drift tending to fill or choke the inlet with sand. He predicts that there must be a critical velocity at which the current must flow if the inlet is to maintain itself. A comparison of the calculated and observed values of V max. and tidal prism was made for Absecon Inlet. The agreement between these two values was excellent.

Escoffier (1940), continuing the work of Brown (1928) concerning the stability of tidal inlets, presents three graphs in his publication to describe his conclusions. Basically, he compares the mean velocity in the inlet throat to the size of the orifice. Assuming a fixed tidal prism, as the size of the orifice increases so will the mean velocity, to a point, then further increase in size (cross-sectional area) will only decrease the current velocities. However, if the maximum mean velocity on this curve does not exceed the critical scouring velocity, the inlet cannot maintain itself, and is therefore unstable and will close.

O'Brien, in a series of publications (1931, 1966, 1969), describes a unique empirical relationship between the flow area of an inlet and the tidal prism. According to O'Brien, the size of the material, the presence or absence of jetties, and the magnitude of the general littoral drift do not appear to effect the equilibrium flow area.

Bruun (1960) outlines nine separate factors which he believes may influence the cross-sectional area. These include: 1) maximum discharge, 2) the shape of the channel, 3) the bottom shear stress, 4) the bottom soil condition, 5) the suspended sediment load, 6) wave action, 7) littoral drift, 8) river discharge, and 9) the time history of the inlet. However, according to Bruun, for inlets on sandy coasts generally most of these factors can be related to the bottom shear stress.

Traditionally, most investigators when considering inlets on sandy coasts, generally assume the tidal inlet channel to incise a bed of material of sand size. It is then assumed to be free to migrate in response to littoral drift, and to scour and fill as the flushing capability of the tidal flow varies. No consideration has been paid to the fact that many inlets on sandy coasts incise barrier island chains, and that many of these transgressive barrier islands are nothing more than thin veneers of sand overlying marsh peats and lagoonal sediments. One might suspect then that the tidal inlet channels in these instances would incise not only sand but cohesive muds, and that these muds might exert some noticeable constraints on the tidal inlet system.

METHODOLOGY, RESULTS AND CONCLUSIONS

Historical Changes in the Inlet Complex Configuration

United States Coast and Geodetic Survey Hydrographic Survey Sheets for 1852, 1871, 1911, and 1934 were compiled and contoured at 0.913 m (3 ft) intervals (Fig. 4, 5, 6, and 7, respectively). It is worthwhile to note that the 1871 and 1934 surveys followed severe storms, and that this may explain the abbreviated south end of Cedar Island apparent in the 1934 survey. A bathymetric survey of the entire Wachapreague Inlet system was made by the author in 1972 (Fig. 8). A Raytheon Recording Fathometer (DE 719) was used to determine depths. Positions were determined by a tracking radar following a transponder placed in the survey boat. Comparison of the charts showed that the axis of the inlet channel has migrated to the south at a rate of 1 meter per year during the last 120 years (Fig. 9). In addition the channel has rotated slightly counter-clockwise from a southeastern axial orientation to a more easterly orientation (Fig. 10). In its migration the channel flow has eroded the northern flank of Parramore Island while leaving a wedge of sand as the southern tip of Cedar Island. The northeastern face of Parramore Island has accreted seaward while the southern end of Cedar Island has migrated landward, thus accentuating the offset.

The long term cross-sectional area of the inlet throat has been relatively stable since 1871 at about 4,200 m (less than 15% variation from mean); however, between 1852 and 1871, the cross-sectional area increased from 1,845 m to 4,473 m (Table 1). Historical evidence (Byrne, personal communication, 1973) indicates that the interior marsh-lagoon system configuration has changed very little since 1852, thus the potential tidal prism appears to have remained unchanged. Flow gaging at the inlet throat indicates the present channel cross-sectional area and spring tidal prism follow the linear relationship noted by O'Brien (1969). At present the ocean and lagoonal tidal ranges are the same. There is insufficient tide information for the 1850 period to determine if the reduced cross-section admitted a smaller tidal prism.

The length of the inlet throat channel (based on the 12 m contour) has increased from 1,600 m in 1852 to about 3,000 m in 1972 (Table 2), significantly increasing the frictional characteristics of the inlet. Various hydraulic radii of the inlet throat cross-sections were calculated based on 1) an unmodified cross-section, 2) a modified cross-section (long shallow tails removed), and 3) a modified and normalized cross-sectional area (expanded to uniform area, yet maintaining geometric similarity in order to allow a valid comparison of hydraulic radii). The results are tabulated in Table 3 and the trend is similar for all three techniques, an increasing hydraulic radius until the turn of the century, then decreasing to the present. Thus, with a steadily increasing channel length, and a decreasing hydraulic radius, Wachapreague Inlet appears to be evolving toward a less efficient channel.

To investigate the possibility that the entire inlet complex is serving as either a source or sink of sand to the littoral drift moving down the barrier island coast, the volume of sand, to a base 21 m below MLW, was calculated for each of the survey charts from 1852 to 1972 (no data for 1871) similar to a study done by Perfit (1970). This was accomplished by dividing each of the contoured charts for 1852, 1911, 1934, and 1972 (Fig. 4, 6, 7, and 8, respectively) into a matrix of smaller areas denoted by 1A, 2A, 1B, 2B, etc. The volume of material in each of these smaller areas was determined by measuring the area between individual contours with a Compensating Polar Planimeter, and multiplying this by the difference between the mean depth of the two contours and 21 meters, the base depth. Then each of these volumes were summed to the total volume of smaller areas (1A, 1B, etc.), and these were summed to the total volume of material in the system at that time.

The net change in total material gained or lost during 120 years was a loss of 7 x $10^6 m^3$, less than 3% of total volume of material present. In addition, there was a negligible change in the sand volume stored on the ebb tidal delta. This is summarized in Table 4. As noted earlier, the inlet channel has migrated to the south during the last 120 years; consequently, the north flank of Parramore Island has lost material while the south tip of Cedar Island has gained sand in the form of a deep sand spit extending from the barrier island. The increase in volume of this sand wedge extension from 1852 to 1972 is $4.5 \times 10^6 m^3$. Thus the migration of the inlet channel has served to develop a localized sand sink, while the system as a whole has experienced a small overall net loss of material.

Short term changes in the geometry of the barrier islands flanking the inlet and of the lateral ramp margin shoals were studied during the period from 1949 to 1973 by using aerial photography. The areas of the variable portions of the barrier islands, and the shoals were measured on maps drawn from the aerial photographs. No corrections were made for tide stage or distortions in the photographs. To test the error of not correcting for photograph distortions, an area measured from a 1971 uncorrected map was compared with the measured area from a distortion (by means of a Kelsh Plotter) corrected map (Penney, personal communication, 1973). There was less than 5% error. Based on the U.S. Army Corps of Engineers thumb-rule that "one square foot of beach is equivalent to one cubic yard of sand" (U.S. Army Corps of Engineers, 1966), the areas of beach or shoal were converted to volumes of sand lost or accreted.

In order to estimate the errors due to not correcting for tide stage, a measurement of the shoreline encompassing each of the planimetered areas was made. Assuming a 10° beach slope, and a 3 ft (.91 m) tidal range, the area of beach covered or exposed by the tide was calculated. These areas were converted to volumes, and these volumes were all less than 5% of the total calculated volumes.

In 1949 (Fig. 11), the Wachapreague Inlet system consisted of a main channel and an apparently well developed north channel. Note the large accretional sand wedge on the northeast face of Parramore Island, and that the lateral ramp margin shoals were well developed. A 1957 photograph (Fig. 12) shows the inlet complex at a critical time in its life history; note the break-through inlet on Cedar Island. Tidal prism lost through this small break-through inlet represents a decreased capability of Wachapreague Inlet to flush itself of sand. More significantly, note the wedges of sand on the northeast face of Parramore Island, and on the south tip of Cedar Island. These accretional features represent $3.3 \times 10^6 m^3$ and $2.4 \times 10^6 m^3$ of sand, respectively; while the north shoal represents $1.5 \times 10^6 m^3$ of sand. Since 1949, this represents an increase of $1.3 \times 10^6 m^3$ of sand on the northeast face of Parramore Island, a decrease of $0.9 \times 10^6 m^3$ on the shoals, and an increase on Cedar Island of $2.5 \times 10^6 m^3$ of sand.

In April of 1962 (Fig. 13), after the "Ash Wednesday" storm, the shoal had disappeared below the water line, a loss of $1.5 \times 10^6 m^3$ of sand. The southeast tip of Cedar Island, although elongated, has lost $0.6 \times 10^6 m^3$ of sand and the northern face of Parramore Island gained about $0.5 \times 10^6 m^3$ to a total volume of $3.8 \times 10^6 m^3$. Note also that the north shoreline of Parramore Island is straight. In 1966 (Fig. 14) the northeast face of Parramore Island had retrograded back to the base line, a loss of $3.8 \times 10^6 m^3$ of sand. A shoal has developed, where in 1962 there was nothing, to a volume of $1.9 \times 10^6 m^3$; and the south tip of Cedar Island has accreted eastward slightly ($0.1 \times 10^6 m^3$). In February of 1970 (Fig. 15) the north shoal had accreted another $1.0 \times 10^6 m^3$ of sand to a total of $2.9 \times 10^6 m^3$, while Cedar Island had lost $0.1 \times 10^6 m^3$. There is no data for Parramore Island at this time.

In June of 1971 (Fig. 16), the north shoal had decreased in size by $1.4 \times 10^6 m^3$, while Cedar Island, narrowed and lengthened, had remained unchanged, and Parramore Island had remained unchanged since the 1966 photograph. But, note that the north lateral ramp margin shoals consists of two shoals now, not one as in February 1970. Also note, the presence of a concavity of the north shoreline of Parramore Island. This is due to diffraction of waves approaching from the northeast sector and then passing through the channel between Cedar Island and the north shoals. In September 1971 (Fig. 17), the system is virtually unchanged since June 1971, with the exception that the shoals have decreased by 0.3 x $10^6 m^3$ of sand. Note the interesting configuration of the eastern section of the north shore of Parramore Island. It appears that a small wedge of sand is building out on a submerged shelf, due to the protection afforded by the shoal, from waves approaching from the north. Again, in November of 1971, there has been very little change in the system.

By February 1972 (Fig. 19), the inlet system had begun to change again. The north lateral ramp margin shoal had decreased in size by 0.7 x $10^6 m^3$. The configuration of the northeast face of Parramore Island has changed, but the total sand present has not changed. The sand has simply been redistributed. This probably can be related to the disappearance of the most seaward shoal of the two shoals that existed in 1971. Note also, the calving or apparent slumping of the sand on that sand wedge that has been accreting on the easterly portion of the north flank of Parramore Island.

By September of 1972 (Fig. 20), the north lateral ramp margin shoals have totally disappeared, a further loss of 0.5 x $10^6 m^3$ of sand since February 1972. The small wedge of sand that had existed on the easterly portion of the north flank of Parramore Island has disappeared probably because of the loss of the protection afforded by the shoals. With the loss of that northeast sand wedge, the apparent concavity in the north face of Parramore Island has disappeared.

By November of 1972 (Fig. 21), another north shoal had emerged with a volume of $0.4 \times 10^6 m^3$ of sand. But more significantly, another sand wedge is developing on the northeast flank of Parramore Island similar to the one that existed in 1949, 1957, and 1962 photographs. This feature represents an accretion of $1.9 \times 10^6 m^3$ of sand in only two months time.

By July of 1973 (Fig. 22), the new north shoal had accreted another $0.5 \times 10^6 m^3$ sand to a total volume of $0.9 \times 10^6 m^3$; while the northeast face of Parramore Island had lost $0.1 \times 10^6 m^3$ of sand.

The results of this twenty-four year survey of available aerial photography are summarized in Table 6.

Beaches on the Eastern Shore of Virginia are shallow, narrow and apparently sand starved. Byrne, et al. (1973) estimate that the net drift from the north of the inlet does not exceed 450,000 m^3/yr. During the period from February, 1970, to September, 1972, a shoal of $2.9 \times 10^6 m^3$ of sand disappeared. Yet by July, 1973, another shoal reappeared with a volume of $0.9 \times 10^6 m^3$; and an accretion of $1.9 \times 10^6 m^3$ occurred on the northeast face of Parramore Island. Changes of this magnitude cannot be reasonably related to fluctuations in littoral drift, but more likely due to cyclic short-term changes on the ebb tidal delta. For example, a 1 m change in the depth over the area of the ebb tidal delta ($4 \times 10^6 m^2$) will yield a volume change of

$4 \times 10^6 m^3$.

Mobile Sediment Distribution of Wachapreague Inlet Complex

The mobile sediment distribution was investigated with respect to both spatial variations over the entire inlet complex and temporal variation in the inlet throat channel. Sediment samples were gathered by a mini-Van Veen grab sampler, along planned transects. Sample sites were determined by shooting azimuths on fixed known locations or by shooting adjacent angle pairs with a sextant; later these were plotted on the 1972 bathymetry chart. In addition to the samples, observations were made by divers in all those areas of the inlet complex that were of particular interest.

All samples were initially described as to contents (shell, sand, mud, etc.). Later, all the samples were again reviewed, and those of which a sufficient quantity of sand was available, were dried and sieved through Quarter PHI screens while shaking in a standard Ro-Tap shaker for 20 minute intervals. Each fraction was then weighed and these weights recorded. Mud samples were analyzed by the pipet method described in Ward (1968), samples were taken at the 4ϕ, 5ϕ, 6ϕ, and 8ϕ intervals. A computer program was written to analyze the data. This is shown in Appendix I. The standard graphic textural parameters were computed for the samples. The equations for the analysis are based on those published by Folk, et al. (1957).

The results of the spatial sediment distribution survey are summarized in Figure 23. The sediments varied from a veneer of very coarse sediments, composed of shell debris, cobbles, and gravels overlying a stiff, cohesive, sandy clay substrate in the deep inlet throat channel, to well sorted, medium to fine sand surrounding the inlet throat to a very fine silty sand both inside and outside the immediate area of the inlet channel. The sediment distribution appears to correlate well with the various depositional environments. That is, coarser sediments are localized in the higher energy areas and the finer sediments are restricted to the low energy areas.

Tables 7, 8, 9, and 10 tabulate the results of the various surveys of the ebb tidal delta, the inlet throat, and the interior lagoons and tidal channels. Several very interesting points came to light as a result of the survey. The apparent flood tidal deltas or bathymetric highs are in fact relative topographic highs of lagoonal sediments, overlain by a thin veneer of fine sand. Secondly, the north flank of Parramore Island, on the steep wall adjacent to the inlet, is an exposure of very firm lagoonal deposits. And finally, that there appears to be a swath of fine sand ($> 2.0\,\phi$, $< 2.5\,\phi$) that intersects the coarser sediments in the inlet axial channel. Perhaps this is a pathway for sand to bypass the inlet; the slope of the channel sides in this area is 2°.

The bottom sediment distribution in the throat of the inlet was sampled fortnightly for a period of three months at various high and low slack waters. Sample stations were located at the deepest part of each of eleven transects that cross the throat of the inlet. The loose sediments recovered from the bottom included medium and coarse grain sands, gravels, boulders (up to 6 inches in diameter), shell debris of various sizes and shapes, and rounded chunks of hard mud. These mud chunks proved to be identical to the substrate material along the south flank and bottom of the inlet throat. The results of these surveys are tabulated in Table 11.

No obvious resorting pattern between high and low slack was observed during the sampling period. In the deepest parts of the inlet throat, below 15 meters, the loose bottom sediment usually consisted of gravels and large shell debris (_Mercenaria_ sp. and _Crassostera_ sp.). Toward the eastern and western extremities of the throat channel, at depths ranging between 12 and 15 meters, the mobile bottom sediments usually varied between coarse sand and smaller shell fragments. The bottom sediment distribution did reflect measured fluctuations in the cross-sectional area of the inlet's throat during the sample period. That is, during the last week in May, 1972, and the first two weeks in June, 1972, appreciable amounts of sand were recovered from most of the transects across the gorge, perhaps indicating a choking or filling in of the throat. Later, this was correlated with an overall decrease in the cross-sectional areas of the transects across the inlet throat (over a 15% decrease at one transect). In mid-July, 1972, principally mud clumps (rounded chunks of lagoonal mud) were recovered at almost all sample stations in the inlet. This indicated erosion in the inlet of the southern flank and the bottom which later was verified by a significant overall increase in the cross-sectional areas.

Verification of the migration of shell debris was accomplished by direct visual observation by divers on the bottom shortly after a slack water work dive. Thus, the inception of shell motion occurred at a relatively low current velocity of the inlet. These shifting coarse sediments appear to be abrading into the hard bottom substrate, as evidenced by pot holes observed in the bottom.

The Geology of the Inlet Complex

The geology of the inlet complex was studied from data from samples, cores, and observations taken while scuba diving, a well recently drilled on Parramore Island, and sub-bottom profiles made across the inlet throat and in Horseshoe Lead, landward of Parramore Island. The first realization that Wachapreague Inlet was different than the typical sandy trough described for inlets on sandy coasts (Brown, 1928) came as a result of the mobile sediment distribution survey. Further observations, cores and samples made by divers along the inlet bottom and south flank confirmed that underlying the coarse sediments on the deep inlet bottom was a stiff, silty clay substrate, with interspersed layers of gravels and coarse sands (Fig. 24 and 25). Samples taken from the south wall of the inlet (6-9 m below MTL) showed it to be composed of lagoonal deposits with a mean grain size of 4.8 (Table 12 and Fig. 26). The "bottom debris samples" taken from 12.2 m listed in Table 12 and shown in Figure 27 had a mean grain size of about 8Ø.

Data was taken by sub-bottom profiling across the inlet throat (Fig. 28) and the interpretation is shown in Figure 29. Note the horizontal reflectors below 20 m; these underlie both the sedimentary deposits to the north and to the south. The sloped reflectors on the north side between 20 and 15 m represent the recent sand deposits of the south tip of Cedar Island as it extends southward. On the south side of the inlet, the reflectors are parallel and horizontal from below 20 m to a depth of 15 m; but note the two strong reflectors between 15 and 16 m. Between 15 and 11 m on the south flank, the reflectors are again inclined toward the bottom, indicating either recent sand deposits or the deposits along the flank of an older channel. From 11 to 6 m the reflectors are again parallel and horizontal. Sub-bottom profiles across Horseshoe Lead (Fig. 30) and the interpretation (Fig. 31) show the recurrence of the pair of strong reflectors between 15 and 16 meters.

In order to be able to correlate the various reflectors shown in Figures 29, 30, 31, and 32 with specific geologic strata, a well was drilled on Parramore Island and continuously split-spoon sampled to 22 m below MTL. Table 13 tabulates the sediment analysis of the well and a summary of this well log is in Table 14. There are some inconsistencies between the samples taken along the mud exposures on the north flank of Parramore Island in the inlet and the well log. The very fine silty sands (mean 3.5Ø) found from 9.0 m to 14.5 m were not found in the samples taken from the inlet south wall. However, immediately below that horizon, the coarse sands, shells, and gravels do correlate well with the two strong reflectors found in the inlet between 15 and 16 m and found also in Horseshoe Lead between 15 and 16 m. Below this there are alternating layers of medium sands, fine sands, gravels, and finally at 22.4 m, a layer of very stiff, silty clay.

Radiocarbon dates were obtained on shell samples taken from the well and from the submerged north flank of Parramore Island. An assemblage of Crassostrea sp. and Mercenaria sp. shells (Fig. 32) taken from the 6.1 m horizon below MTL on the north flank of Parramore Island was dated at 3,490 years B.P. Shell samples taken from the 15 m and 20 m horizon of the well were dated at 18,750 and 19,600 years B.P., respectively.

SUMMARY AND FINAL CONCLUSIONS

Historical Changes in the Inlet Complex Configuration

Over the last 120 years the inlet channel has migrated to the south at a rate of 1 meter per year. Since 1871, the cross-sectional area of the inlet throat has remained relatively constant at about 4,200 m^2 (4,000 ft^2). Byrne (personal communication, 1973) calculated the potential tidal prism for the Wachapreague Inlet Complex to be $6.5 \times 10^7 m^3$ ($2.3 \times 10^8 ft^3$) for the mean tide range case. The tidal prism is defined as the volume of water entering the system from a low to a high water. An empirical determination of the inlet cross-sectional area can be made employing O'Brien's equation: $A = 2.0 \times 10^{-5}P$, where: P is tidal prism in cubic feet, A is inlet throat cross-sectional area in square feet (O'Brien, 1966). The calculated value for the Wachapreague Inlet cross-section is then 4,270 m^2 (46,000 ft^2). The predicted area compares well with the measured average over the last 100 years. Thus, Wachapreague Inlet follows the relationship found by O'Brien as do many tidal entrances both on the west and east coasts of the United States.

The system has not served as either a significant long-term source or sink of sand. The main channel has progressively evolved to a less efficient configuration. In contrast, the short-term changes in the inlet are dramatic. The volume of sand involved in the growth and decay of the lateral ramp margin shoal, and sand wedge on the northeast face of Parramore Island is quite large when compared to estimates of littoral drift. Sand must be moving on and off the ebb tidal delta and the offshore area, for these features to appear and disappear. It is interesting to note also, that while the inlet channel has migrated south, the ebb tidal delta has moved very little, giving rise to an apparent counter-clockwise rotation of the channel axis.

Mobile Sediment Distribution

The mobile sediment distribution of the inlet was investigated with respect to spatial variation over the entire inlet complex and temporal variations in the deep inlet throat. The sediment distribution correlated well with the various depositional environments ranging from gravels in the deep inlet throat to silty sands on the flood tidal delta. Changes in the inlet throat sediment distribution were monitored over a 3-month period. Short-term fluctuations in the inlet cross-sectional areas correlated with overall changes in the bottom sediment characteristics in the inlet throat. Also, the loose shells and gravels of the inlet throat appear to be abrading the hard mud bottom as they migrate back and forth with each change in tidal flow direction.

Geology of the Area Surrounding Wachapreague Inlet

Investigations into the geology of the inlet orifice have shown the north flank to be a sandy spit extending south from the barrier island, while the south flank is a firm cohesive lagoonal mud. Thus, as Wachapreague Inlet migrates south in response to a predominately southerly littoral drift, it leaves in its path a wedge of sand (the only sand sink in the system) and erodes into firm marine lagoonal deposits.

The geology of the area has had an influence on Wachapreague Inlet. The firm cohesive lagoonal muds on the south flank of the inlet have had a stabilizing effect on the inlet both by apparently slowing the rate of migration and by allowing the inlet cross-section to assume a more efficient geometry on at least the south side. Thus, Wachapreague Inlet is an inlet on a sandy coast, but does not have the ideal sandy throat that other investigators assume, nor is it totally free to migrate but is constrained by the geology of its south flank.

Three separate shell assemblages were collected for radiocarbon analysis. Sample No. 1, *Mercenaria* sp. and *Crassostrea* sp. shells (Fig. 32) was taken by divers from a mud outcrop along the south flank of Wachapreague Inlet (DeAlteris, et al., 1973) at a depth of 6.1 m (20') below MTL, and was dated 3490 ± 125 years B.P. Samples No. 2 and 3, shells (Fig. 33), were recovered from core taken from the northwest tip of Parramore Island adjacent to

Wachapreague Inlet. Sample No. 2, dated 18,750 ± 750 years B.P., was taken from a depth of 15 m (46') below MTL and Sample No. 3, taken at 20 m (62'), was dated 19,600 ± 500 years B.P. All three samples were shells in mint condition, precluding the possibility of transport from afar, and were collected from silty sands with abundant Foraminifera. They are therefore considered to be representative of shallow, low energy, marine environment near Wachapreague, Virginia, 19,000 years B.P.

Based on eustatic sea level changes as summarized by Shepard (1963), sea level was lower than present sea level by 3 m (10') 3500 years B.P., 107 m (345') 18,750 years B.P., and 112 m (360') 19,600 years B.P. These data are summarized in Table 15.

Sample No. 1, taken 6.1 m below present MTL, was dated at 3490 years B.P., when sea level was estimated to be 3 m below present level. This Sample No. 1, an assemblage of *Crassostrea* sp. and *Mercenaria* sp. shells, was probably deposited in lagoonal mud sediments. Kraft (1971) found a similar assemblage of *Crassostrea* sp. shells in the growth position 10.7 m (35') below present MTL; these were radiocarbon dated 3430 years B.P.

Samples No. 2 and 3, assemblages on small gastropod and pelecypod shells, dated 18,750 and 19,600 years B.P., were taken from deposits presently only 15.0 (46') and 20.0 m (62') below MTL. However, eustatic sea level was 107 m (345') and 112 m (360') below present MTL 18,750 and 19,600 years B.P. In order to deposit marine sediments in the area of Wachapreague, Virginia, the earth's surface must have been at least 92 m (310') lower than present. This implies that some time during the period from 18,750 years B.P. to 3500 years B.P. the crystaline basement in the area of Wachapreague Inlet, Virginia, uplifted at least 92 m (310'). If the shells were not deposited at sea level, but at depths of 1, 2, or 3 m of water, the implied uplift would be even greater.

Late Quaternary uplifts have been described for other areas of the east coast of North America. Kaye and Barghoorn (1964) report 290' of crustal rise in Boston Harbor occurring between 14,000 and 6,000 years B.P. They theorized that the uplift was possible in response to deglaciation. Harrison, et al. (1965) suggested 170' crustal uplift in about the last 15,000 years in the area of Chesapeake Bay entrance. This conclusion was based on channel depths and expectable stream gradients by the thalweg of the buried Susquehanna River, as proposed by Hack (1957).

Several mechanisms can be postulated to account for the uplift in the area of Wachapreague Inlet. Woollard (1955) proposed an arcuate fracture in the underlying basement racks running northwesterly through Virginia's Eastern Shore. The proposal was based on earthquake data, and the western side of this fracture, including lower Chesapeake Bay and up to Wachapreague Inlet would have been on the upthrown side of the fracture. Murray (1961) also suggests either faulting, simple uplift or a combination of both processes in the Norfolk-Fort Monroe uplift area. Taylor, et al. (1968) and Drake (1969) describe anomalies in the magnetic and gravity data for the southern Delmarva Peninsula. Sabet (1973), interpreting the results of gravity and magnetic investigations of the eastern shore of Virginia, suggests a fault trending N. 30°W through Exmore with a structural throw of 400 m (1300').

In addition to evidence based on tectonic activity in the crystalline basement complex, evidence of uplift also exists in the overlying sedimentary rocks. Inspection of the west-east geologic sections across the eastern shore peninsula from Sinnott and Tibbetts (1969) show a gentle upwarping of the base of the Chesapeake Group of undifferentiated sediments of Miocene Age. This upwarping amounts to 122 m (400') in the area of Wachapreague, Virginia.

Variations in the textural characteristics of the beach zone sediments to the north and to the south of Wachapreague Inlet are presently being investigated (Carey Ingram, personal communication, 1973). Sands of greater size and lesser angularity were found north of Wachapreague Inlet when compared to the sands from the beaches to the south. A conclusion that may be drawn from this data is that difference in the sediment textural characteristics is due to the exposure of different geologic formations caused by differential warping or possibly a fault normal to the coastline, in the area of Wachapreague, Virginia.

The importance of the proposed uplift is that it may make a significant contribution not only to the understanding of the evolution of the present lower Delmarva Peninsula and in understanding the present geomorphology of the mid-Atlantic Coastal Plain, but also indicates possible recent active tectonism in this geologic province.

TABLE 1

Historical Cross-sectional Areas of Wachapreague Inlet Throat

Year	Area (m^2)
1852	1845
1871	4473
1911	3760
1934	4572
1972	4047

TABLE 2

Channel Length (based on 12 m contour)

Year	Length (m)
1852	1662
1871	no data
1911	1701
1934	1909
1972	3046

TABLE 3

Historical Hydraulic Radii (m)

Year	Unmodified	Modified	Modified and Normalized
1852	2.5	4.3	6.7
1871	6.9	10.3	9.6
1911	9.6	9.6	9.4
1934	4.7	9.6	8.9
1972	6.1	7.4	7.4

TABLE 4

Wachapreague Inlet Complex, historical changes in the volume of material present. (Base depth 21 meters below M.T.L., expressed in millions of cubic meters).

Region	1852	1911	1934	1972
(1A)	14.6	14.3	No data	13.9
1B	14.1	14.7	14.9	14.6
1C	13.1	13.1	12.9	12.5
1D	12.0	12.3	11.9	11.6
1E	11.6	11.3	10.8	10.8
2A	12.6	12.7	12.3	12.4
2B	13.8	14.1	13.7	14.3
2C	13.6	13.9	13.3	13.2
2D	13.9	14.0	13.8	13.4
2E	13.3	12.9	13.2	12.9
2F	11.6	11.1	12.7	12.2
3A	12.3	11.3	12.1	10.8
3B	14.1	12.1	12.6	12.0
3C	13.5	11.8	12.5	11.8
3D	11.9	11.5	11.5	11.8
3E	12.3	12.3	12.0	11.4
3F	12.9	13.0	13.0	12.7
(4A)	13.7	No data	No data	11.8
4B	15.1	15.1	15.1	14.7
4C	13.9	15.1	15.0	14.7
4D	13.9	13.9	13.7	14.3
4E	13.3	12.6	13.5	13.3
4F	12.7	14.1	12.6	12.9
5D	13.7	13.7	13.2	13.8
5E	13.1	12.7	12.7	12.5
Total material at time of survey, less regions 1A and 4A	302.3	299.3	299.0	295.0

TABLE 5

Cedar Island sand wedge volumes.

Year	Volume $(10^6 m^2)$	Total Change from 1852
1855	14.6	+0.5
1934	15.1	+1.3
1972	19.1	+4.5

TABLE 6

Recent historical volume changes from aerial photography, expressed in $10^6 m^3$.

Date	N.E. Face Parramore		Lateral Ramp Margin Shoal		Cedar Island	
	total	change	total	change	total	change
1949	2.0		2.4		0.0	
		+1.3		-0.9		+2.5
1957	3.3		1.5		2.5	
		+0.5		-1.5		-0.6
04/1962	3.8		0.0		1.9	
		-3.8		+1.9		+0.1
10/1966	0.0		1.9		2.0	
		No Data		+1.0		-0.1
02/1970	No Data		2.9		1.9	
		No Data		-1.4		NC
06/1971	0.0		1.5		1.9	
		NC		-0.3		NC
09/1971	0.0		1.2		1.9	
		NC		NC		NC
11/1971	0.0		1.2		1.9	
		NC		-0.7		NC
02/1972	0.0		0.5		1.9	
		NC		-0.5		NC
09/1972	0.0		0.0		1.9	
		+1.9		+0.4		NC
11/1972	1.9		0.4		1.9	
		-0.1		+0.5		NC
07/1973	1.8		0.9		1.9	

TABLE 7

Wachapreague Inlet Complex, bay sediment samples.

Sample #	Mean Grain Size (phi units)	Skewness	Standard Deviation	Kurtosis
B-1	1.876	0.746	0.592	0.482
B-2	3.105	0.847	0.544	0.352
B-3	3.236	0.816	0.585	0.781
B-4	2.905	1.038	0.701	0.491
B-5	2.692	0.061	0.436	0.274
B-6	2.578	-0.015	0.429	0.270
B-7	2.130	0.326	0.497	0.466
B-8	2.332	0.014	0.555	0.543
B-9	2.451	0.217	0.489	0.375
B-10	2.650	0.110	0.372	0.321
B-11	2.678	0.039	0.406	0.232
B-12	2.758	0.209	0.516	0.372
B-13	2.621	0.000	0.440	0.249
B-14	2.680	-0.012	0.472	0.337
B-15	2.588	-0.010	0.490	0.357
B-16	2.407	-3.469	0.289	0.172
B-17	2.426	1.105	0.328	0.212
B-18	2.332	0.526	0.304	0.181
B-19	2.458	-1.016	0.348	0.228
B-20	2.450	-0.063	0.499	0.423
B-21	2.500	-0.033	0.522	0.428
B-22	2.551	-0.036	0.485	0.377
B-23	2.343	-0.103	0.335	0.206
B-24	3.011	-1.409	0.718	0.584
B-25	2.500	0.015	0.376	0.489
B-26	2.301	0.129	0.457	0.407
B-27	2.187	0.261	0.381	0.258
B-28	2.110	0.315	0.352	0.271
B-29	2.372	0.355	0.335	0.222
B-29'	2.392	0.242	0.438	0.358

*(') indicates a replicate sample.

TABLE 8

Wachapreague Inlet Complex, inlet channel sediment samples.

	Mean Grain Size (phi units)	Skewness	Standard Deviation	Kurtosis
I 1	1.964	-0.785	0.448	0.333
I 2	1.994	-0.468	0.371	0.229
I 3	2.004	-0.321	0.343	0.267
I 4	2.341	0.228	0.372	0.252
I 5	1.604	0.031	0.363	0.269
I 6	2.071	1.351	0.427	0.261
I 7	2.101	0.634	0.372	0.321
I 8	1.790	-0.042	0.455	0.355
I 9	1.681	1.270	0.593	0.624
I 10	1.344	0.252	0.393	0.277
I 11	2.027	0.334	0.427	0.364
I 12	1.869	0.230	0.496	0.430
I 13	1.763	0.454	0.502	0.456
I 14	1.937	1.261	0.398	0.256
I 15	2.179	0.030	0.354	0.227
I 16	1.727	0.388	0.255	0.114
I 17	2.173	-0.479	0.384	0.284
I 18	2.099	-0.001	0.364	0.240
I 19	2.117	-0.030	0.392	0.297
I 20	2.105	0.494	0.321	0.206
I 21	1.773	1.191	0.587	0.636
I 22	2.000	1.346	0.426	0.437
I 23	2.046	1.163	0.337	0.212
I 24	1.554	1.177	0.516	0.648
I 25	1.987	0.170	0.363	0.219
I 26	2.130	-0.303	0.357	0.221
I 27	2.031	0.216	0.434	0.231
I 28	1.423	0.236	0.516	0.527
I 29	1.514	-3.028	0.575	0.644
I 30	1.894	-0.012	0.538	0.554
I 31	1.534	-0.559	0.326	0.223
I 32	2.029	0.209	0.489	0.377
I 33	2.096	0.176	0.432	0.261
I 34	2.033	-2.755	0.295	0.159
I 35	2.015	-0.226	0.400	0.331
I 36	2.373	0.226	0.441	0.361
I 37	2.360	2.154	0.355	0.252
I 38	2.313	-1.103	0.304	0.186

TABLE 8 (Cont'd.)

	Mean Grain Size (phi units)	Skewness	Standard Deviation	Kurtosis
I 24'	1.773	1.191	0.582	0.636
I 28'	1.615	0.329	0.627	0.783
I 30'	1.879	0.109	1.135	0.482
I 35'	2.090	-0.047	0.428	0.341

*(') indicates a replicate sample.

TABLE 9

Wachapreague Inlet Complex, offshore sediment samples.

Sample #	Mean Grain Size (phi units)	Skewness	Standard Deviation	Kurtosis
01	2.971	0.837	0.703	0.658
02	3.048	0.921	0.713	1.158
03	3.554	0.434	0.514	0.593
04	2.751	-2.464	0.508	0.452
05	3.302	-2.765	0.560	0.751
06	2.697	0.053	0.506	0.350
07	2.434	0.347	0.327	0.200
08	2.396	0.388	0.342	0.240
09	2.427	-1.599	0.337	0.226
010	2.360	2.154	0.355	0.252
011	2.058	-0.171	0.373	0.242
012	2.529	-0.719	0.311	0.173
013	2.685	0.060	0.476	0.321
014	2.992	1.033	0.612	0.402
015	2.987	1.008	0.609	0.385
016	2.571	0.137	0.526	0.326
017	2.610	0.527	0.875	0.683
019	2.10	0.174	0.362	0.234
020	1.739	0.222	0.422	0.327
021	1.617	0.522	0.442	0.372
022	1.415	-0.293	0.424	0.224
023	2.332	-0.055	0.433	0.374
024	2.948	1.502	0.739	1.207
025	3.565	0.425	0.586	0.782
026	3.536	0.434	0.578	0.787
027	2.202	0.317	0.433	0.365
028	2.048	0.228	0.944	1.659
029	2.058	-0.581	0.455	0.311
030	2.03	-0.413	0.379	0.427
011'	2.146	0.234	0.341	0.228
026'	3.449	0.535	0.633	0.898

*(') indicates a replicate sample.

TABLE 9 (Cont'd.)

Sample #	Mean Grain Size (phi units)	Skewness	Standard Deviation	Kurtosis
032	2.424	0.032	0.590	0.758
033	2.440	-0.004	0.593	0.794
034	3.046	5.264	0.716	0.918
035	2.772	-0.824	0.512	0.462
036	3.109	0.169	0.754	1.286
037	3.085	-1.870	0.704	0.922

TABLE 10

Wachapreague Inlet Complex, bay mud sediment analysis, results of pipet analysis.

Sample #	50% Mean (phi units)	% Sand	% Silt	% Clay
TB 1 #5	4.2	44	40	16
TB 2 #5	3.9	51	37	12
TB 9 #4	5.0	26	51	23
TB 1 #6	4.2	42	41	17
TB 1 #4	5.8	18	56	26
TB 1 #3	6.0	17	50	33
TB 2 #6	< 4.0	61	30	9
TB 2 #7	4.4	42	42	16

TABLE 11

Temporal variations Wachapreague Inlet throat sediments, 1972.

Transect	High Water 4 May	High Water 18 May	High Water 2 June	High Water 13 June	High Water 27 June	High Water 14 July	Low Water 26 July	Low Water 10 August
1	hard dark green clay, sand 1.49ϕ	small shell frags. sand 1.68ϕ	sand 1.94ϕ	mud, sand, shell	sand 1.72ϕ	sand, mud chunks	sand	shells, gravels, large shells
2	clay, mud, sand, gravel, 1.76ϕ	sand, shells, gravels	sand 1.68ϕ	sand	shell, sand, mud, gravel	no sample	no sample	no sample
2-2	mud, sand, gravel, 1.38ϕ	shells, gravels, clay smear on sample	sand	sand, shell	no sample	mud chunks	shells, sand, gravels	no sample
2-2-A	no sample	large shells, gravels	sand, gravel	no sample	no sample	no sample	no sample	no sample
3	firm green clay mud	large shells, gravels	sand, large shell frags.	large shell, sand	hard mud	mud, gravel, shells	large shells	shells, sand, small shell
4	no sample	shells, sand, gravels	sand, shells	no sample	shells	shells, mud, gravels	large shells	shells, mud, sand

* mean grain size in PHI units

TABLE 11 (Cont'd.)

Transect	High Water 4 May	High Water 18 May	High Water 2 June	High Water 13 June	High Water 27 June	High Water 14 July	Low Water 26 July	Low Water 10 August
5	large shell debris, green clay, mud	large shell debris	large shells	sand, mud	shells	shells, mud chunks	shells, mud, sand	shells, sand, gravel
6	no sample	large shell debris	shell, sand 1.61ϕ	large shell on hard mud	hard mud	shells, mud chunks	mud	sand, mud
7	large shell frags.	shells, sand	shells, sand	shells, sand	shells, sand, mud	mud chunks	shells, sand, mud	shells, mud
8	large shell frags.	clean sand	sand 1.75ϕ	sand, shells	shells, sand, mud	shells, mud chunks	large shells	shells, sand
9	sand 1.29ϕ	no sample	sand	shells, sand	sand	sand	sand, shell, gravel	shells, sand

* mean grain size in PHI units

TABLE 12

Inlet south wall sediment samples, transect #2-2.

Sample #	50% Mean (phi units)	% Sand	% Silt	% Clay	% H_2O	Comments
Shelf Edge 18'	5.4ϕ	28%	54%	18%	13	Substrate
Slope 20'	4.7	31	49	20	13	Substrate
Slope 20'	4.5	34	62	4	28	Substrate R.C. shell sample
Slope 28'	4.9	28	52	20	18	Substrate
Slope 33'	5.0	22	75	23	-	Substrate
40'	8.0	4	46	50	19	Bottom debris
40'	> 8.0	4	23	73	-	Bottom debris
40'	> 8.0	7	39	64	44	Bottom debris
40'	3.5	58	40	2	55	Local loose sediments

TABLE 13

Sediment analysis Parramore Island well log.

Sand Sieve Analysis

Sample #	(meters)	Mean (phi units)	Skewness	Standard Deviation	Kurtosis	Blows/of/Hammer
37-39	(11.6)	3.476	0.014	0.677	0.709	5-6-6-8
40-42	(12.5)	3.604	-0.457	0.454	0.439	5-10-11-12
42-44	(13.1)	3.300	0.662	0.673	0.815	9-8-10-10
47-49	(14.6)	3.464	-0.026	0.635	0.880	13-19-22-28
52-54 (Top Half)	(16.1)	1.712	0.589	1.124	1.489	Top Half
57-59	(17.7)	1.743	-0.158	0.893	1.753	14-15-52-40
59-61	(18.3)	2.525	-2.319	0.881	1.437	15-12-12-20
62-64	(18.9)	2.278	-9.249	1.136	2.016	12-10-5-4
65-67	(20.2)	1.983	0.281	1.112	2.172	10-7-8-3
67-69	(20.8)	1.885	0.039	0.996	1.967	9-9-8-22
70-72	(21.7)	2.876	0.036	1.048	1.495	6-11-12-35
72-74	(22.3)	1.830	0.118	1.010	1.862	Top
72-74	(22.3)	1.958	0.937	1.341	4.449	14-6-5-1(Middle)

TABLE 13 (Cont'd.)

Pipet Analysis

Sample #	(meters)	50% Mean ϕ	% Sand	% Silt	% Clay
17-19	(5.5)	5.8	12	81	7
20-22	(6.4)	4.4	38	58	4
25-27	(7.9)	4.9	23	73	4
54	(16.5)	5.8	12	85	3
74	(22.6)	5.3	18	79	3

TABLE 14

Summary of Parramore Island well log.

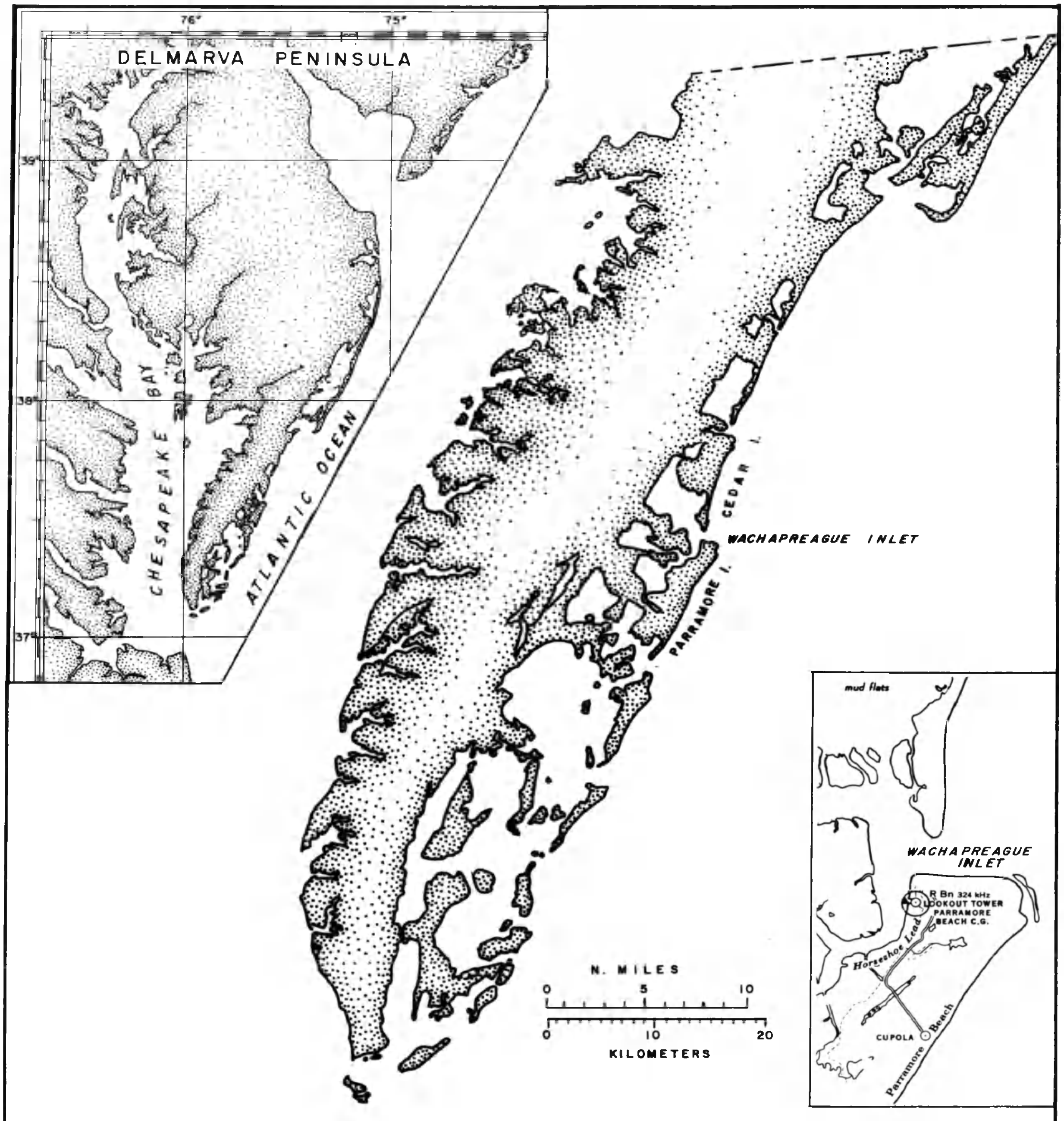
Depth Below MTL (meters)	Mean Grain Size (phi units)	Comments
0 - 8.9	5.0	firm lagoonal mud, shells and rhizomes
9.0 - 14.5	3.5	very fine silty sand, shells
14.6 - 15.3	1.71	medium sand, shells and shell fragments
15.4 - 15.7	transition zone	no samples
15.8 - 16.4	5.8	firm silty clay mud, small shell
16.5 - 17.4	1.74	medium sands, shells and gravels
17.5 - 19.0	2.40	clean fine sands, small shells
19.1 - 20.4	1.93	medium sand, shells fragments
20.5 - 20.9	2.87	fine sands
21.0 - 21.3	transition zone	no samples
21.4 - 21.6	-4.0	gravels, shell fragments
21.7 - 21.9	1.89	medium sands, shell fragments
22	-4.0	gravels
22.1 - 22.3	5.25	very stiff silty mud

TABLE 15

Summary of radiocarbon dates, present sample depths and hypothesized eustatic sea levels.

Sample No. and Material	Recovered Depth Below MTL	Radiocarbon Date Years B.P.	Eustatic Sea Level Lower than Present
#1, Shells	6.1 m (20')	3490 ± 125	3 m (10')
#2, Shells	15.0 m (46')	18,750 ± 750	107 m (345')
#3, Shells	20.0 m (62')	19,600 ± 500	112 m (360')

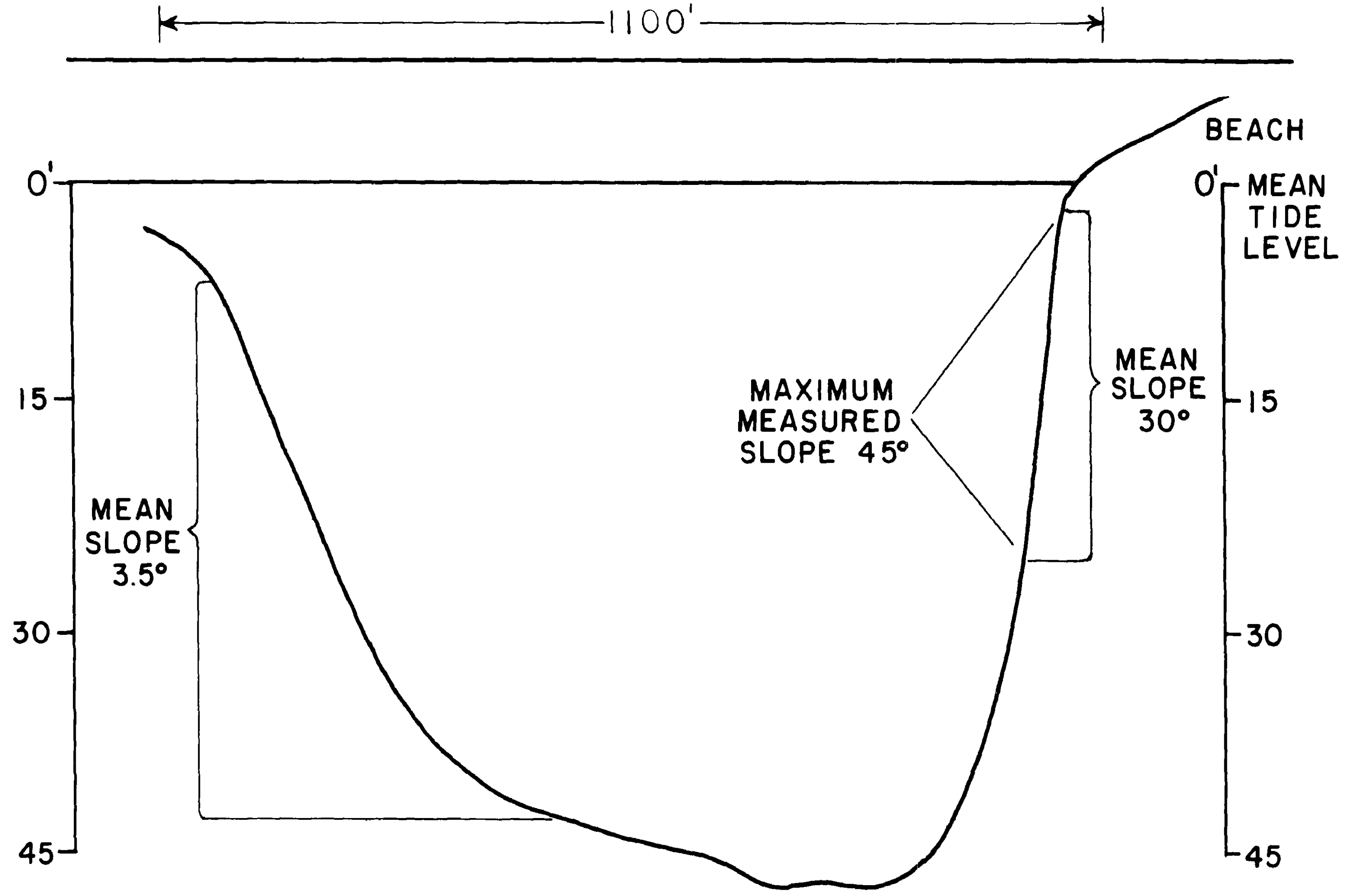
Figure 1. Wachapreague Inlet on the eastern shore of the southern Delmarva peninsula.



SOUTHERN DELMARVA PENINSULA

Figure 2. A cross-section of the eastern end of the Wachapreague Inlet channel.

WACHAPREAGUE INLET CROSS-SECTION #7



SURVEY DATE
8 SEPT., 72

MAXIMUM DEPTH = 46'

Figure 3. Proposed Geologic Contact Surfaces, Wachapreague, Virginia, to Cedar Island cross-section.

PROPOSED GEOLOGIC CONTACT SURFACES WACHAPREAGUE, VA. TO CEDAR ISLAND CROSS-SECTION

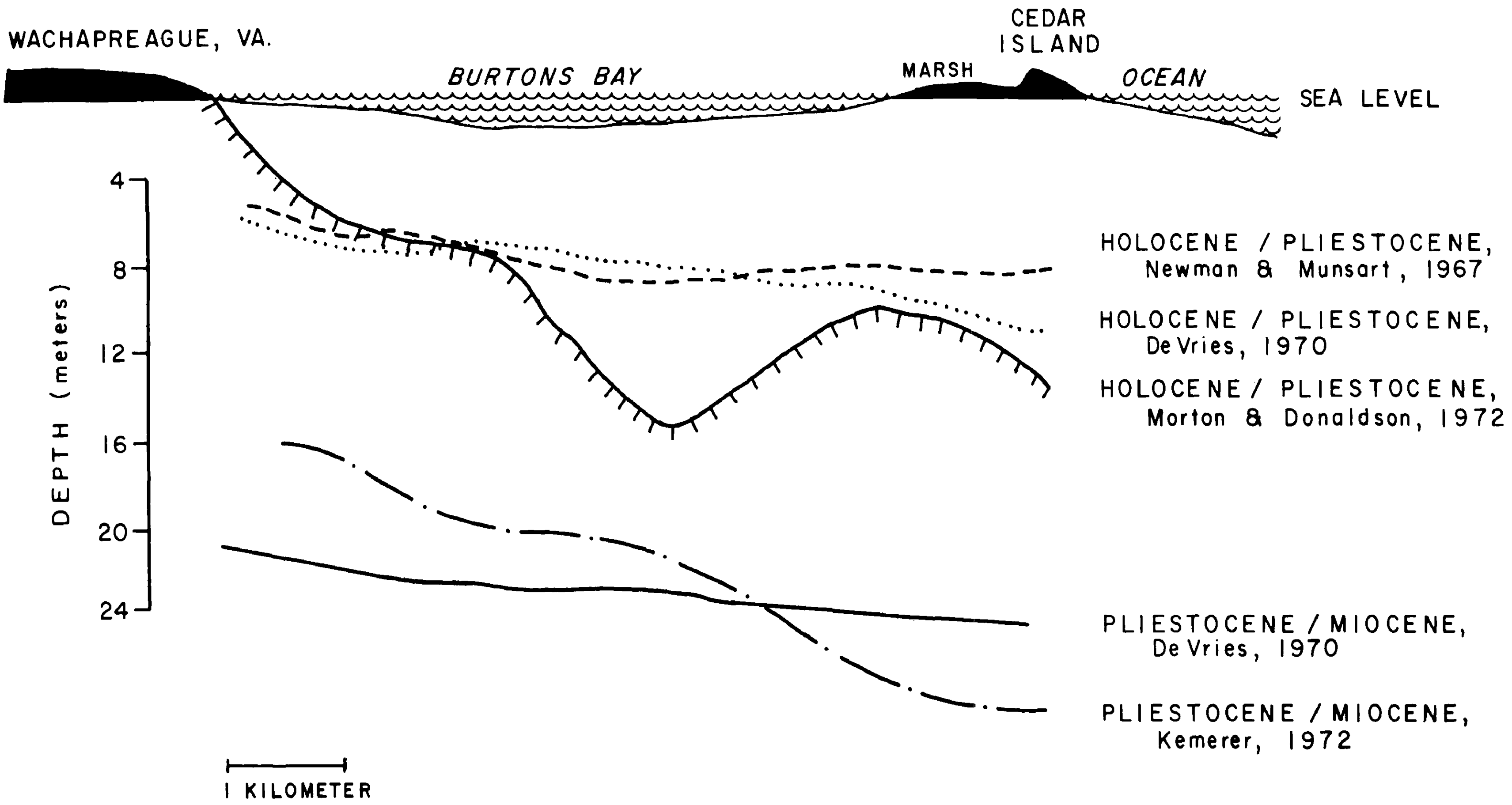
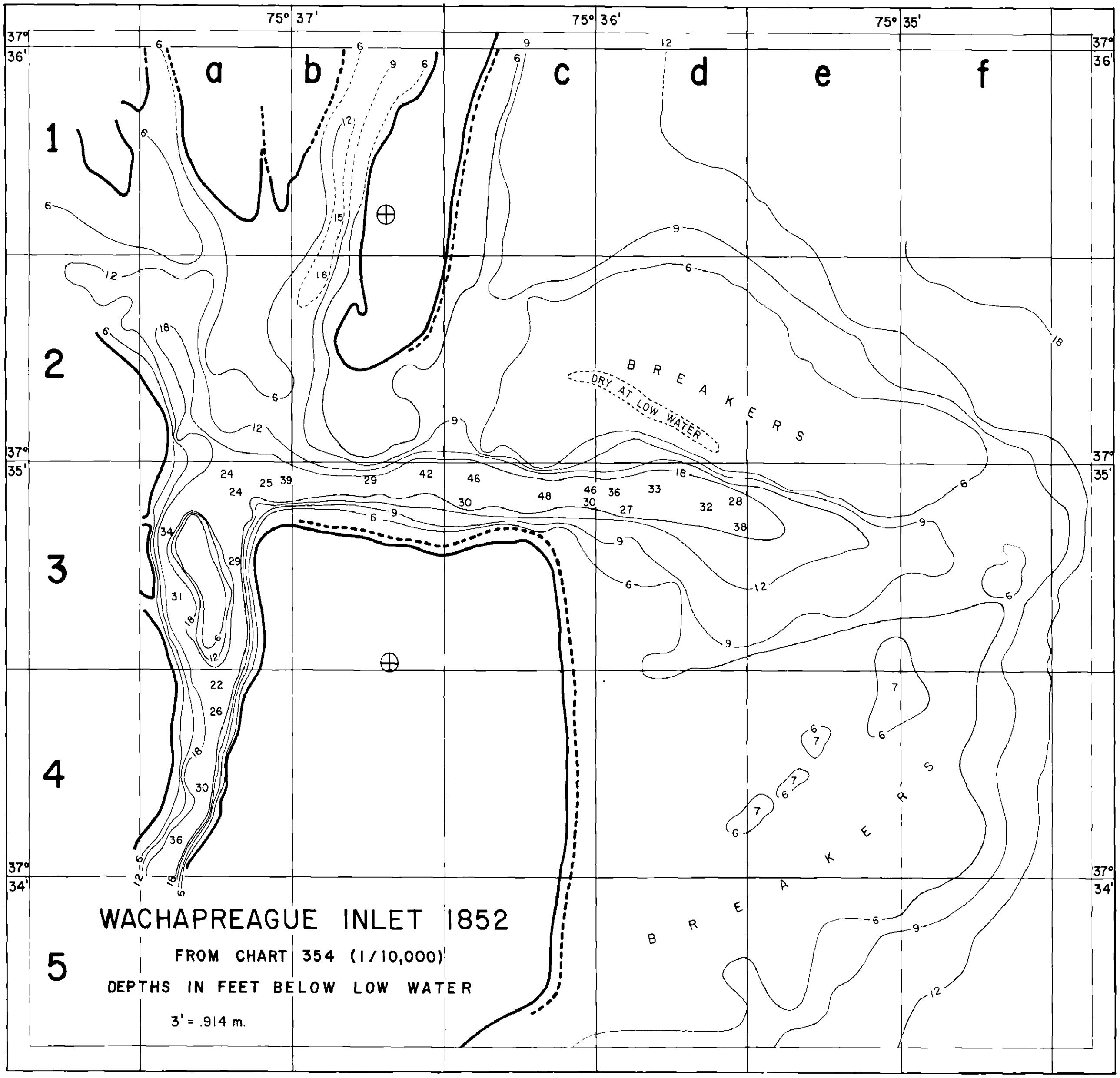


Figure 4. Wachapreague Inlet Complex, 1852.



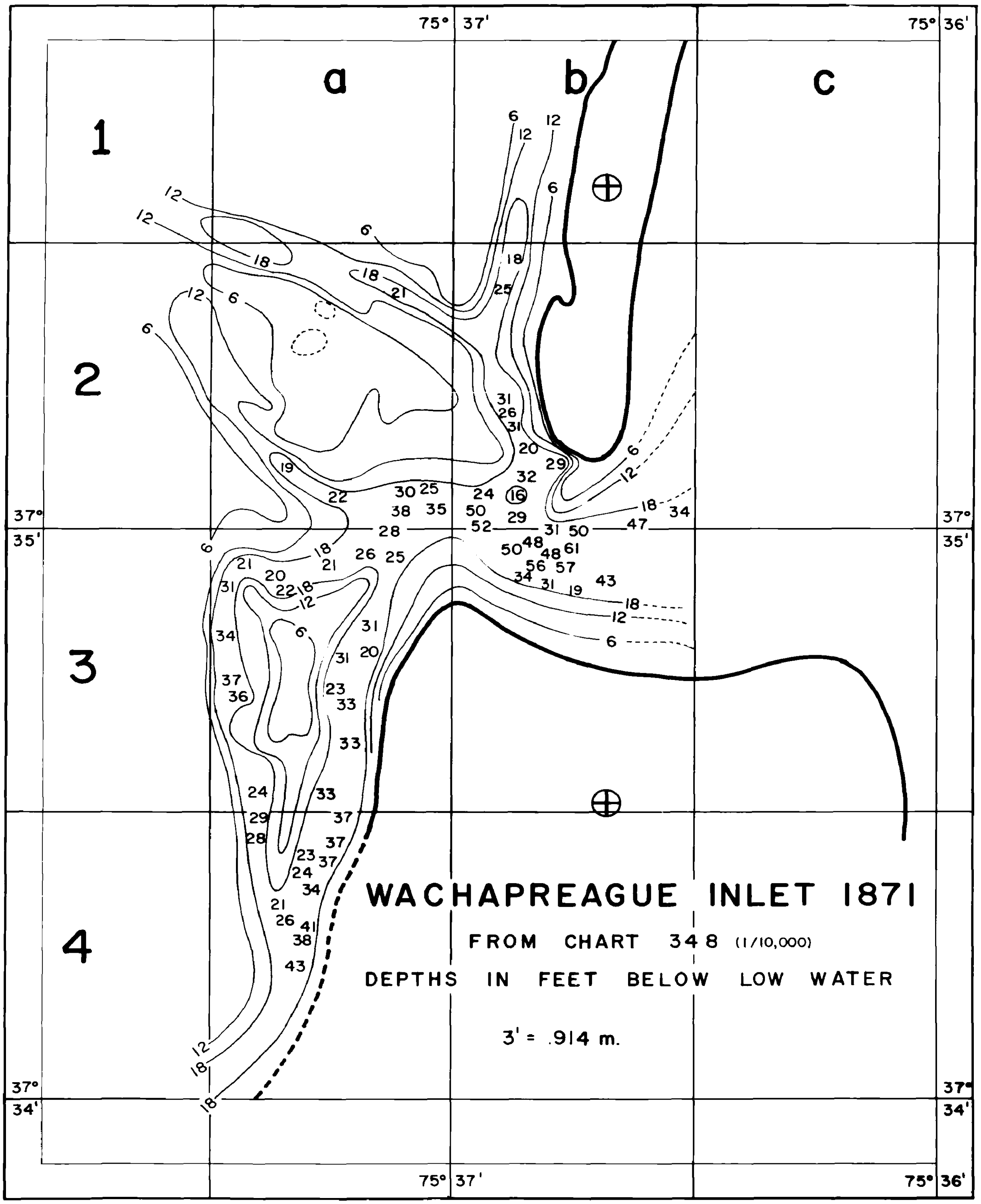
WACHAPREAGUE INLET 1852

FROM CHART 354 (1/10,000)

DEPTHS IN FEET BELOW LOW WATER

3' = .914 m.

Figure 5. Wachapreague Inlet Complex, 1871.



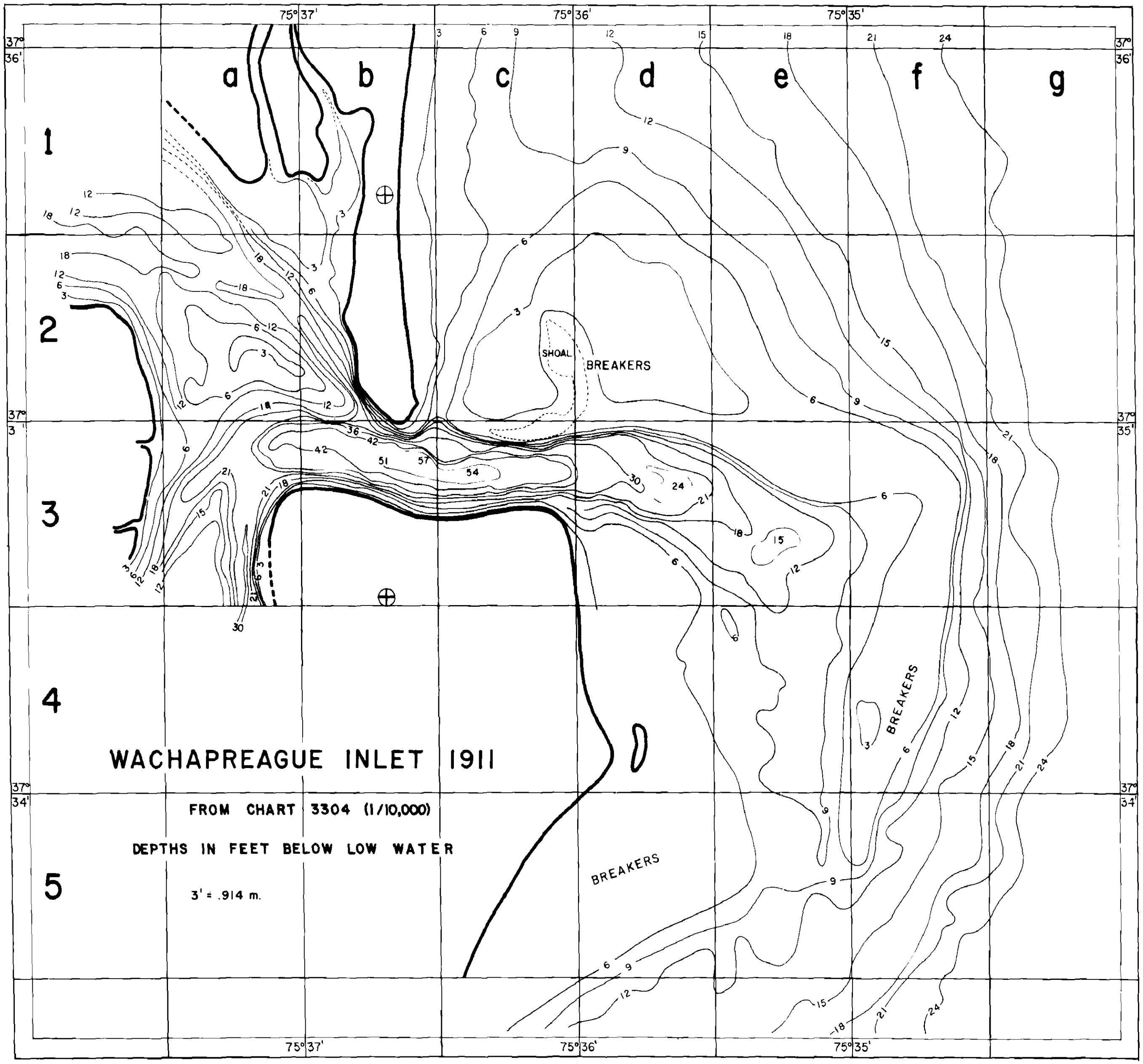
WACHAPREAGUE INLET 1871

FROM CHART 348 (1/10,000)

DEPTHS IN FEET BELOW LOW WATER

3' = .914 m.

Figure 6. Wachapreague Inlet Complex, 1911.



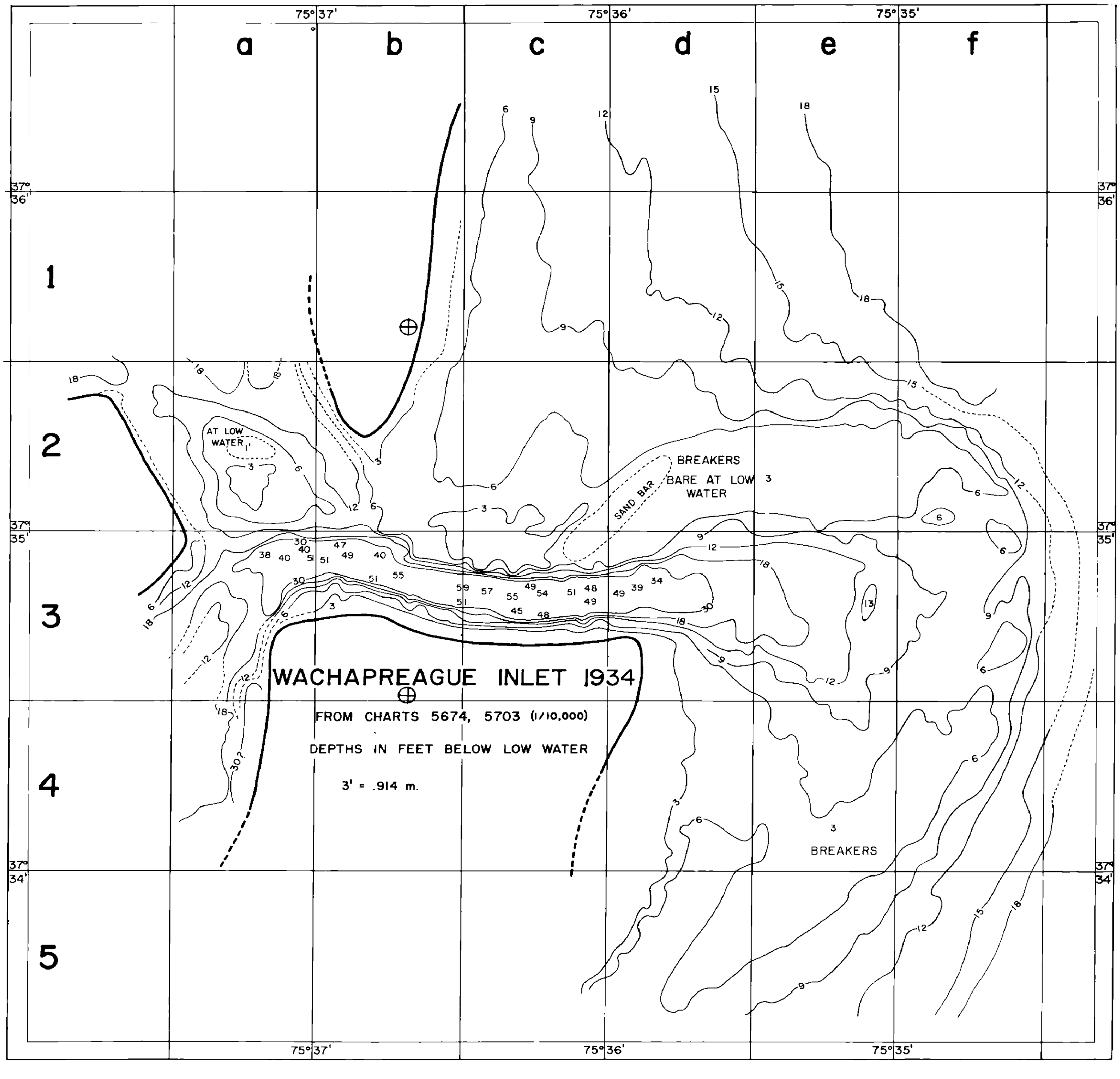
WACHAPREAGUE INLET 1911

FROM CHART 3304 (1/10,000)

DEPTHS IN FEET BELOW LOW WATER

3' = .914 m.

Figure 7. Wachapreague Inlet Complex, 1934.



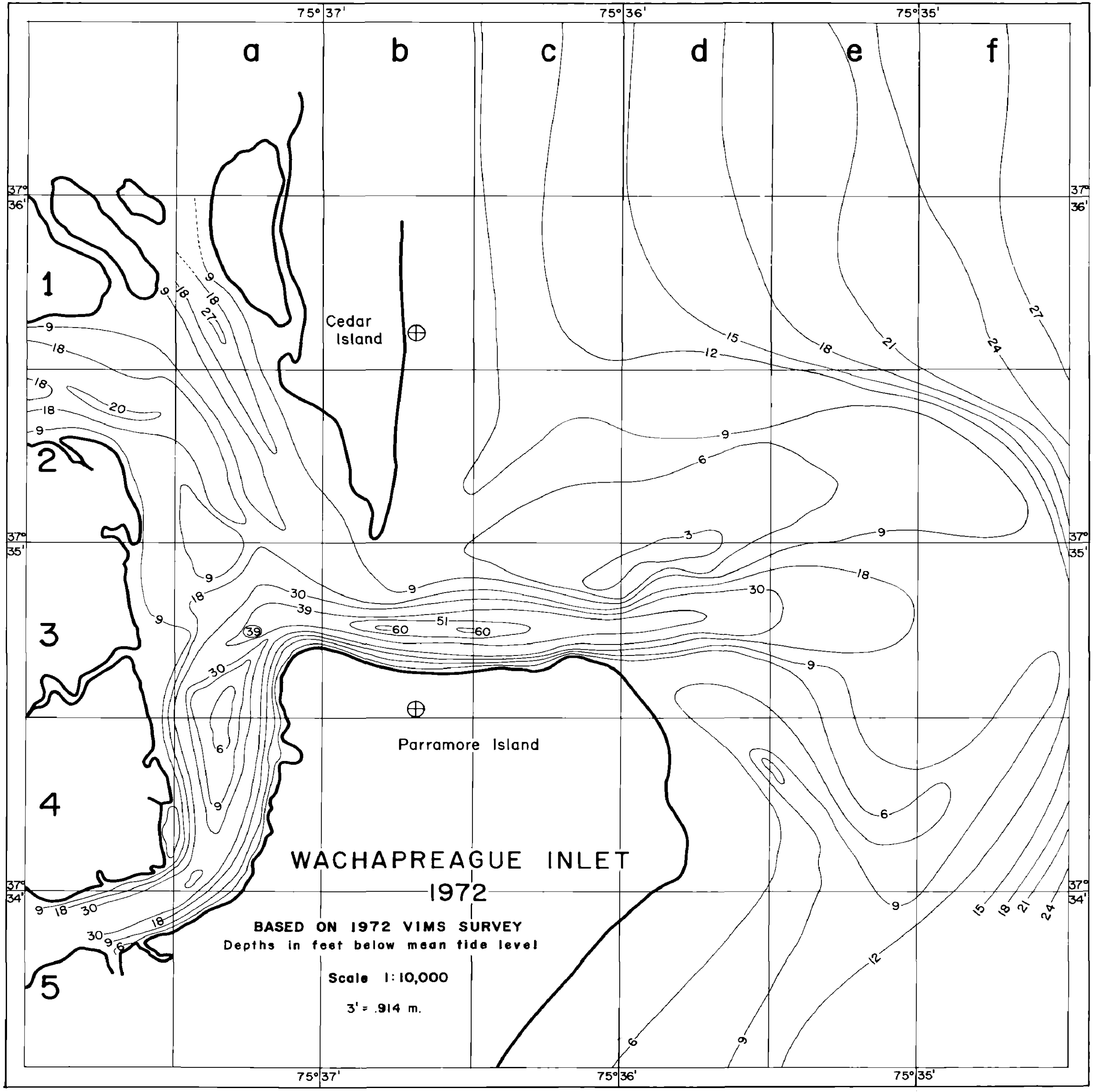
WACHAPREAGUE INLET 1934

FROM CHARTS 5674, 5703 (1/10,000)

DEPTHS IN FEET BELOW LOW WATER

3' = .914 m.

Figure 8. Wachapreague Inlet Complex, December, 1972.



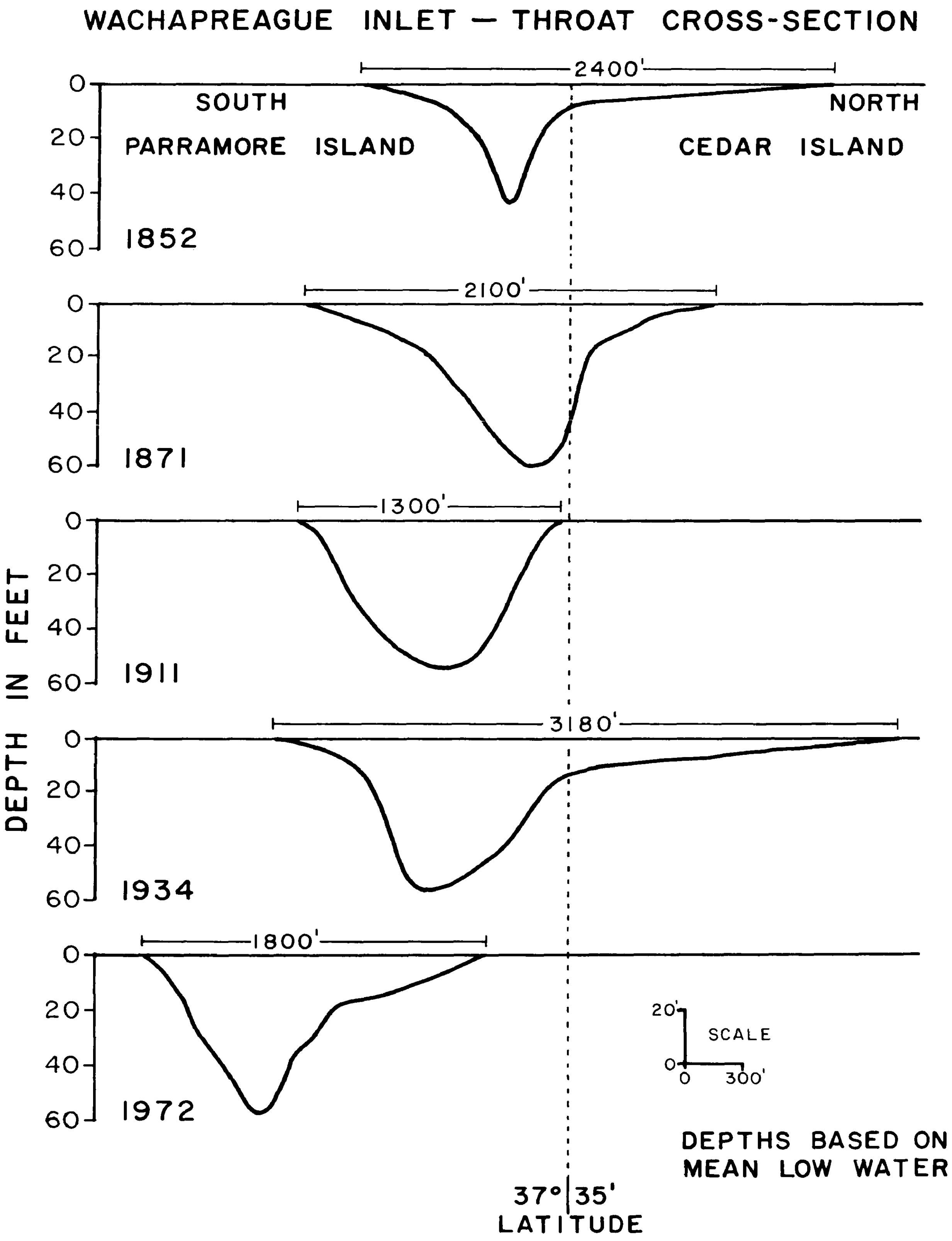
WACHAPREAGUE INLET
1972

BASED ON 1972 VIMS SURVEY
Depths in feet below mean tide level

Scale 1:10,000

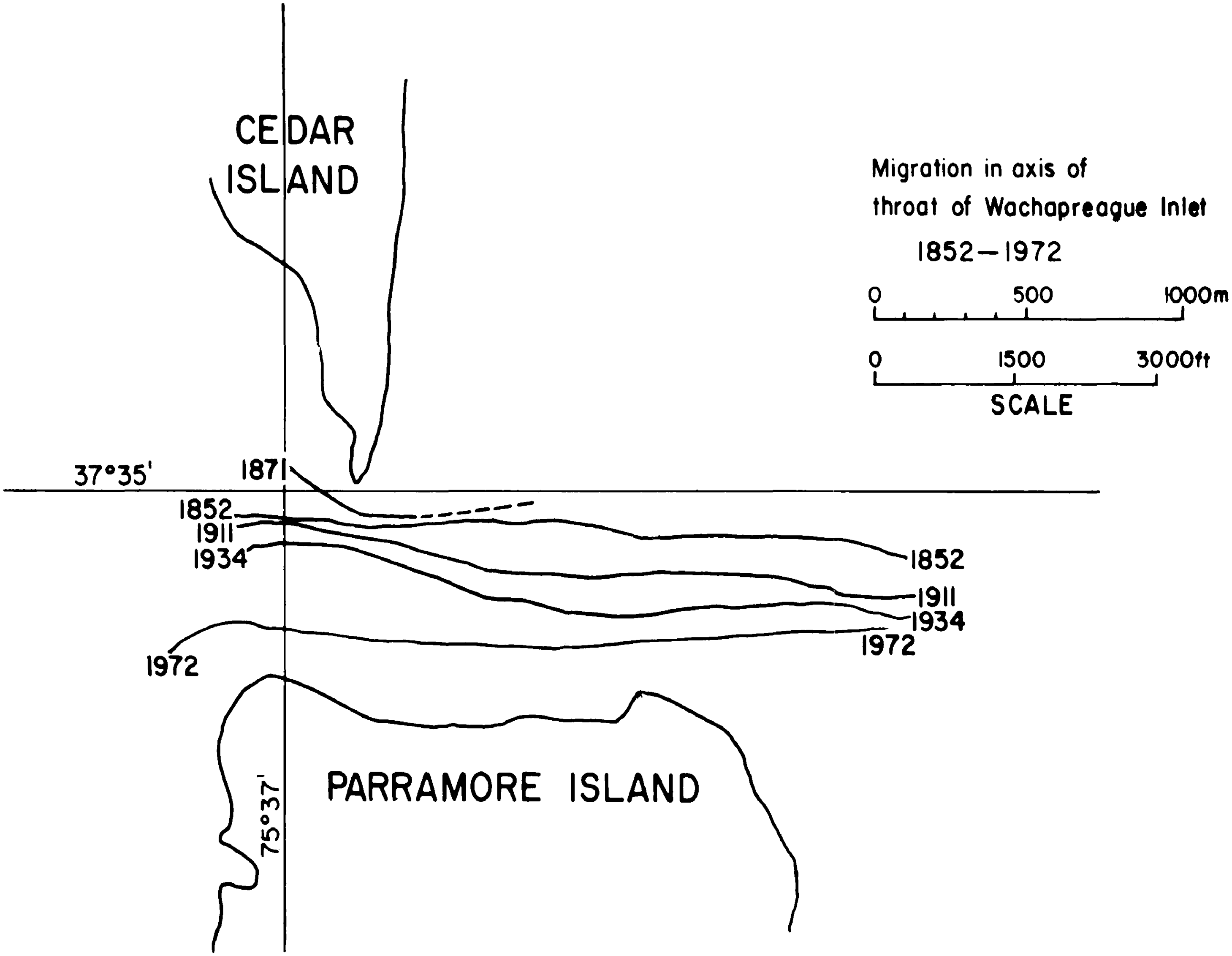
3' = .914 m.

Figure 9. Throat cross-sections, Wachapreague Inlet.



WACHAPREAGUE INLET — THROAT CROSS-SECTION
2400'
SOUTH
PARRAMORE ISLAND
NORTH
CEDAR ISLAND
1852
2100'
1871
1300'
1911
3180'
1934
1800'
1972
DEPTH IN FEET
0
20
40
60
SCALE
20'
0
300'
DEPTHS BASED ON MEAN LOW WATER
37° 35'
LATITUDE

Figure 10. Migration of Wachapreague Inlet channel axis (shoreline based on 1962 survey).



Migration in axis of throat of Wachapreague Inlet 1852—1972

Figure 11. Wachapreague Inlet, 1949.

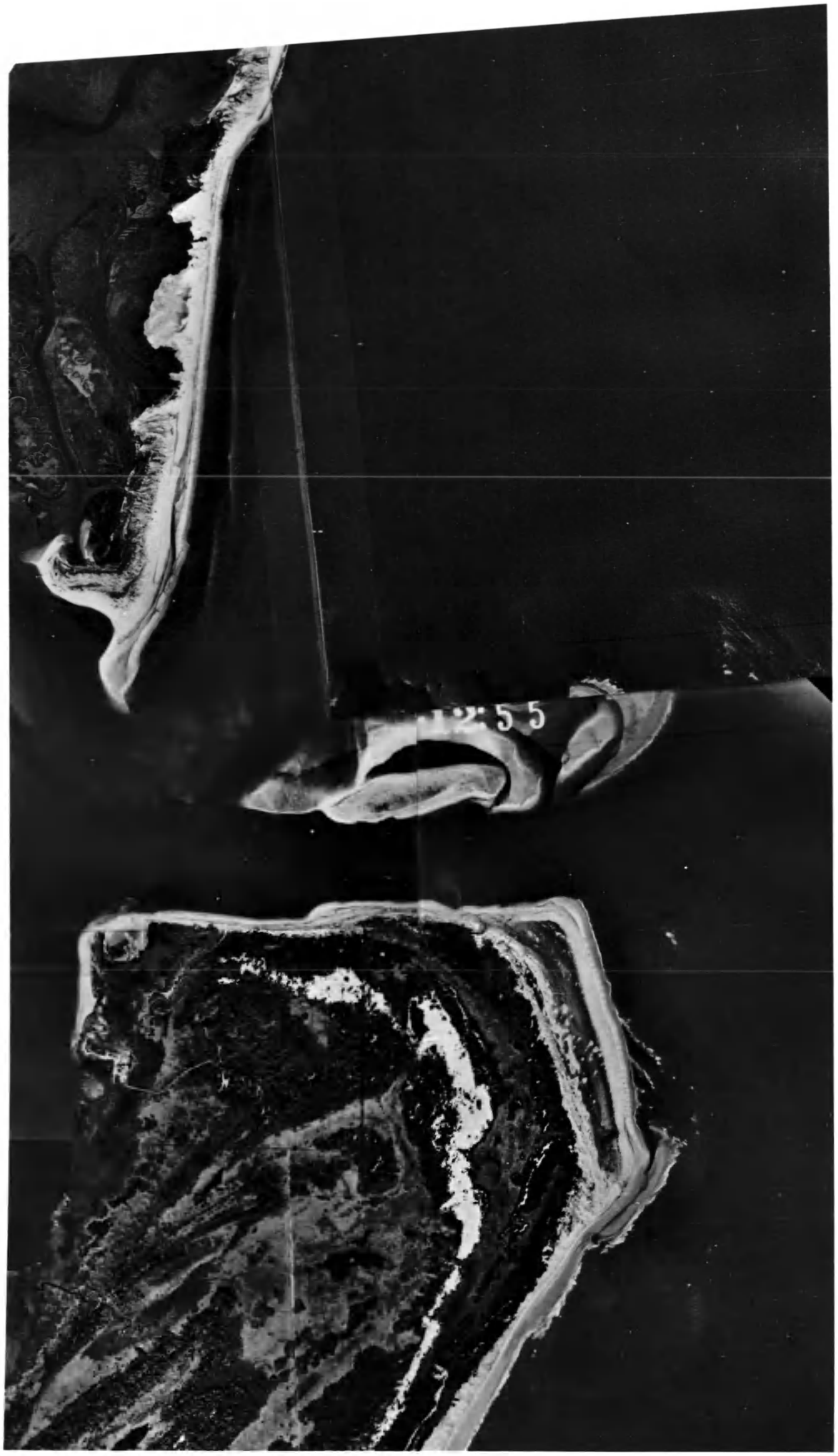

12:55

Figure 12. Wachapreague Inlet, 1957.

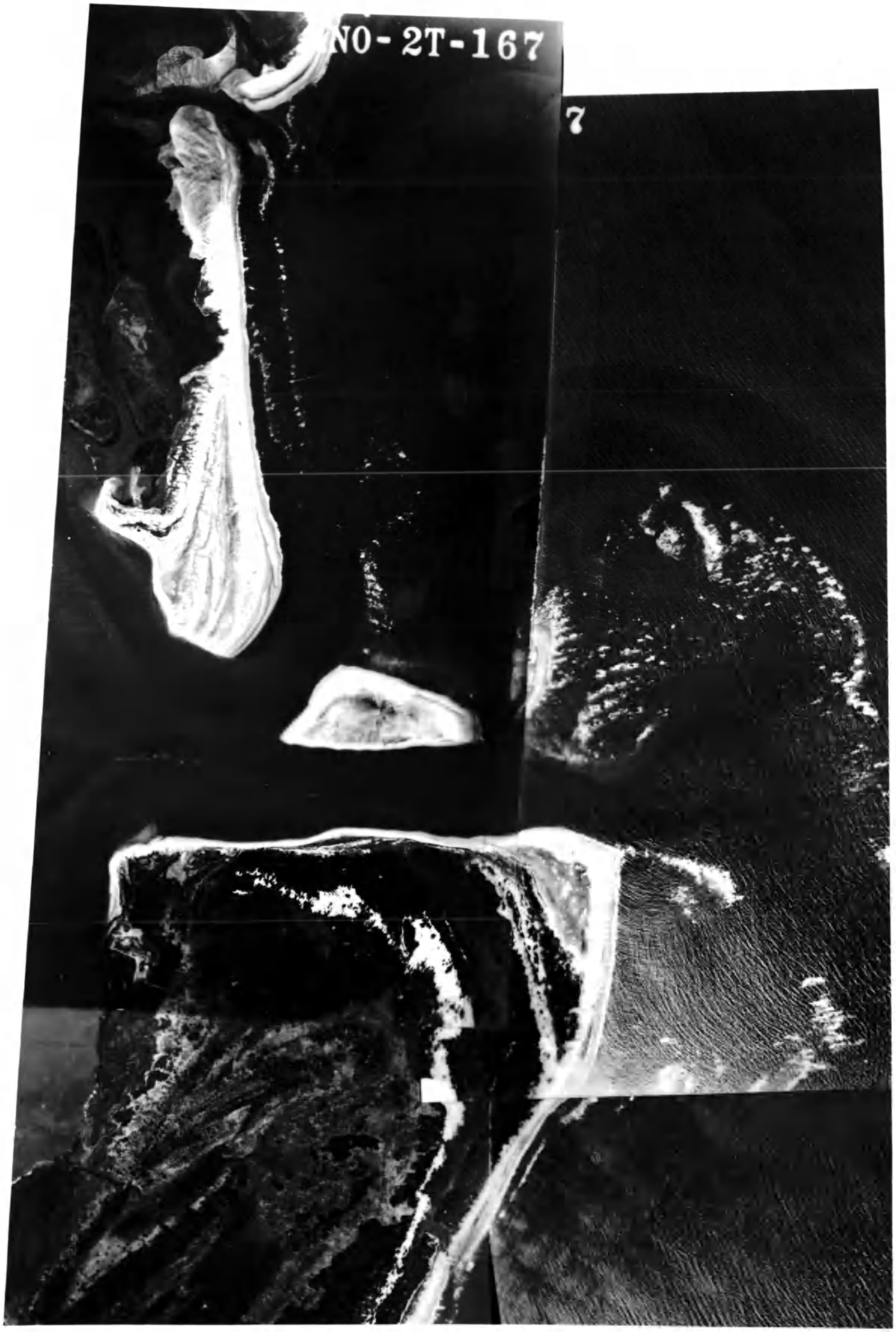

NO-2T-167
7

Figure 13. Wachapreague Inlet, April, 1962.

CGS 28 APR 62 W3877

Figure 14. Wachapreague Inlet, October, 1966.

Figure 15. Wachapreague Inlet, February, 1970, (2 hours after high water).

Figure 16. Wachapreague Inlet, June, 1971.

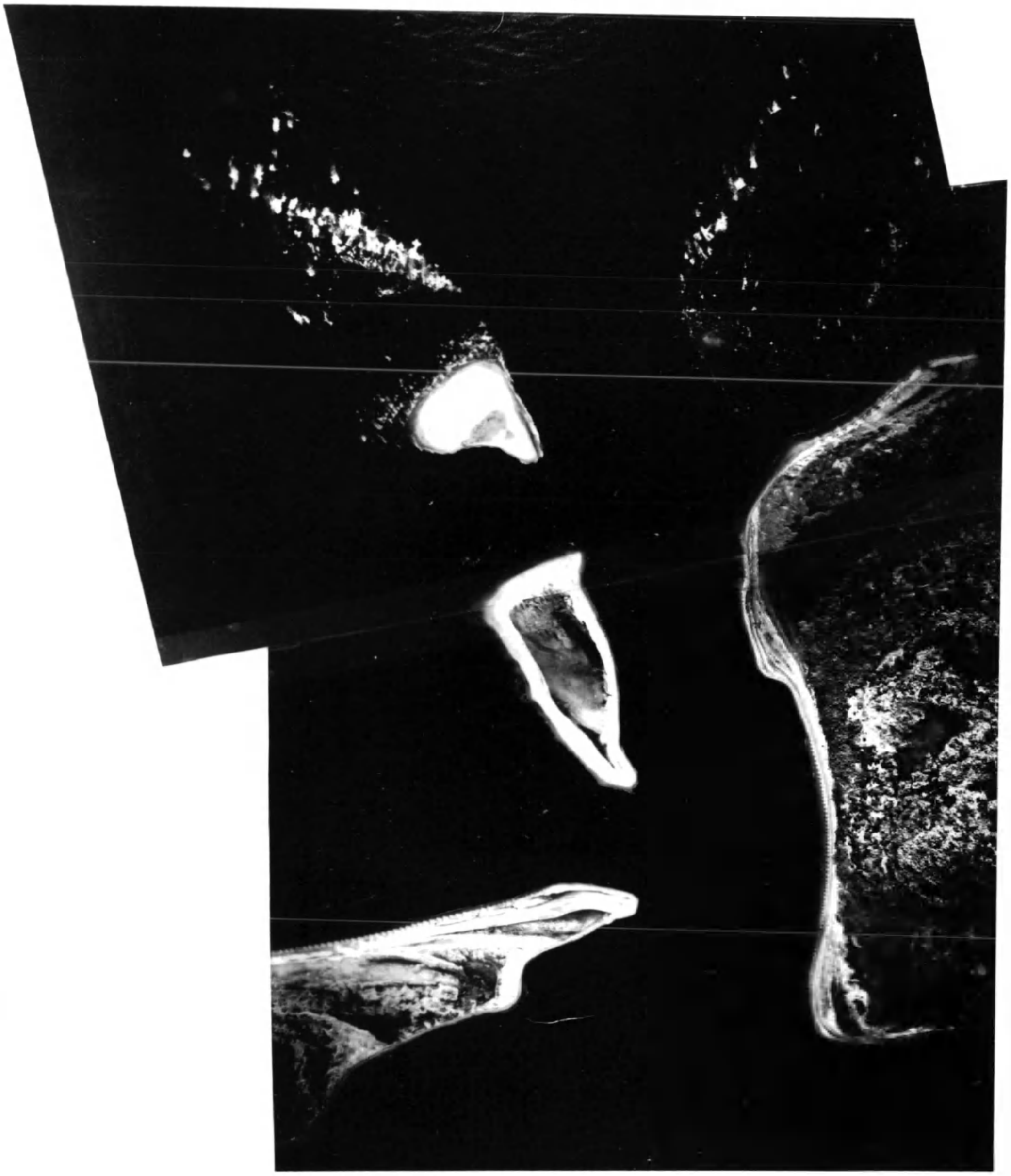


Figure 17. Wachapreague Inlet, September, 1971.

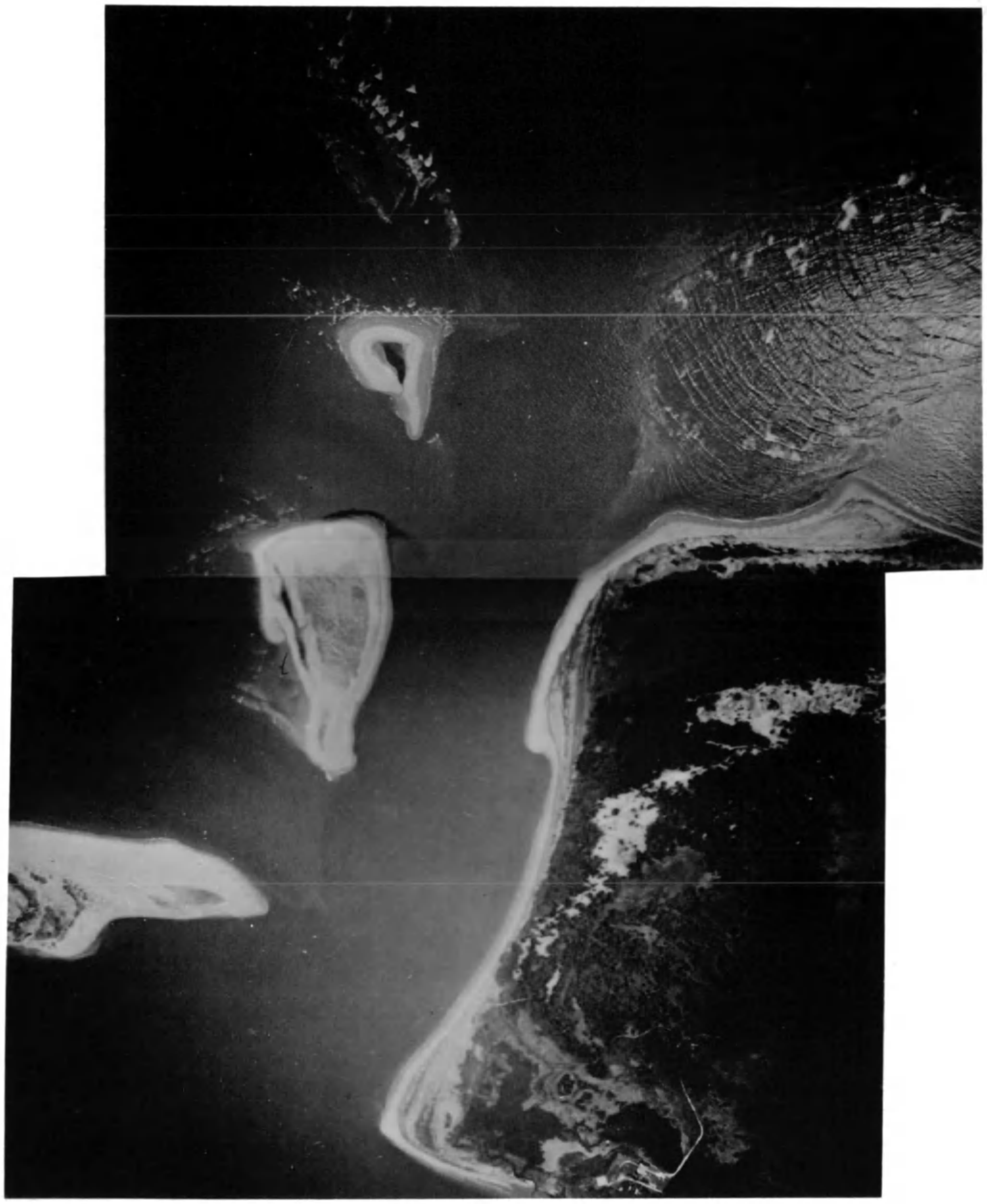


Figure 18. Wachapreague Inlet, November, 1971.

Figure 19. Wachapreague Inlet, February, 1972 (2 hours prior to low water).

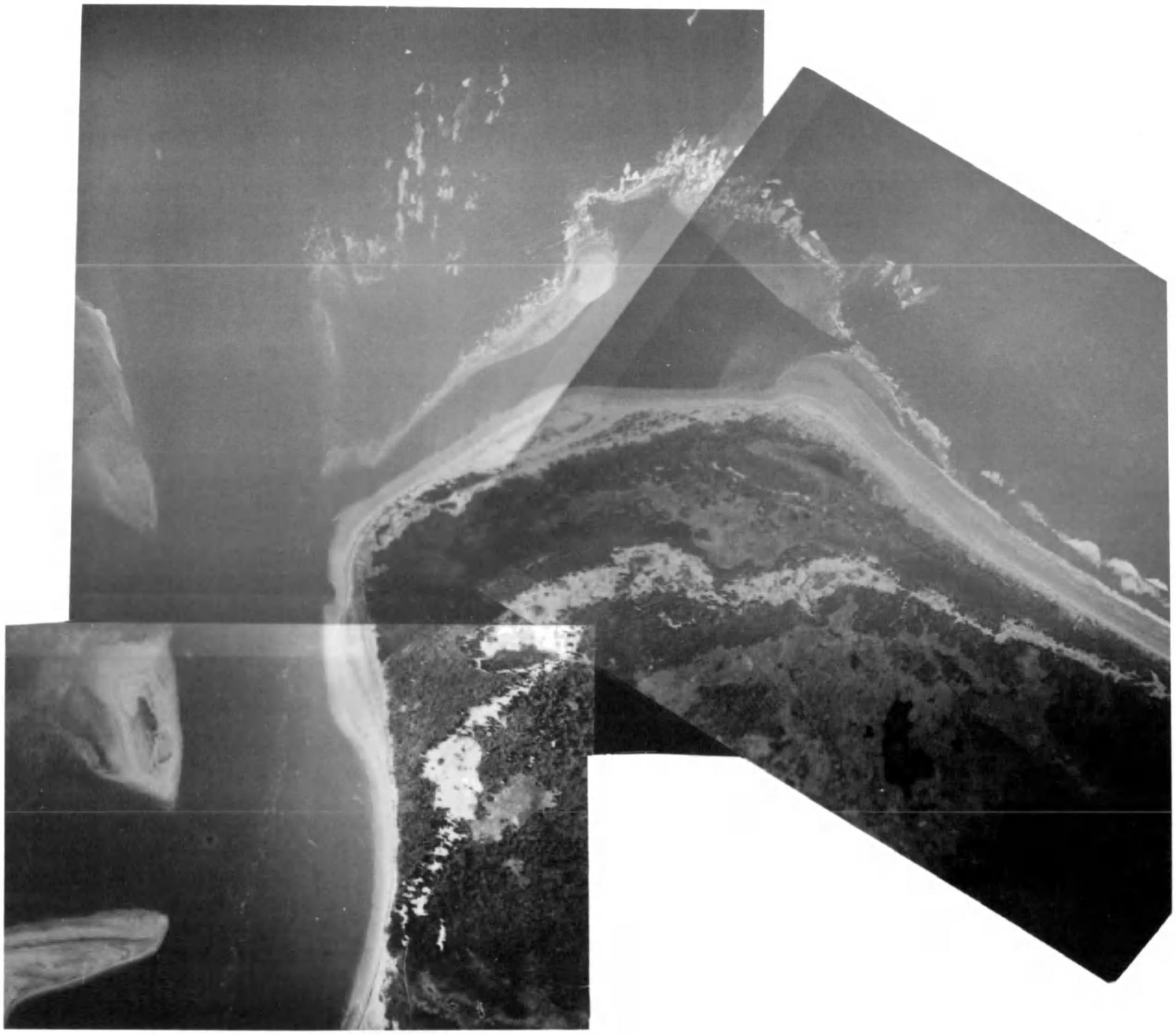


Figure 20. Wachapreague Inlet, September, 1972
(1 hour after high water).

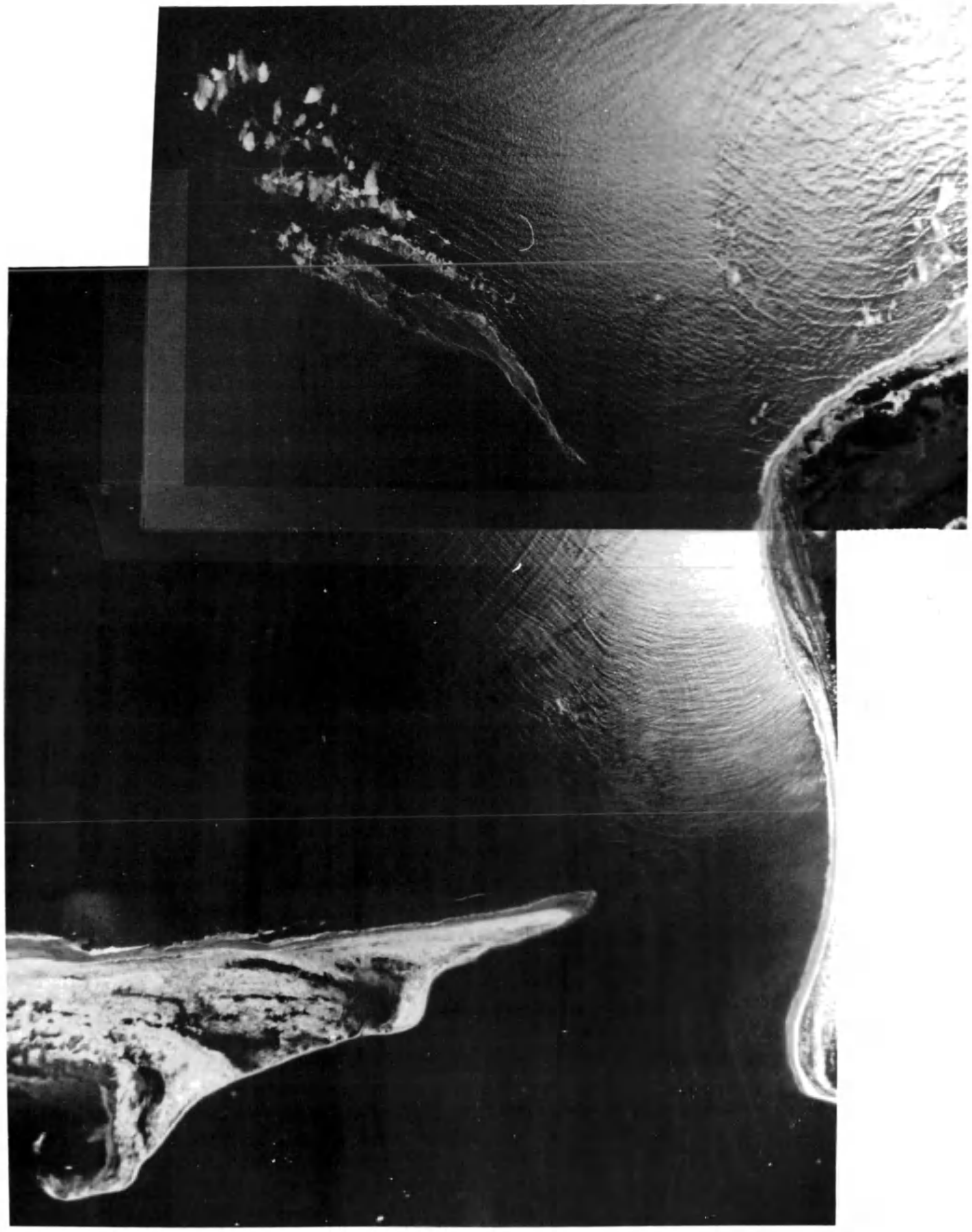


Figure 21. Wachapreague Inlet, November, 1972
(1 hour prior to low water).

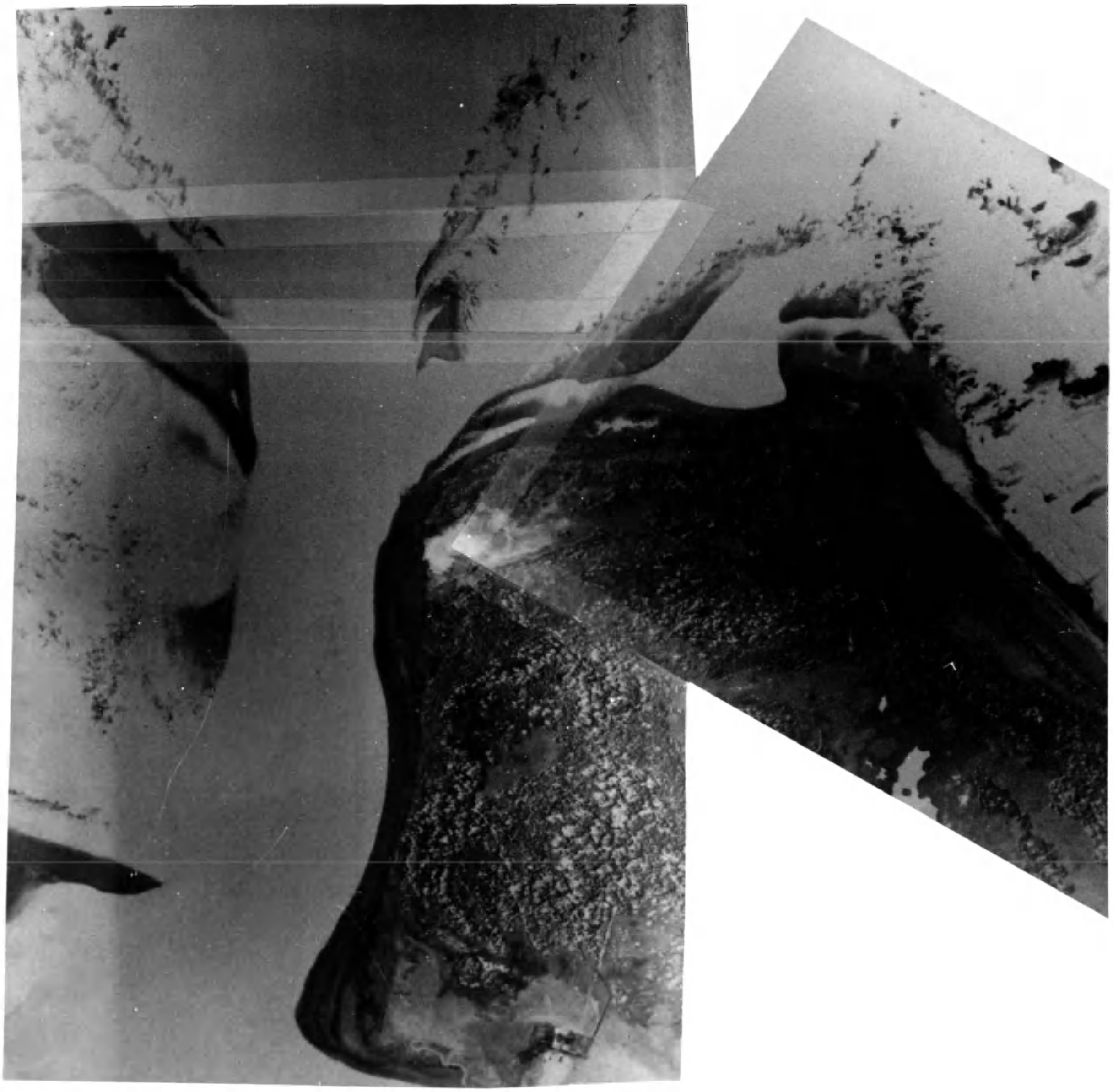


Figure 22. Wachapreague Inlet, July, 1973.

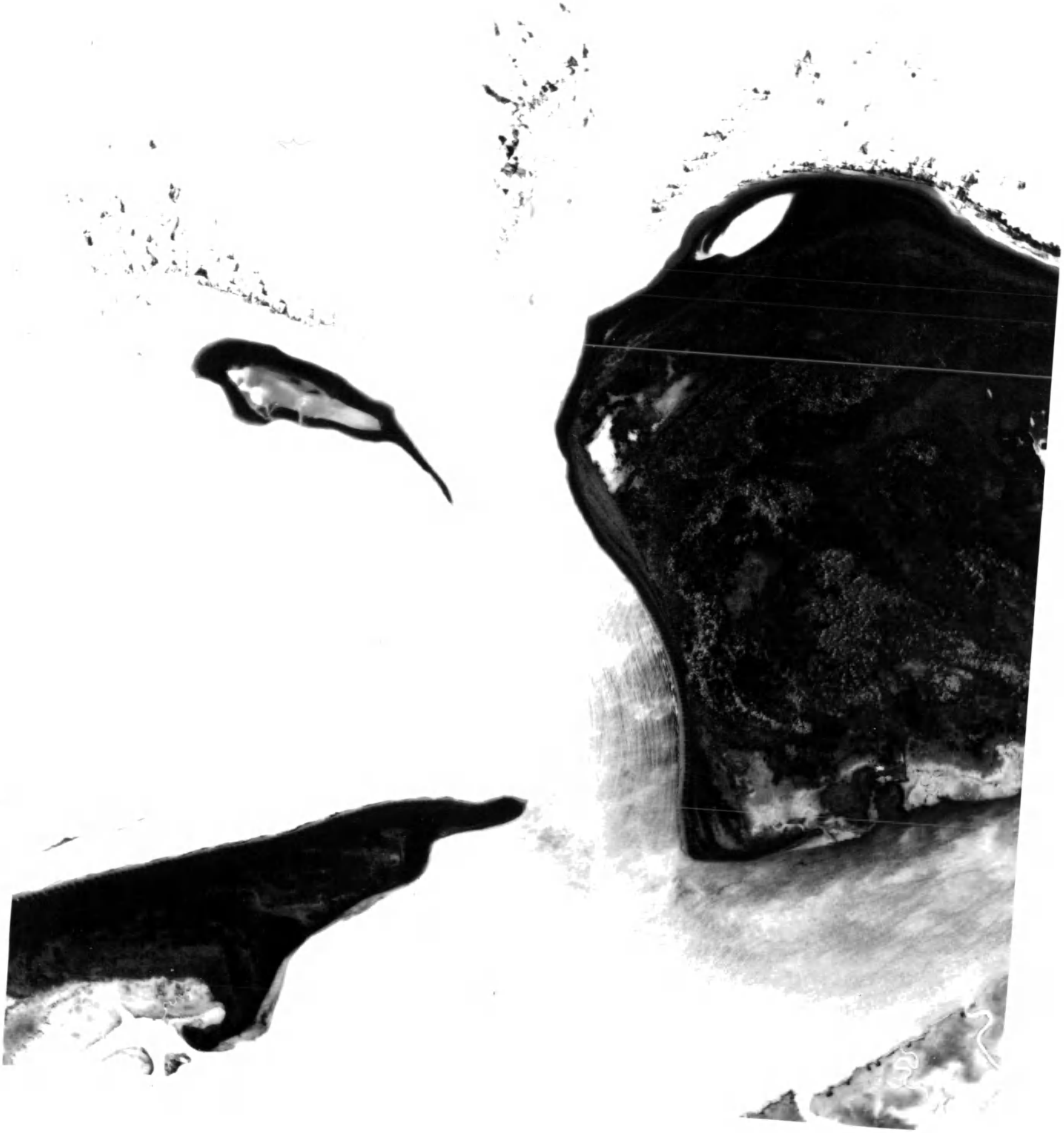
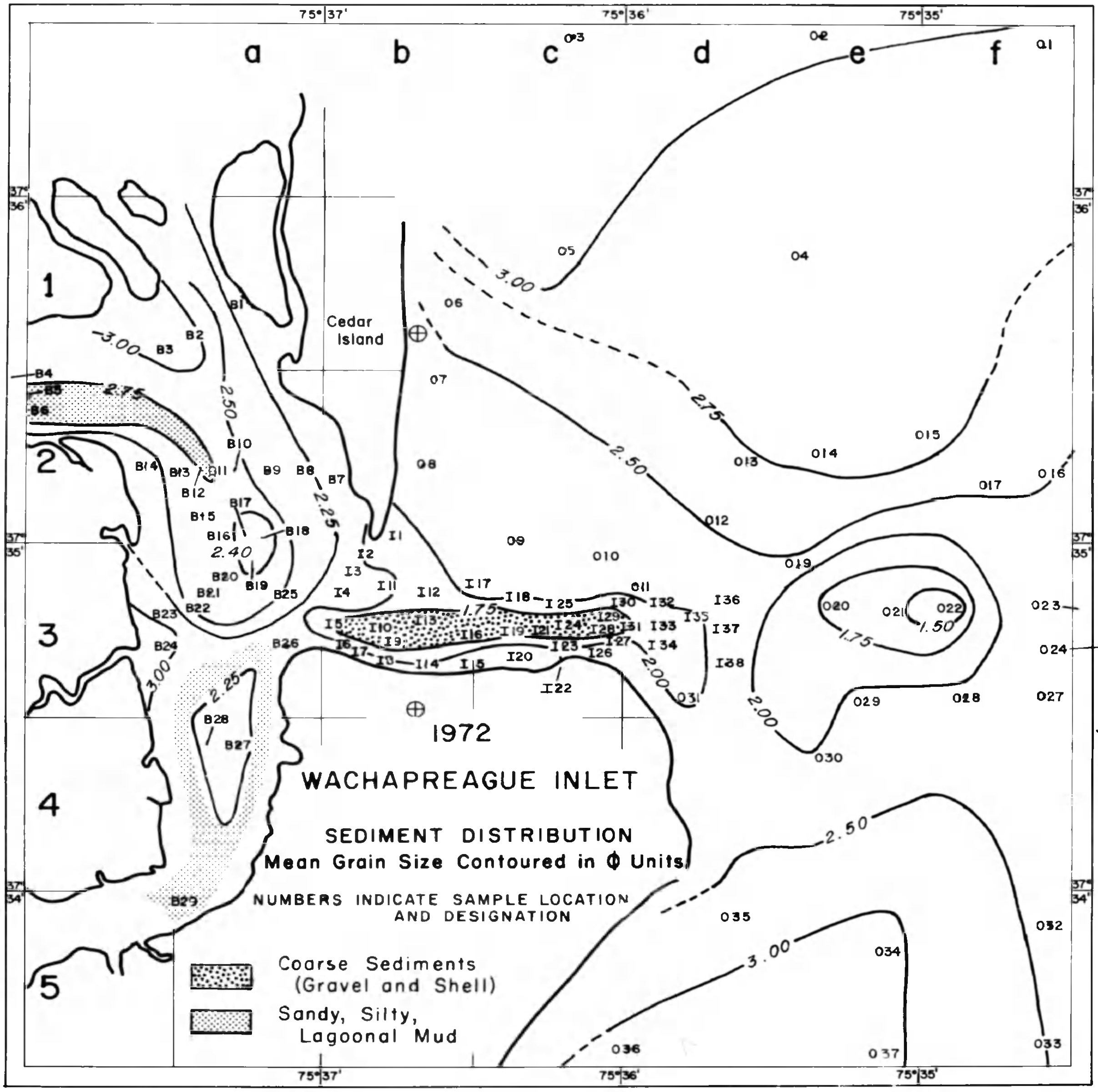


Figure 23. Mobile sediment distribution, Wachapreague Inlet, July, 1972.



1972
WACHAPREAGUE INLET
SEDIMENT DISTRIBUTION
Mean Grain Size Contoured in Φ Units
NUMBERS INDICATE SAMPLE LOCATION AND DESIGNATION
▨ Coarse Sediments (Gravel and Shell)
▨ Sandy, Silty, Lagoonal Mud
Cedar Island
75°37'
75°36'
75°35'
37° 36'
37° 35'
37° 34'
a
b
c
d
e
f
1
2
3
4
5
3.00
2.75
2.50
2.25
2.40
2.00
1.75
1.50
B1
B2
B3
B4
B5
B6
B7
B8
B9
B10
B12
B13
B14
B15
B16
B17
B18
B19
B20
B21
B22
B23
B24
B25
B26
B27
B28
B29
I1
I2
I3
I4
I5
I6
I7
I8
I9
I10
I11
I12
I13
I14
I15
I16
I17
I18
I19
I20
I21
I22
I23
I24
I25
I26
I27
I28
I29
I30
I31
I32
I33
I34
I35
I36
I37
I38
O1
O2
O3
O4
O5
O6
O7
O8
O9
O10
O11
O12
O13
O14
O15
O16
O17
O19
O20
O21
O22
O23
O24
O25
O26
O27
O28
O29
O30
O31
O32
O33
O34
O35
O36
O37

Figure 24. Short core from the inlet bottom at transect #2-2 in 62 ft water.

surface 20" deep

Note: a layer of gravels, sand and silt, over a very stiff sandy clay.

CORE 2-2

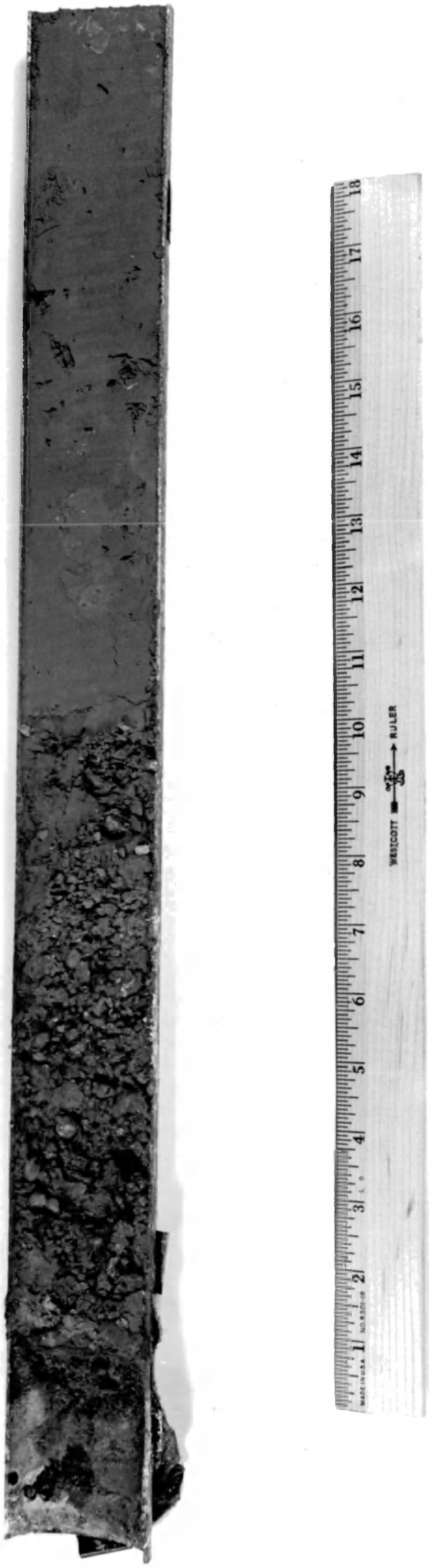


Figure 25. Short core from the inlet bottom at transect #3 in 58' of water.

26" deep surface

Note: 4" of gravels, sand and silt, over medium sands, then interspersed layers of stiff sandy, and silty clays.

T-3

Figure 26. A sediment sample carved from a mud outcrop on the south flank of the Wachapreague Inlet channel at transect #2-2.

T2-2
≈ 28'
INSITU

Figure 27. Mud ball taken from the south flank of Wachapreague Inlet, transect #2-2, at a depth of 40'.

T 2-2.
40 Ft.
Bottom Debris

Figure 28. Sub-bottom profile across Wachapreague Inlet throat, from north to south.

North South

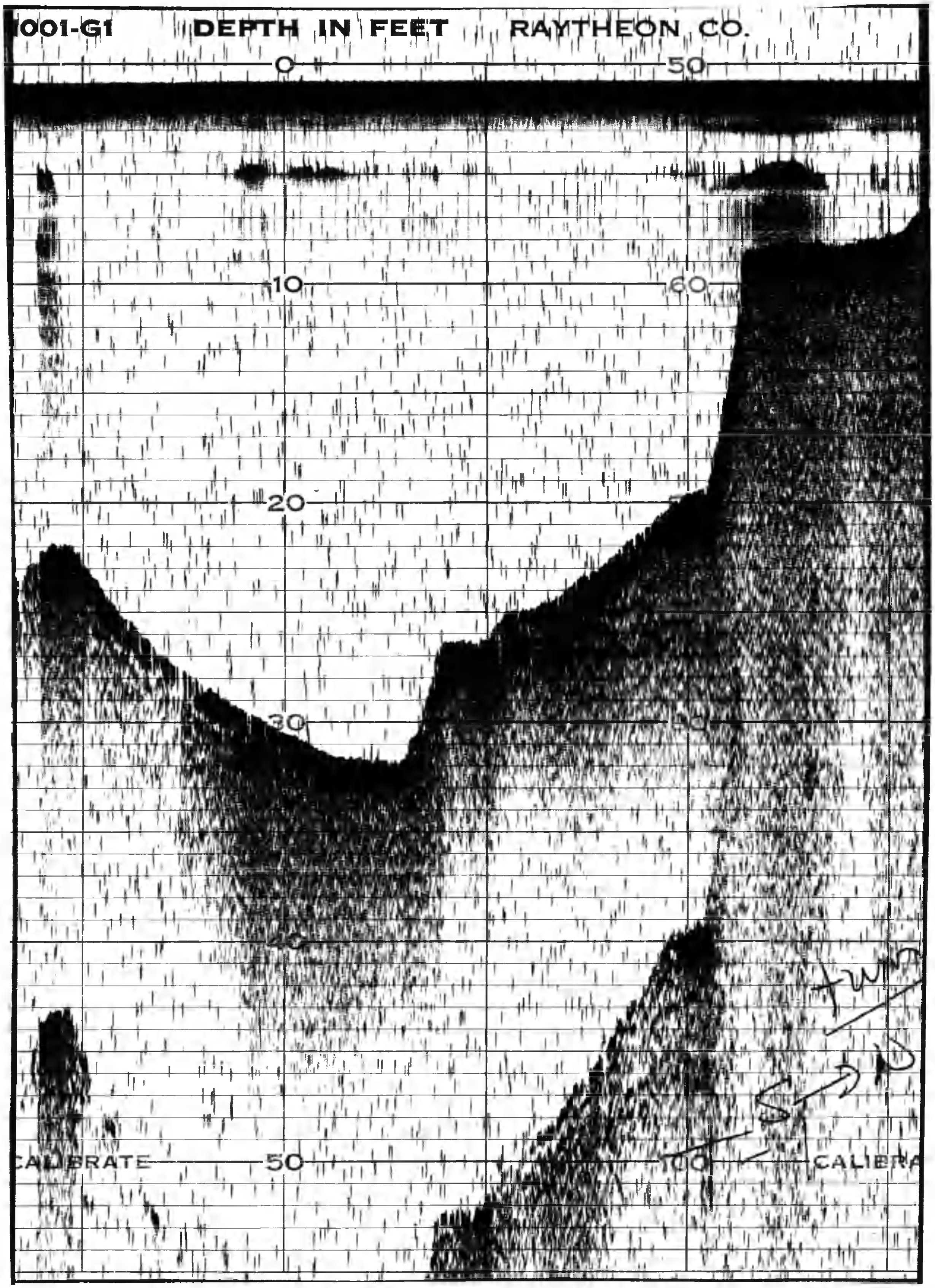
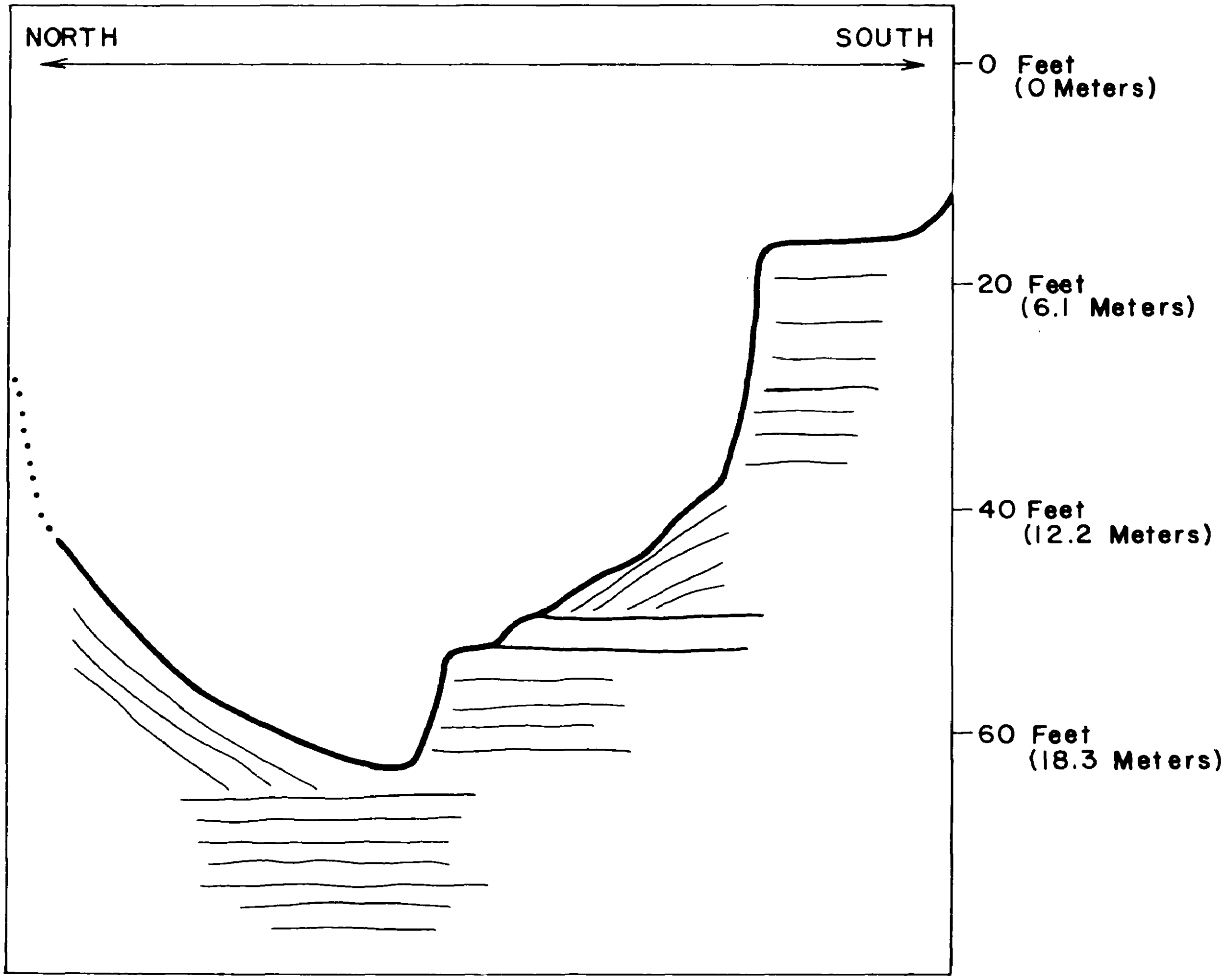

001-G1
DEPTH IN FEET
RAYTHEON CO.
0
50
10
60
20
30
40
CALIBRATE
50
100
CALIBRA
twin
S

Figure 29. Interpretation of sub-bottom profile of Wachapreague Inlet throat cross-section.



WACHAPREAGUE INLET
THROAT CROSS-SECTION - 1972
CEDAR ISLAND TO PARRAMORE ISLAND
INTERPRETATION OF SUB-BOTTOM PROFILE

Figure 30. Sub-bottom profile in a portion of Horseshoe Lead, a tidal channel landward of Parramore Island.

East West

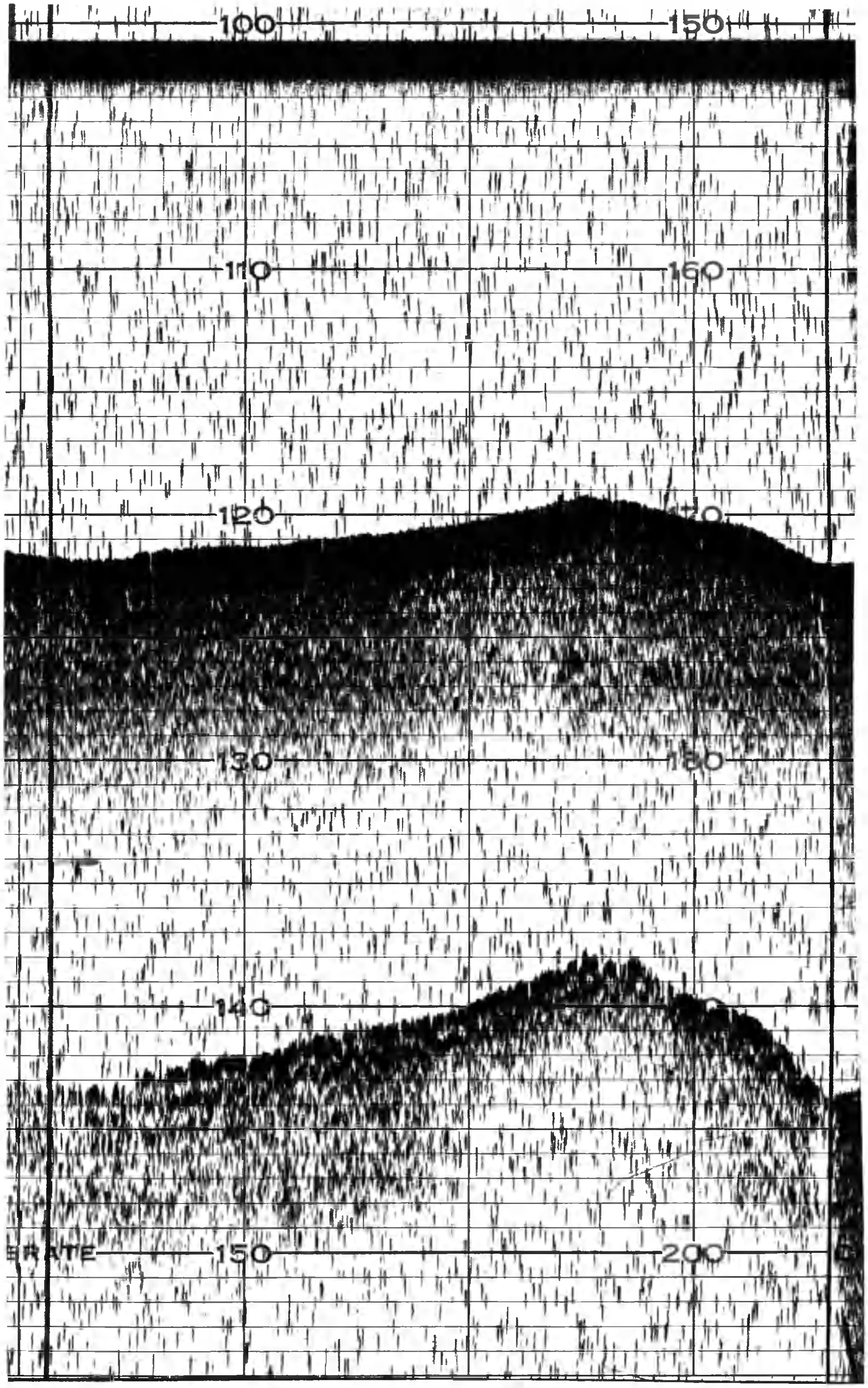
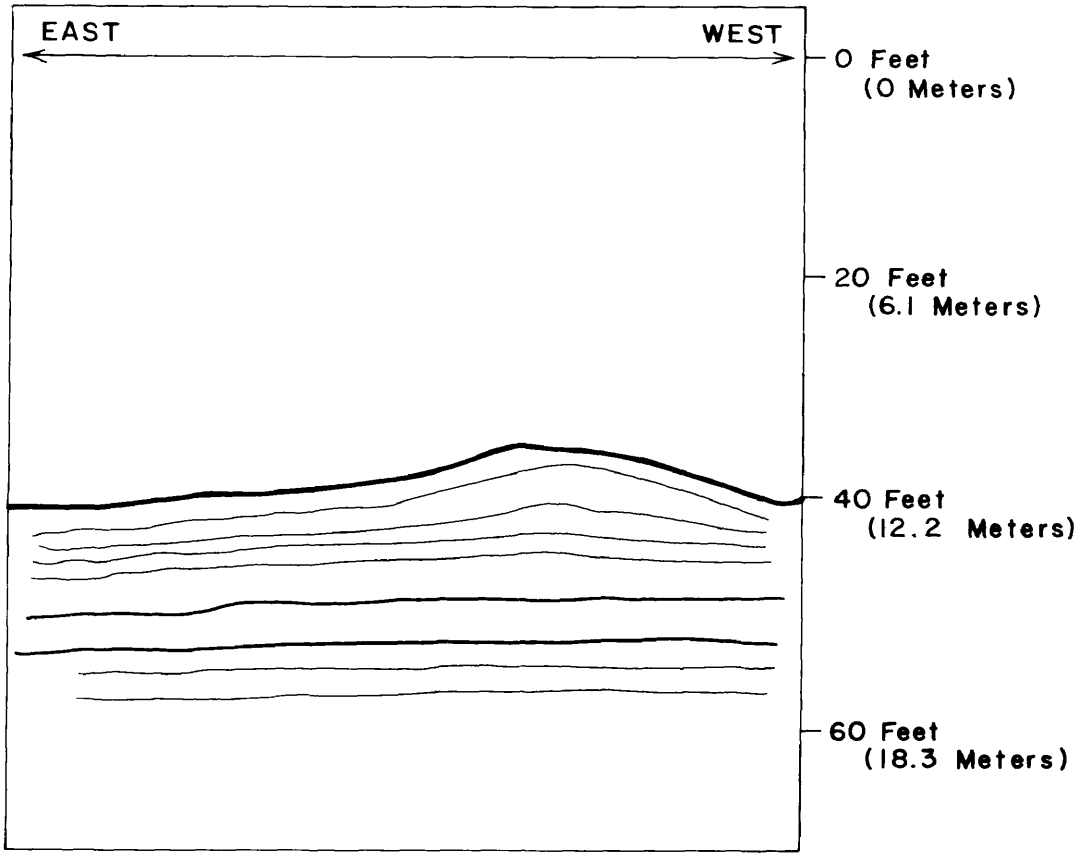

100
150
110
160
120
170
130
180
140
190
ERATE
150
200

Figure 31. Interpretation of sub-bottom profile.

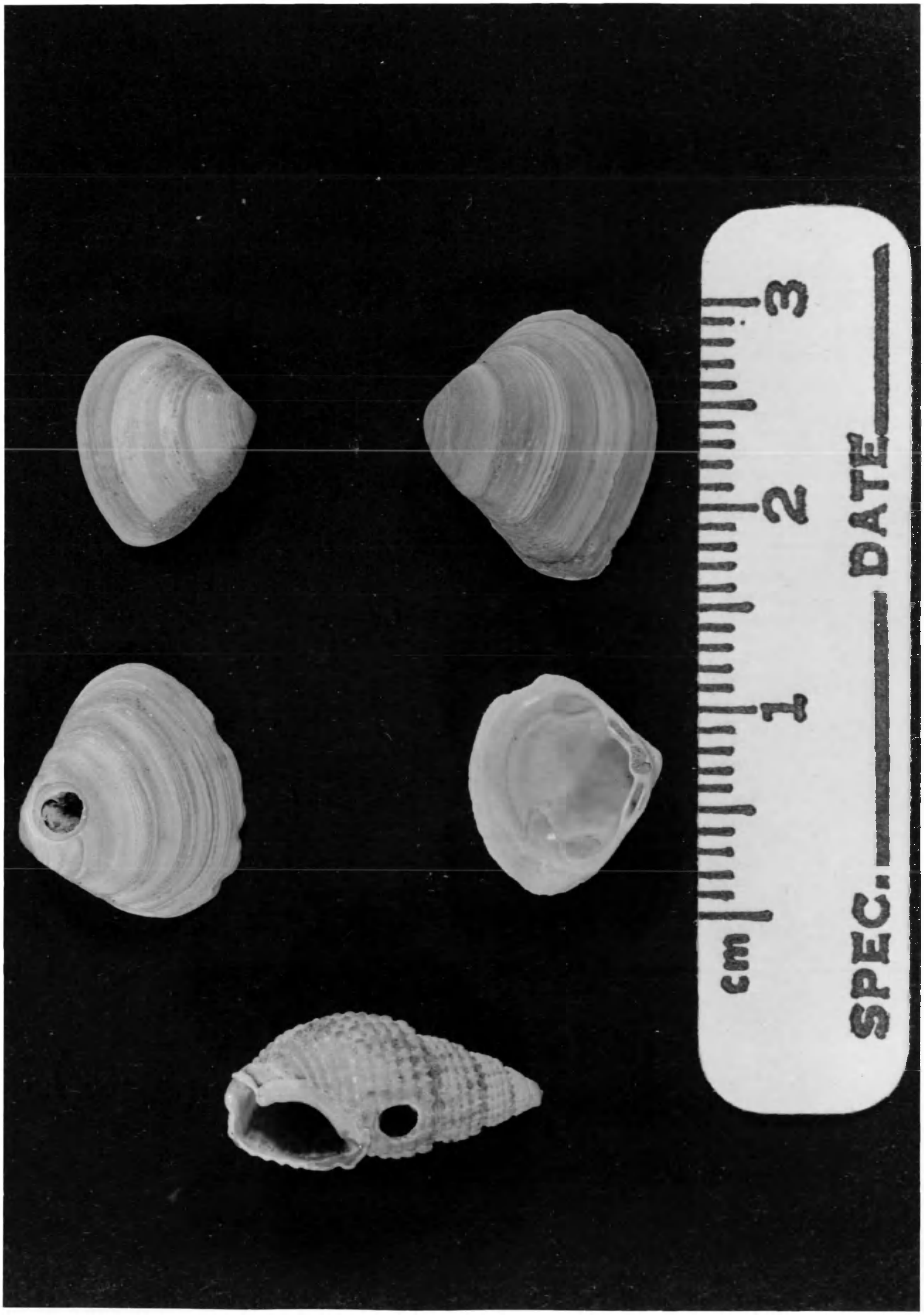


HORSESHOE LEAD, WACHAPREAGUE, VA.
INTERIOR CHANNEL CROSS SECTION 1972
INTERPRETATION OF SUB-BOTTOM PROFILE

Figure 32. An assemblage of shells taken from a horizon 25 ft (7.6 m) below M.T.L. along the south flank of the inlet channel at transect #7, similar to those taken at 20' (6.1 m) at transect #2-2, and dated at 3490 years B.P.


T-7
25'
WESTCOTT RULER

Figure 33. An assemblage of shells taken from the Parramore Island well log at horizons 15 m and 20 m below M.T.L.


cm
1
2
3
SPEC.
DATE

APPENDIX I

```
C       DEALTERIS  SEDIMENT ANALYSIS
C       PROGRAM TO READ DRY WIEGHTS AT QUARTER PHI INTERVALS, CONVERT TO PERCENTS,
C       THEN CUMULATIVE PERCENTS, THEN PHI PERCENTILES, THEN
C       DETERMINE THE GRAPHIC PARAMETERS AS DESCRIBED BY FOLK & WARD, 1957.
C       I(1)=-1.0 PHI, I(2)=0.0 PHI, I(3)=.25,I(4)=.50,I(5)=.75, I(6)=1.00
C       I(7)=1.25,I(8)=1 50,I(9)=1.75,I(10)=2.00,I(11)=2.25,I(12)=2.50
C       I(13)=2.75,I(14)=3.00,I(15)=3.25,I(16)=3.50,I(17)=3.75
C       I(18)=4.00,I(19).GT.4.00 , I(20)= OPEN
        REAL M,GK
        DIMENSION  WGS(20), PCT(20), CUMPT(20),NO(9),PPT(9) ,PHI(20)
     99 CONTINUE
        DO 100 I= I,20
        CUMPT(I) =0.0
        WGS (I) =0.0
        PCT (I) =0.0
    100 CONTINUE
        PHI(1)= -1.0
        PHI(2)=0.0
        DO 88 I=3,20
        PHI(I)=PHI(I-1)+0.25
     88 CONTINUE
        READ(2,2)  (WGS(I), I=1,10) ,A1,A2,A3,A4,A5,A6
        READ(2,2) (WGS(I), I=11,20)
      2 FORMAT (10F6.2,7X,6A2)
        WRITE (5,69) A1,A2,A3,A4,A5,A6
     69 FORMAT (1H1,    '      THE SAMPLE DESIGNATION IS    ' ,  6A2)
        TOTAL=0.0
        DO 101 I=1,20
        TOTAL = TOTAL+WGS(I)
    101 CONTINUE
        DO 102 I=1,20
        J=I-1
        PCT (I) = WGS(I)/TOTAL*100
        IF (I-1)  37,37,38
     37 CUMPT(I)=PCT(I)
        GO TO  39
     38 CONTINUE
        CUMPT(I)=CUMPT(J)+PCT(I)
     39 CONTINUE
        WRITE (5,3)  I,WGS(I), PCT(I), CUMPT(I)
      3 FORMAT  (1X,I2,10X,F6.2,10X,F6.2,10X,F6.2)
    102 CONTINUE
        NO(1)=05
        NO(2)=10
        NO(3)=16
        NO(4)=25
        NO(5)=50
        NO(6)=75
        NO(7)=84
        NO(8)=90
        NO(9)=95
        DO 103 K=1,9
        DO 104 I=1,20
        IF(CUMPT(I)-NO(K)) 104,27,26
     26 IF (I-1)28,30,28
     27 KY=I
        GO TO 31
     28 KY=I
        GO TO 32
    104 CONTINUE
```

```
 30 PPT(K)=999.0
    GO TO  103
 31 PPT(K)= PHI(KY)
    GO TO 103
 32 X1 = NO(K)-CUMPT(KY-1)
    X2 = CUMPT(KY)-CUMPT (KY-1)
    FWD= X1 /X2
    PPT(K)= PHI(I-1)+FWD*0.25
103 CONTINUE
    DO 170 I=1,9
    WRITE(5,4) NO(I), PPT(I)
  4 FORMAT ( 1X,I2,1X,'PERCENT', 10X, 'PHI SIZE',2X, F6.2)
170 CONTINUE
    M=( PPT(3) + PPT(5)+PPT(7))/3.0
    SD= (PPT(7) -PPT(3))/4.0 + (PPT(9)-PPT(1))/6.6
    AA=(PPT(3)+PPT(7)-2.0*PPT(5))/2.0*(PPT(7)-PPT(3))
    BB=(PPT(1)+PPT(9)-2.0*PPT(5))/2.0*(PPT(9)-PPT(1))
    SK=AA/BB
    GK=(PPT(9)-PPT(1))/2.44*(PPT(6)-PPT(4))
    WRITE(5,11)M
 11 FORMAT(1X,'THE MEAN IS',10X,F6.3)
    WRITE(5,12)SK
 12 FORMAT(1X,'INCLUSIVE GRAPHIC SKEWNESS IS',10X, F6.3)
    WRITE(5,13) SD
 13 FORMAT (1X,'STANDARD DEVIATION IS' ,10X, F6.3)
    WRITE (5,14) GK
 14 FORMAT (1X,'GRAPHIC KURTOSIS',10X, F6.3)
    GO TO 99
999 CONTINUE
    END
```

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