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An Investigation of the Late Quaternary Morphology of Mobjack Bay, VA and Application of a Facies Model

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AN INVESTIGATION OF THE LATE QUATERNARY MORPHOLOGY OF MOBJACK BAY, VA AND APPLICATION OF A FACIES MODEL

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ABSTRACT

Analyses of a closely-spaced network of high-resolution seismic records taken within Mobjack Bay, VA reveal several deep paleochannels as well as a complex fill pattern resulting from the infilling of a drowned river valley. These paleochannels, which are the precursors of the modern day North, Ware, and Severn Rivers, converged in Mobjack to form a single channel that was incised approximately 30 meters below present sea level into Tertiary material during the last glaciation.

Three Holocene transgressive fill sequences were identified: Unit Q1 is the basal, fluvial sequence deposited when stream gradients decreased; Unit Q2 is believed to be restricted estuarine deposits consisting of fine sand and mud; Unit Q3 is the modern sequence deposited during the relatively smooth sea level rise of the past 3,500 years.

Due to the relatively low intensity of wave, tide, and riverine energy in Mobjack Bay, the application of a facies model, which is based on two end-members influenced by moderate to high intensity wave and tidal forces, was not conclusive. However, seismic records may indicate the predominance of tidal forces over wave energy during the process of infilling prior to the overtopping of the channel banks by sea level. In the last 3,500 years of continuous, slow sea level rise, waves probably have had more effect on the morphology of Mobjack than tides.

Since the marine transgression began at the end of the last glaciation, Mobjack Bay has become a sink. Sediments transported along the western flank of the Chesapeake Bay and from the continental shelf are deposited in Mobjack. Eroded material from the shoreline do not appear to leave the Bay, but are instead deposited on shoals while muds carried by the four small rivers entering Mobjack are deposited in the deeper, central portion of the bay.

AN INVESTIGATION OF THE LATE QUATERNARY MORPHOLOGY OF MOBJACK BAY, VA AND APPLICATION OF A FACIES MODEL

I. INTRODUCTION

General Statements

This study of the formation and preservation of Late Quaternary paleochannels and depositional sequences in Mobjack Bay, which is located in the Virginia portion of Chesapeake Bay (Figure 1), is part of the overall investigation of the evolution of the Chesapeake Bay.

The Chesapeake Bay is a dynamic, continually evolving system that has become a very important natural resource. Increased awareness of the Bay's complex network of processes has prompted many studies to decipher the puzzle. The interpretation of Quaternary deposits is essential to the understanding of earlier deposits all of which can then become an analog to modern processes by assuming modern processes were operating at the time of deposition. We are able to use Late Quaternary deposits because sea level fluctuations are fairly well understood for this time period and can be correlated to subbottom deposits. Also, the relative shallowness of the deposits are within the resolution of current equipment.

An important consideration is the effect tributaries, as sources or sinks, have on sedimentation processes in Chesapeake Bay. Colman and Hobbs (1987) postulated that the sedimentation processes involved in the formation of each generation of the Susquehanna fluvial channel\Chesapeake Bay due to marine regressions and transgressions are still working in the present bay. An integral part of this is the antecedent geologic systems upon which present systems form and migrate.

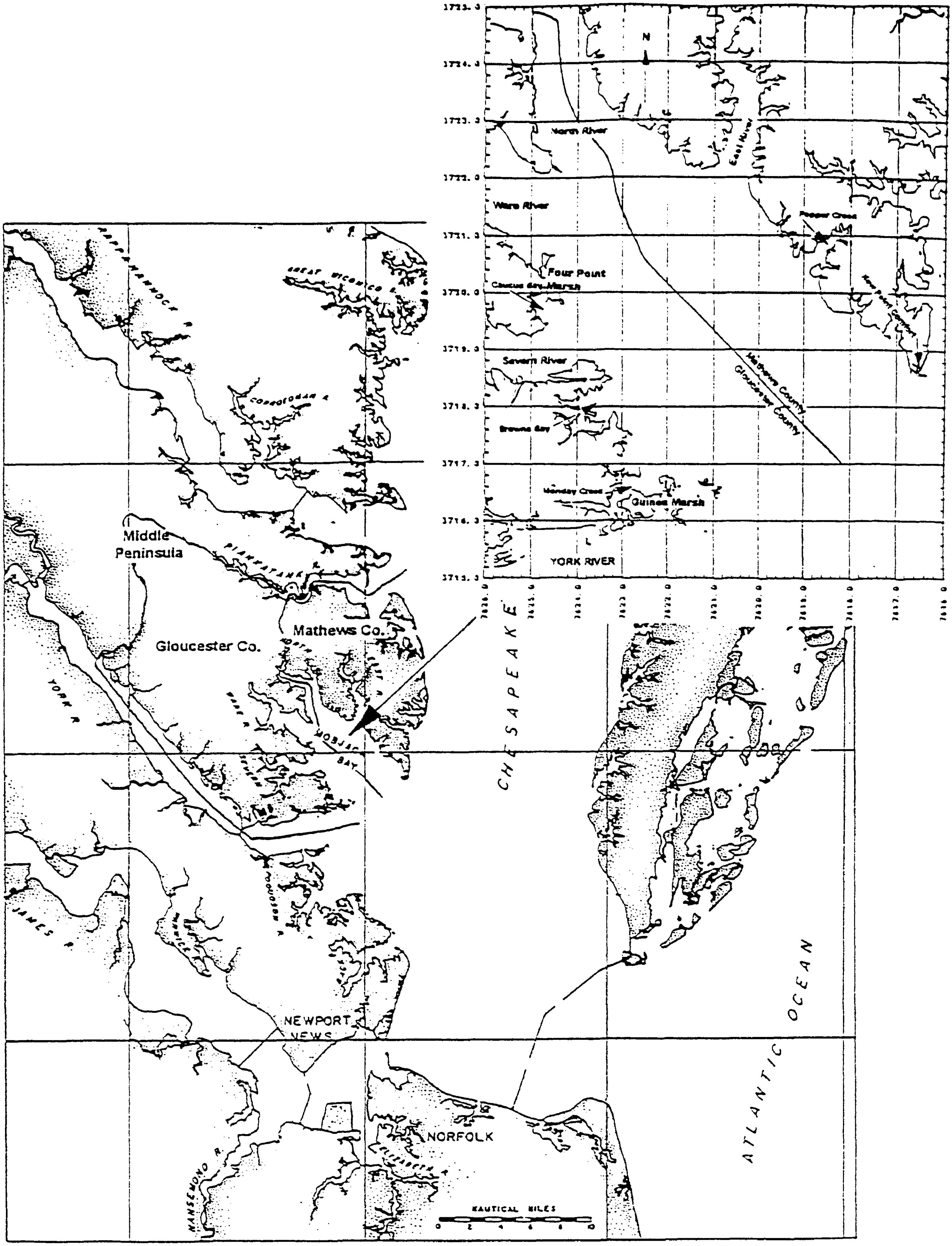


Figure 1. Location of study area.

While studies have clearly delineated the paleogeology of the main portion of the Chesapeake Bay (Colman *et al.* 1990; Halka *et al.* 1989; Colman and Hobbs 1987), few studies in the southern bay have included any tributaries or embayments, particularly, Mobjack Bay. Colman and Hobbs (1987) mapped a drainage channel that formed during the last glaciation and branched off from a Susquehanna River paleochannel to the mouth of Mobjack Bay, but they did not actually trace the channel into the bay (Figure 2).

Stratigraphy Resulting from Sea Level Oscillations

Late Tertiary and Quaternary paleogeology is recorded in sediment deposited under conditions analogous to modern-day processes. In general, the landward limit of a marine transgressive sequence is a shoreline feature, such as an erosional scarp or beach, whereas a level or gently inclined terrace develops seaward of the paleo-sea level position (Figure 3). This system of erosional scarps and terraces is progressively lower and younger both seaward and toward major rivers (Peebles, 1984).

Due to the emergence and subsequent erosion of deposits during a marine regression, each stratigraphic unit is separated from others by unconformities. Channels, created by water flows transporting sediment during periods of lowered sea level, are incised into older sediments creating the lower unconformity while subaerial erosion dissects the coastal plain. This creates a landscape with flat to rolling interfluves between incised streams (Peebles, 1984)

As sea level rises, stream gradients decrease such that coarse lag deposits accumulate in the main channel and change laterally into crossbedded

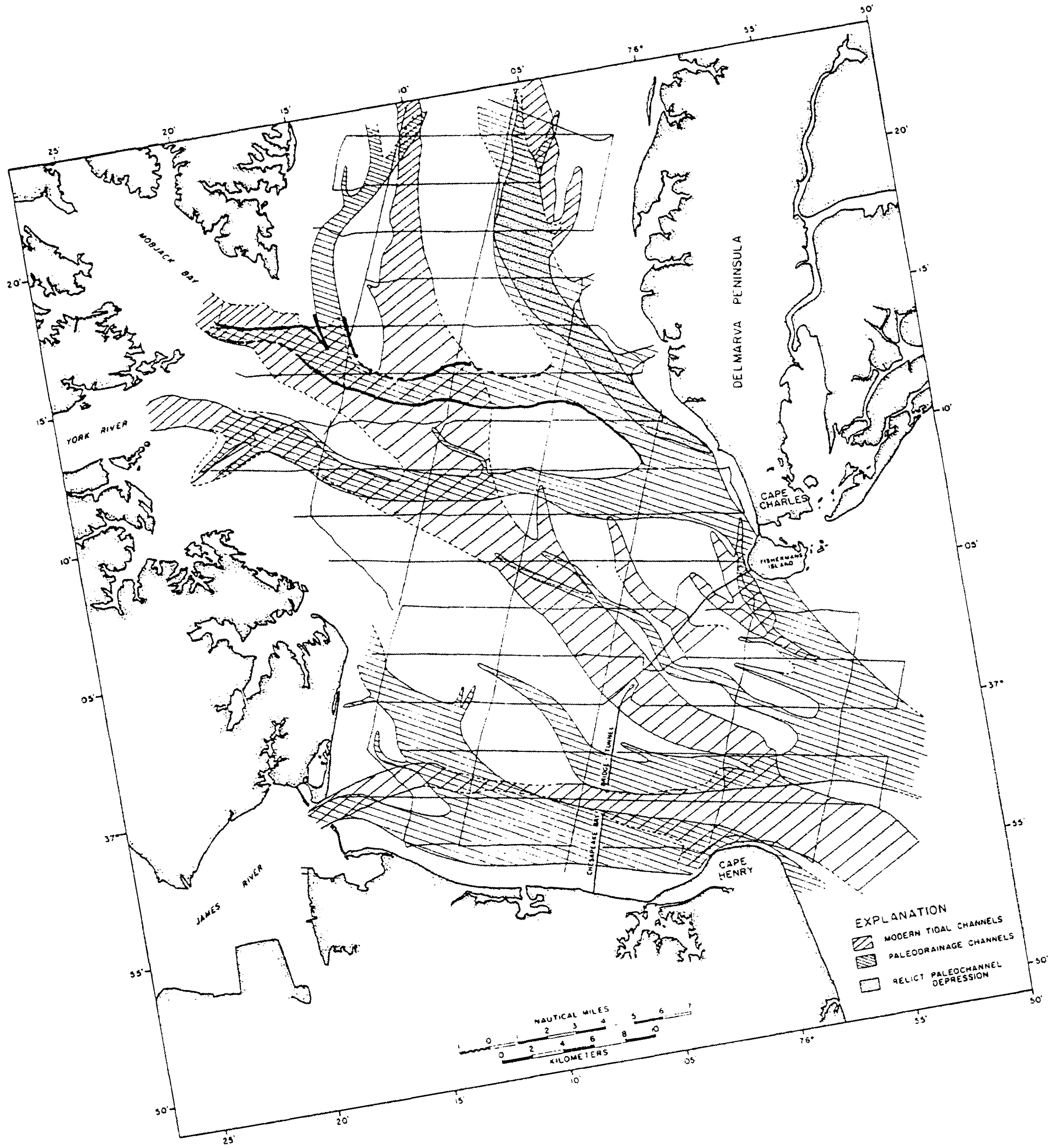


Figure 2. Previously mapped Mobjack Bay paleo-drainage channel (Colman and Hobbs, 1987).

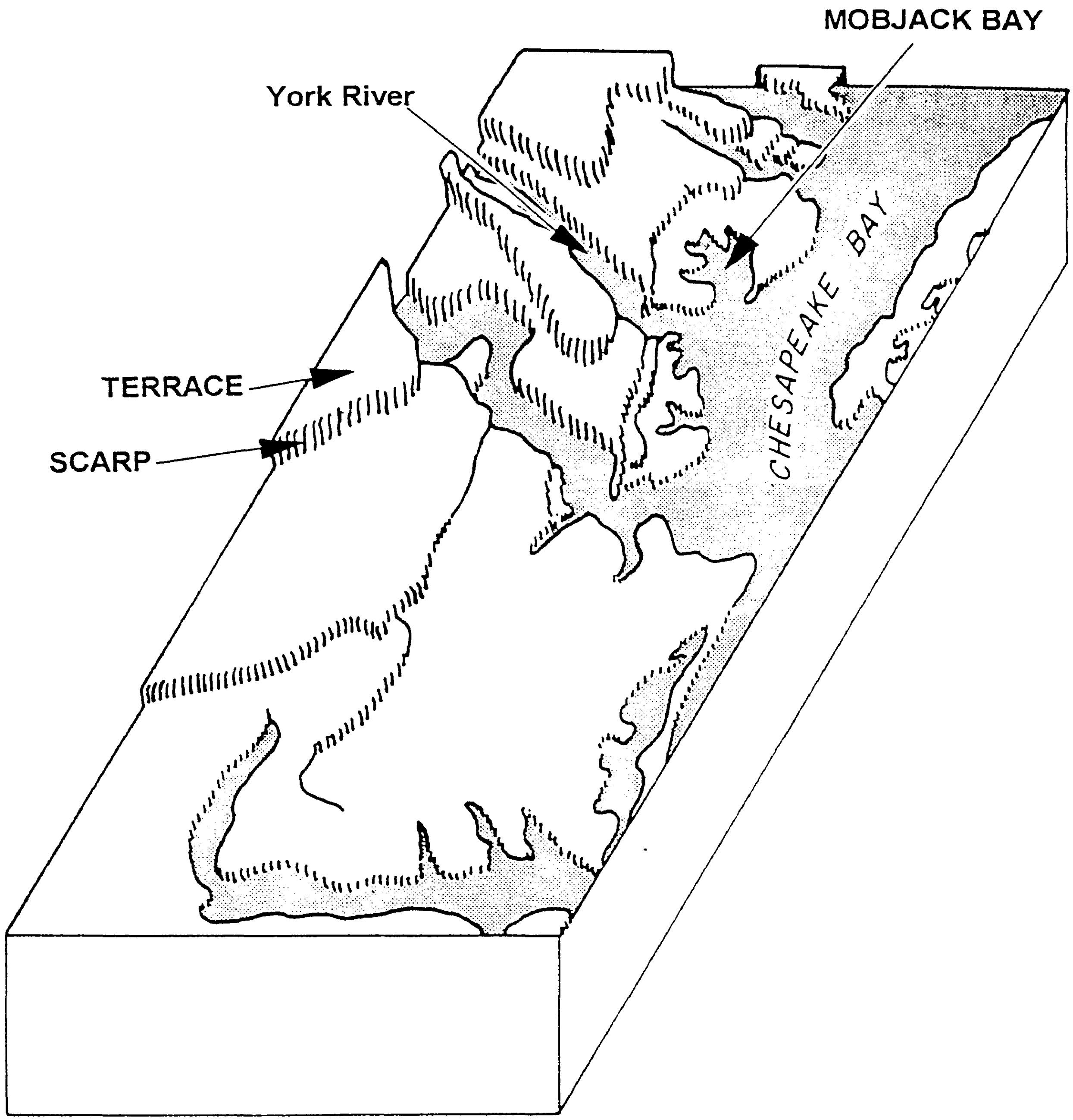


Figure 3. Diagram of scarps and terraces in northern North Carolina and the Coastal Plain of Virginia (Peebles, 1984).

coarse levees and point bars. Horizontally laminated silts and clays deposit in the flood plain (Harms and Fahnestock, 1965). The decrease in stream gradient causes the transition of channel and floodplain environments to swamp and eventually marsh (Figure 4) as the flow in the channels changes from unidirectional, fluvial flow to bi-directional, estuarine flow. The channels are eventually filled by sediments that are younger than the channel itself. Hack (1957) compared the boring logs of 14 bridge sites to boring logs of the Chesapeake Bay Bridge Tunnel and found that sequence of marine transgression and regression was similar over the entire length of the Chesapeake Bay.

Study Area Description

Mobjack Bay is an embayment within the Chesapeake Bay system (Figure 1). It is a wide, shallow, irregularly-shaped bay formed by flooding due to sea-level rise. The embayment is approximately 11 km long, 8 km wide, and averages 4 m in depth; the maximum depth is 8 m. Even though four small rivers, the Severn, Ware, North, and East, along with a multitude of creeks feed into Mobjack creating its irregular shape, fresh water inflow is believed to be minimal; however, no reference could be found to verify this. Notable features of Mobjack Bay include the broad marsh areas, the many intertidal sand flats, and the subaqueous sand shoals on either side of the bay's mouth.

Since the Bay is open to the southeast, it is exposed to both wind waves and swell, creating wave-induced oscillations up to 20-30 cm s^{-1} during storms; net littoral drift in the North River is to the east (Hardaway *et al.*, 1982). The

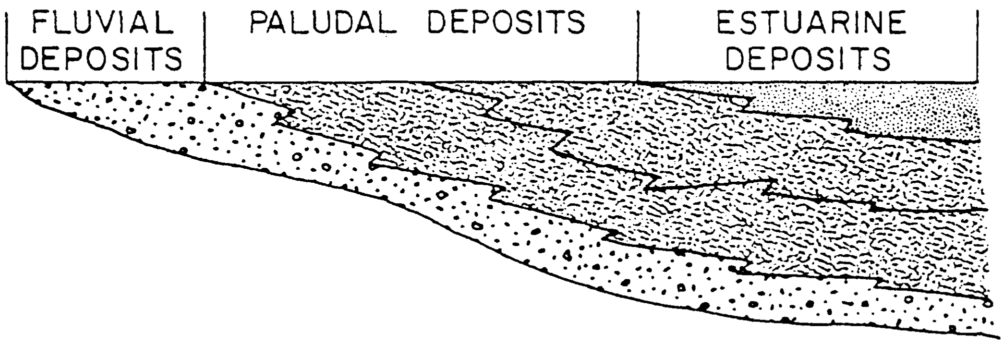


Figure 4. Cross-sectional profile indicating the typical succession of channel deposits during a marine transgression (Peebles, 1984).

primary forcing of the mean current is tidal at a speed of approximately 20 cm s^{-1} (Wright *et al.*, 1987); the tidal range averages 0.75 meters.

From November 1989 to August 1990, a bottom-mounted wave gage was maintained near the Wolf Trap Light Tower offshore of Mathews County (Boon *et al.*, 1992). A summary of the wave data obtained from this deployment may provide a typical wave climate for Mobjack Bay since fetch exposures are similar between the location of the gage and Mobjack; however, the gage's exposure to waves originating from the northeast was greater than Mobjack's. The normal wave climate at Wolf Trap was found to have an average wave height of only 0.16 meters with relatively few waves with a significant height of more than 0.2 meters (Boon *et al.*, 1992). During an extratropical northeast storm, the maximum significant wave height reached 1.5 meters with a largest individual wave height of 2 meters. The waves observed at Wolf Trap are generally locally generated since the direction of wave advance coincided with the local wind direction at the time of observation (Boon *et al.*, 1992).

II. OBJECTIVES

The primary objective of this study is to determine the paleogeology of Mobjack Bay. This includes determining the processes involved in its formation as well as mapping the paleochannels and describing and interpreting depositional sequences in the seismic data.

In order to determine how a paleochannel formed in Mobjack Bay, the regional geology and Late Quaternary sea level oscillations are examined. The sea level oscillations in the Pleistocene have had a profound effect on the stratigraphy and landforms of the area surrounding Mobjack Bay. One important effect was the development of many scarps and terraces on the Middle Peninsula. Peebles (1984) illustrated the paleo-shorelines of three late Quaternary transgressions. About 187 ka during the middle Pleistocene, the York River was located slightly north of its present course while the Piankatank and Rappahannock Rivers were situated slightly south (Peebles, 1984). During the following marine regression, a drainage basin probably would not have been available to allow the formation of a paleochannel in Mobjack Bay. In the following minor sea level oscillations, the Middle Peninsula's configuration was changed significantly because of the development of scarps prior to the latest glaciation. When sea level dropped, a new channel was created to drain a portion of the Middle Peninsula and joined the Susquehanna River paleochannel forming the Mobjack Bay paleochannel.

By applying Vail *et al.*'s (1977) method for seismic analysis on a regional level to Mobjack Bay, several types of stratigraphic interpretations necessary to achieve all of the objectives of this study can be made. These interpretations will determine the unconformity beneath the depositional sequences shown in the seismic records and describe these sequences in terms of their thickness and depositional environment as well as their relative sea level correlation and burial history.

A secondary objective is to determine the sources and distribution patterns of sediments within the past and present Mobjack Bay. For this, it is necessary to look at the Recent sedimentation of the Chesapeake Bay as a whole. In addition, an estuarine sedimentation model and facies development scheme will be applied to the information derived from the patterns of deposition in order to develop a theoretical stratigraphic succession of facies within Mobjack. The stratigraphic facies model will be applied to the results of the seismic analysis for comparison.

How the estuary fills is determined by the relative influence of river flow, tidal forces and wave action on available sediments. Whether a shoreline is wave-dominated or tide-dominated is strictly relative; it is not based on absolute wave or tide parameters, but rather the set of physical processes that is dominated by one energy source or the other (Davis and Hayes, 1984). Dalrymple *et al.* (1992) synthesized two idealized models of estuarine sedimentation and facies development: wave-dominated estuaries and tide-dominated estuaries. Both of these models predict a stratigraphic succession of facies based on the sediment distribution patterns.

A wave-dominated estuary typically exhibits a marine sand body, which could consist of subtidal shoals or a flood-tidal delta, at its mouth where wave energy is most intense. At the head of the estuary, sand is deposited by the river creating a bay-head delta, and in between, the central basin accumulates fine-grained sediments (Figure 5A). As the estuary fills, both the bay-head delta and the marine sand body prograde towards one another over top of the central basin exhibiting an upward coarsening profile.

The morphology of a tide-dominated estuary is somewhat different. The fine-grained silts and clays usually accumulate in tidal flats or salt marshes while sands accumulate in the tidal channel or elongate sand bars (Figure 5B). Another characteristic is the "straight-meandering-straight" form of the tidal channel. The tidal channel will remain fairly straight in higher energy zones such as near the mouth and the head, but in the lower mixed energy zone, the tidal channel may exhibit tight meanders.

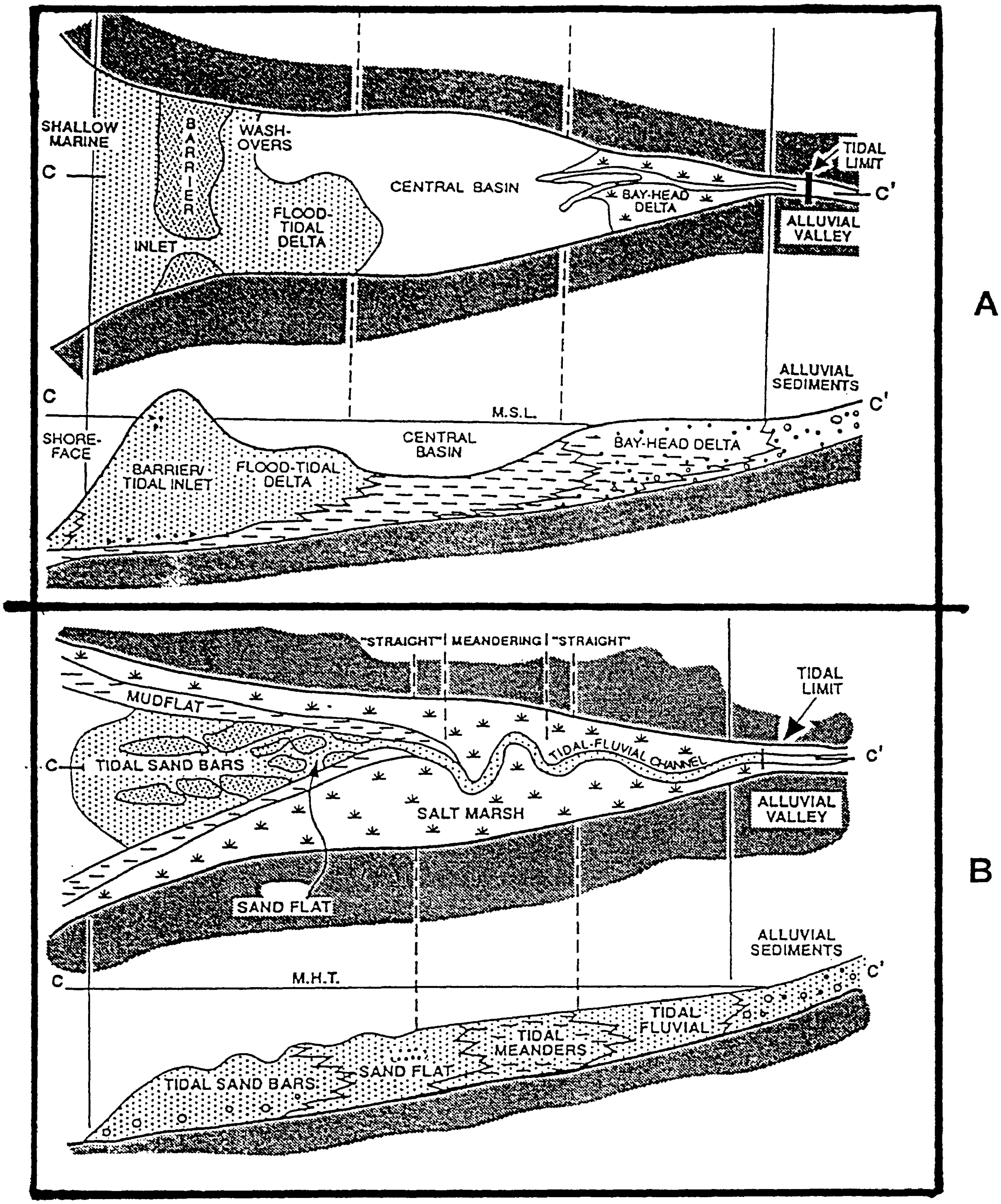


Figure 5. Distribution of morphology in plan view and sedimentary facies in longitudinal section of idealized A.) Wave-dominated; B.) Tide-dominated estuaries (Dalrymple *et al.*, 1992).

III. CHESAPEAKE BAY HISTORY

The Chesapeake Bay is described as a classic coastal plain estuary (Pritchard, 1955). Its channel was incised by erosion during the last glacial period which ended about 18 ka ago and subsequently flooded as sea level rose. The bay is the largest estuary in the United States; it is about 300 km long, averages about 20 km wide, and its surface area covers nearly 6,000 km^2 (Figure 1). The shoreline is highly irregular consisting of many tributaries and embayments which characterize a drowned river valley.

Geologic History

During the Cenozoic Era, which began about 50 ma, numerous marine transgressions occurred on the mid-Atlantic Coastal Plain creating shallow seas that accumulated relatively thin sheets of open marine sediment. Sediments that began accumulating 25 ma are the Chesapeake Group, comprised of the Calvert, Choptank, St. Marys, Eastover, Yorktown, Chowan, and Bacons Castle formations, and range in age from lower Miocene to upper Pliocene. As these formations were being deposited, the Coastal Plain was undergoing warping and uplift which began in Maryland and spread southward until the end of Yorktown time.

Since the Chesapeake Group contains open marine deposits and constitutes the basement of the Chesapeake Bay, the Bay could not have existed during the late Tertiary (Johnson and Peebles, 1985). The delivery of glacial material to the Susquehanna River during deglaciation shifted the loci of marine deposition southward and allowed the accumulation of sand and gravel in what is now New Jersey and the Eastern Shore of Maryland and Delaware. The paleo-Susquehanna and Potomac Rivers adjusted their courses during a sea level lowstand such that they flowed southward between the newly formed Maryland Eastern Shore and the western uplands (Byrne *et al.*, 1982).

Quaternary Sea Level Fluctuations

Sea level oscillations that accompanied the Pleistocene glacial cycles have been well documented. While the many different studies may not agree on exact sea-level curves, the general trends are the same, and the variations can be explained as regional differences.

Shackleton and Opdyke (1973) labeled glacial and interglacial cycles as stages defined by $^{18}O/^{16}O$ ratio variations in deep sea cores. Higher proportions of the ^{16}O isotope is regarded as an interglacial period (odd numbered stage) while the glacial maximums are characterized by larger amounts of the ^{18}O isotope (even numbered stage).

Cronin et al. (1981) determined five relatively highstands of sea level during the past 200,000 years from uranium-series dates of corals along the US Atlantic coastal plain. Both uranium-series and radiocarbon dating methods were used by Chappell and Shackleton (1986) to determine sea level highstands from corals in New Guinea. Figure 6 shows a sea level curve and the Shackleton and Opdyke (1973) stage reference numbers.

From these investigations, an estimate of the Late Pleistocene sea level changes can be made. Sea level highstands are believed to have occurred 200,000 years BP, and 120,000 years BP. Prior to the onset of the Wisconsin glaciation approximately 75,000 years BP, several minor sea level oscillations,

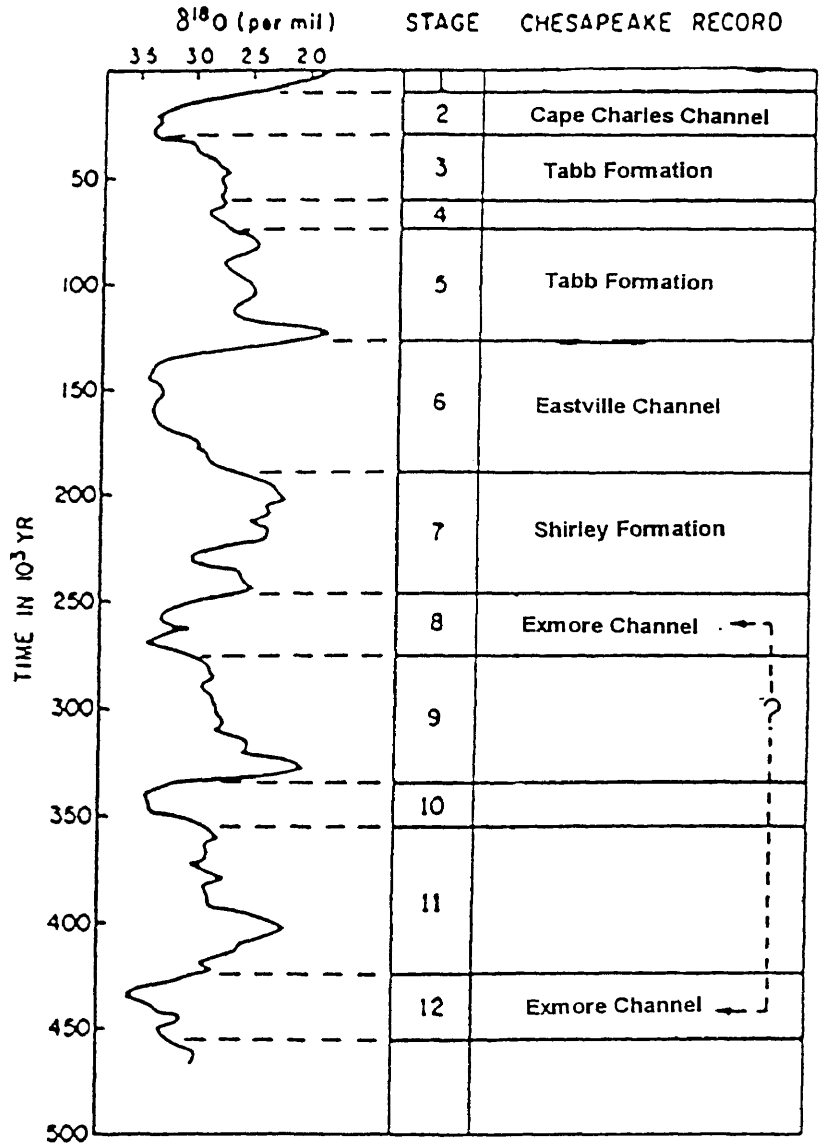


Figure 6. Sea level curve with Stage reference numbers

whose maximum height of sea level decreased with each cycle, occurred during the Stage 5 and 3 interglaciations.

During the last glacial maximum, sea level was probably 120 m below the present level and since 18,000 years ago, has been continually rising at different rates. Fairbanks (1989), using radiocarbon dates from coral in Barbados, reported two rapid rises in sea level due to melt-water spikes (Table 1) as well as one period of slowed sea level rise known as the Younger Dryas event.

Table 1. Sea level change based on the sea level curve of Fairbanks (1989)

Yrs BP	Sea level rise (m)	Comments
17,100-12,500	20	First phase of deglaciation
12,000	24	Melt-water pulse IA
11,000-10,500	12	Younger Dryas event
10,500-9,500	28	Melt-water pulse IB
9,500-6,000	20	Slowing rate of sea-level rise
6,000-present	10	Smooth curve rise

Bard *et al.* (1990) disputed the dates older than 9,000 in Fairbanks (1989) and suggested that the deglaciation began 3,000 years earlier than previously thought. Even though the dates are different in Bard *et al.* (1990), the same trends listed in Table 1 where supported. Based on the amount of sea level rise and the dates in Fairbanks (1989) as well as the incised depth of previously mapped paleochannels, the Chesapeake Bay would have begun flooding when sea level was at -50 meters so what we know of today as the Bay was initiated approximately 10,000 yrs BP and probably reached its present form 3500 yrs BP.

Paleochannels

Over the past 40 years, researchers have tried to identify the paleogeology of the Chesapeake Bay and have postulated several ancient drainage channels of the Susquehanna River which are incised into pre-Holocene deposits. Colman *et al.* (1990) presented a detailed history of the previous work. Halka *et al.* (1989) and Colman *et al.* (1990) identified three distinct generations of Quaternary paleochannels that have been called the Exmore, the Eastville, and the Cape Charles because of landmarks near where they cross the Delmarva Peninsula (Figure 7).

A distinctive feature of these channels is that the younger system is generally located both south and west of the older one. During interglacial, sea level highstands, the tidal channel migrated westward as the former fluvial channel filled with estuarine sediments, and at the bay mouth, the channel had to migrate as the Delmarva Peninsula prograded southward (Colman *et al.*, 1990). The processes involved in the fluvial channel migration resulted in the preservation of each generation of the relict Susquehanna River and Chesapeake Bay.

The seismic records produced by the earlier studies showed similar fill patterns for all three generations of the relict Susquehanna River (Colman and Mixon, 1988). Overlying the basal boundary reflectors of the paleochannels were two distinct fill units. The lower unit at the base of each valley was characterized by strong, discontinuous, and irregular reflectors while the upper

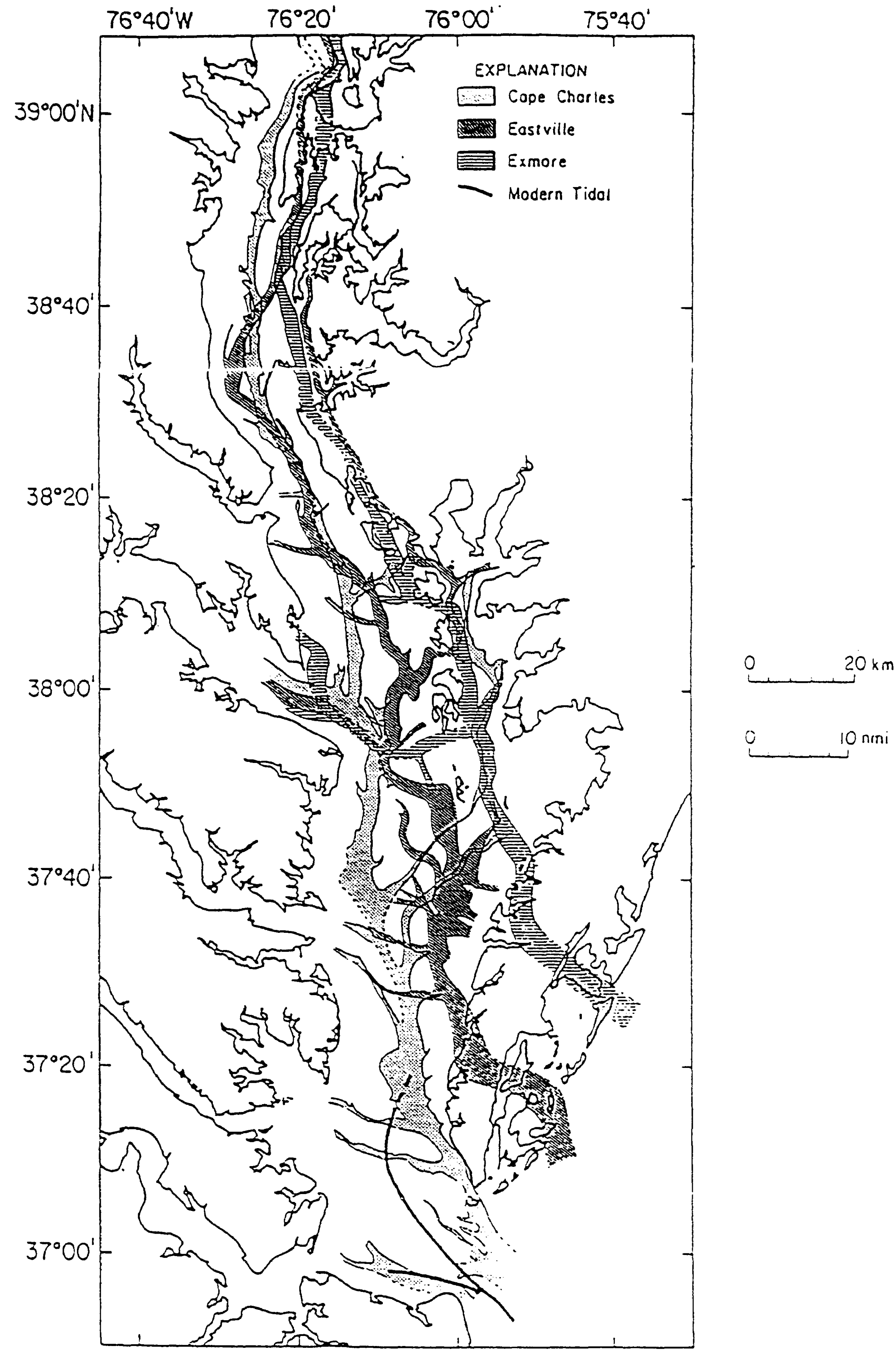


Figure 7. Map indicating the position of the three major Quaternary paleochannel systems (Colman *et al.*, 1990).

unit consisted of fill sediments that exhibited weak, long, and smooth reflectors or were nearly reflection free. These patterns are consist with Hack's (1957) findings in his study of bridge boreholes which showed that the submerged river valleys were filled with sand and gravel deposits overlain with sandy silt of estuarine origin.

The paleochannel known as the Exmore is the oldest channel identified by both Halka *et al.* (1989) and Colman *et al.* (1990). It is believed that the channel was created at about either 270 or 430 ka during a major sea level lowstand (Colman and Mixon, 1988). The Exmore is located generally eastward of both the Cape Charles and the Eastville channels and crosses the Delmarva Peninsula about 80 km north of the present bay mouth.

The Eastville seems to have been cut about 150 ka ago during the Illonian glaciation (Colman and Mixon, 1988). It is primarily located along the eastern side of the Chesapeake Bay and crosses the Delmarva Peninsula near the town of Eastville approximately 40 km north of the present bay mouth.

The Cape Charles, the youngest channel, was formed during the last major sea level lowstand and is incised into the underlying Tertiary strata to depths of 50-70 m. Because the channel has only partially filled with Holocene sediments, for the most part it follows the present bathymetry of the bay's axial channel except where the progradation of Holocene spits has altered the shape and path of the channel (Halka *et al.*, 1989). In addition, the paleochannel is offset approximately 12 km to the north of the present mouth of the bay.

It is believed that the processes involved in the formation and preservation of the aforementioned paleochannels is still occurring in the Bay. Colman and Hobbs (1987) noted that the present channel of the Chesapeake

Bay is displaced both south and west of the Cape Charles paleochannel. In addition, a bayward-prograding wedge of sand is located north and east of the present Bay channel whereas south and west, only a thin layer of bay-bottom sediments exists.

Regional Pleistocene Formations

The present morphology of the Chesapeake Bay and its surrounding uplands is due in large part to the many sea level oscillations of the Quaternary. These oscillations on the outer Coastal Plain of Virginia created a stair-step topography formed by terraces separated by scarps (Figure 3). Two formations are evident in the uplands surrounding Mobjack Bay. These are the Shirley Formation and the Tabb Formation (Figure 8). The Tabb Formation has three members, the Sedgefield, Lynnhaven, and Poquoson.

The Shirley formation is of middle Pleistocene age since it was formed approximately 187 ka $\pm$ 20,000 yrs before present when sea level was 14 meters above present sea level (Figure 9A) (Peebles, 1984). It was deposited during the sea-level highstand prior to the Stage 6 glaciation. On the Middle Peninsula, its sediments are part of the Newport News terrace that parallels the York River and are separated from older deposits to the north by the Hazelton scarp and from younger deposits to the east by the Big Bethel scarp (Figure 10). It uncomformably overlies the Yorktown formation which is Tertiary in age. The location of the Formation parallel to the York River suggests that the previous York River was located slightly north of its present location. Deposits near the Piankatank and Rappahannock Rivers suggest that they were located slightly south of their present location (Peebles, 1984).

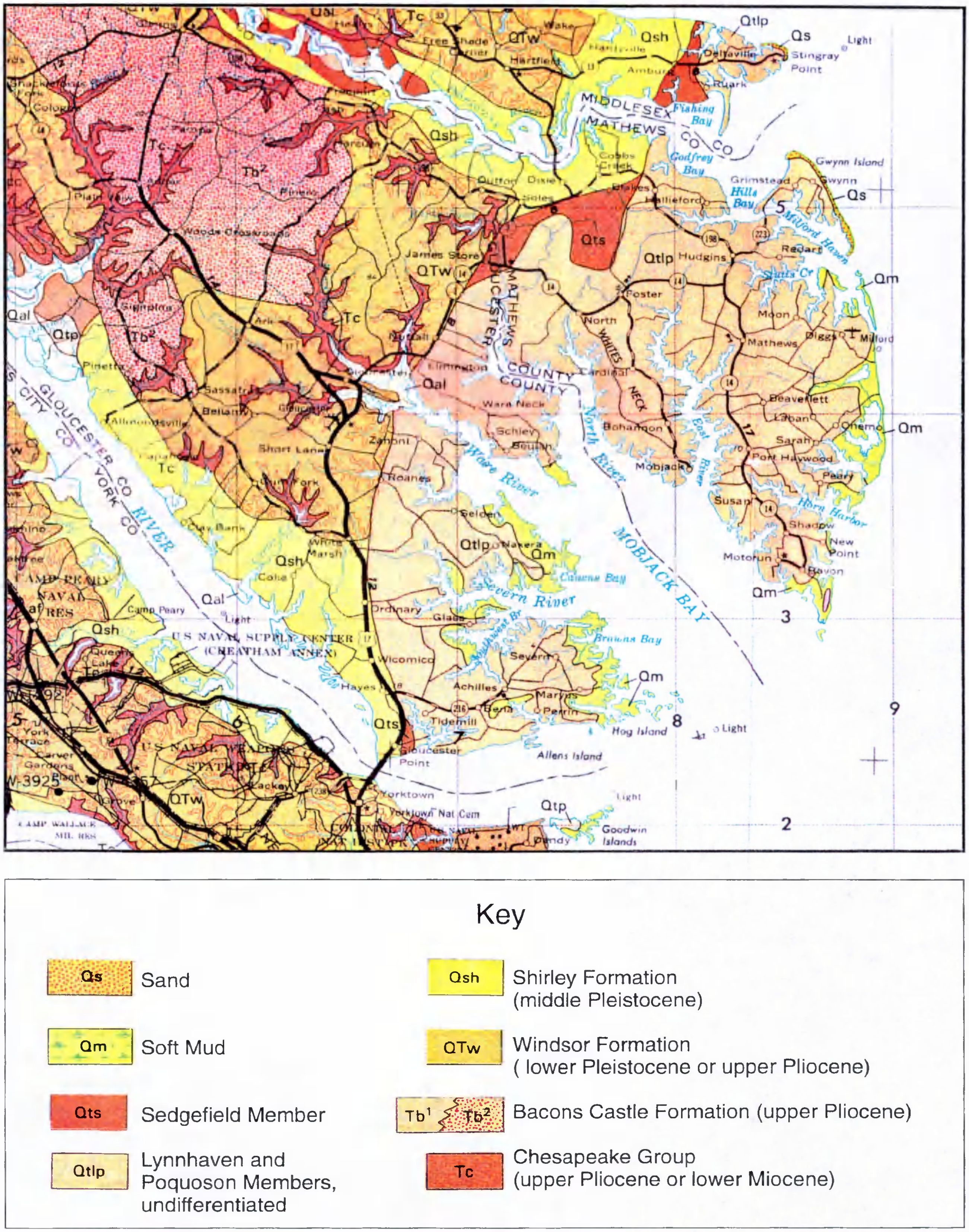


Figure 8. Mobjack Bay upland stratigraphy (from Mixon *et al.*, 1989).

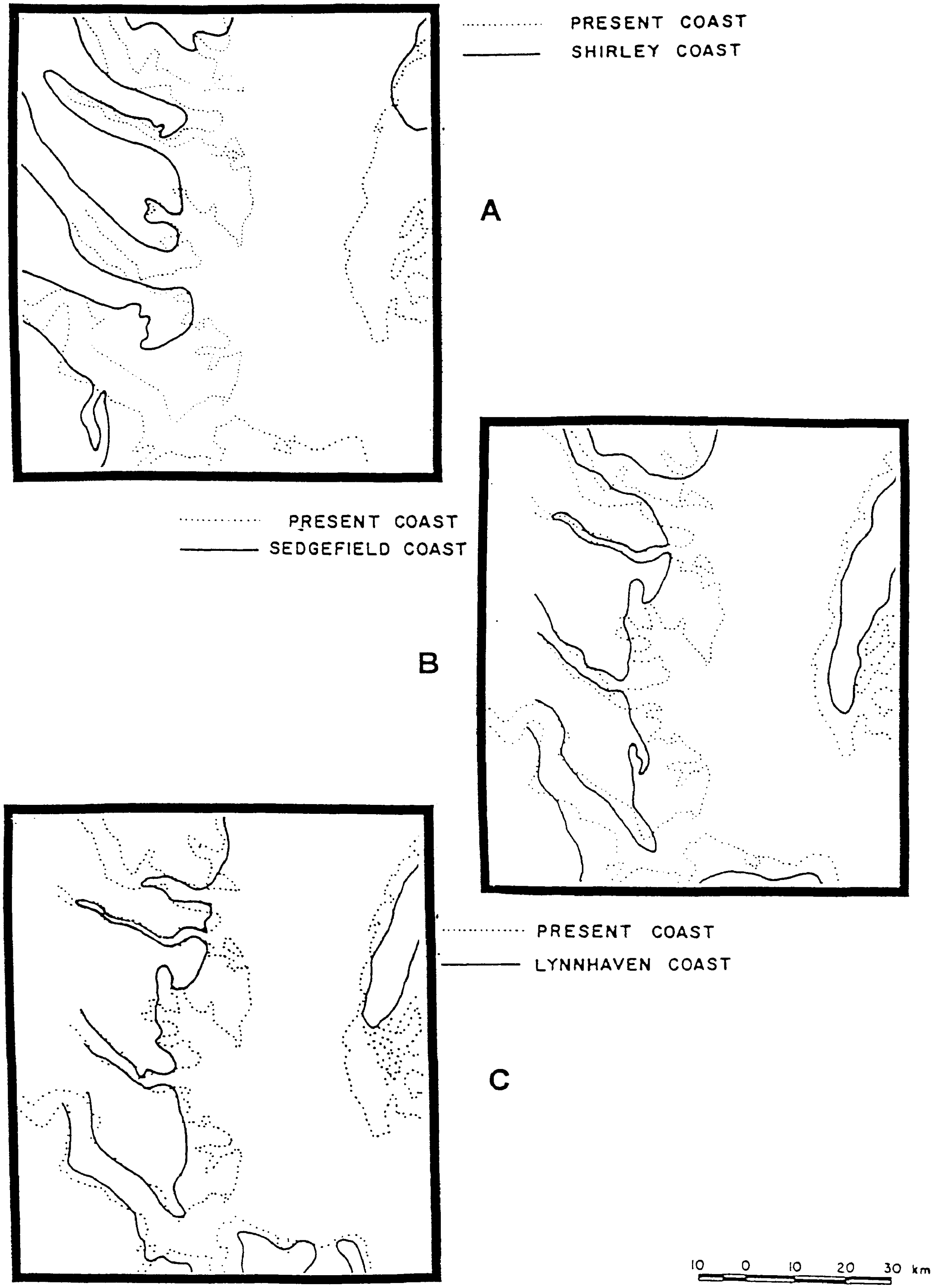


Figure 9. Location of Quaternary shorelines during the deposition of the A.) Shirley Formation; Tabb Formation B.) Sedgefield Member C.) Lynnhaven Member (from Peebles, 1984).

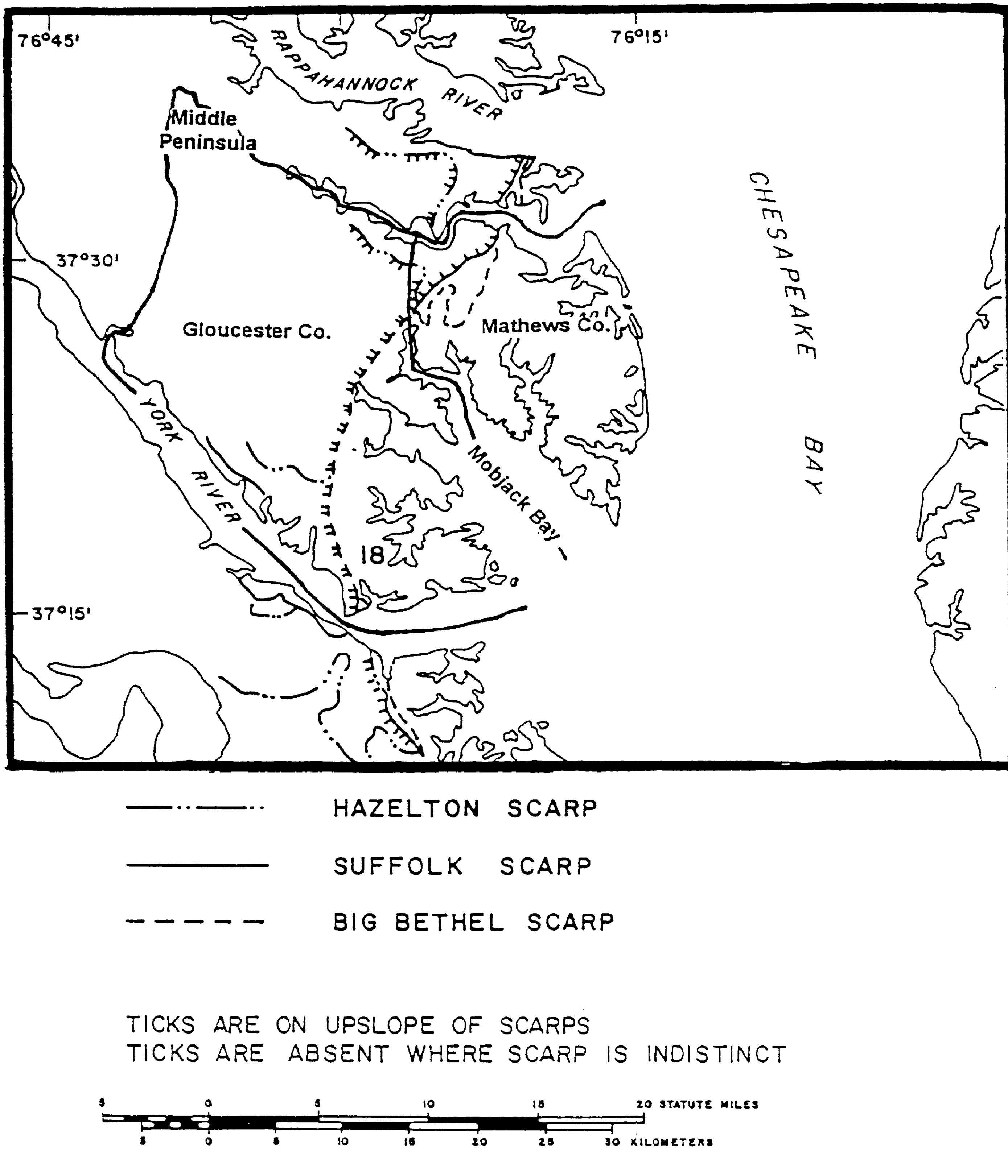


Figure 10. Locations of Middle Peninsula scarps (from Peebles, 1984).

The Tabb formation is subdivided into three separate members, the Sedgefield, Lynnhaven, and Poquoson, all of which are Late Pleistocene deposits formed during the Stage 5 and 3 interglaciations (Johnson and Peebles, 1985). The Sedgefield member, which is not evident in much of the area surrounding Mobjack Bay, was formed 70-90 ka when sea level was 9-9.7 meters above present sea level (Figure 9B). A small portion of the Rescue terrace, whose deposits make up the Sedgefield member, occurs just north of the North River on the Middle Peninsula, and the terrace is separated from younger sediments by the Big Bethel scarp. Most of the Sedgefield member probably was eroded during the many minor sea-level oscillations which formed the Lynnhaven and Poquoson members and occurred prior to the last glaciation (Johnson and Peebles, 1985). Lynnhaven sediments accumulated on what is now called the Chesapeake terrace (Peebles, 1984), and the Big Bethyl scarp, which separates it from older sediments, is the youngest scarp evident on the Middle Peninsula. The Lynnhaven shoreline (Figure 9C) and Poquoson shoreline varied little from the Sedgefield shoreline since the changes in sea level were relatively minor and short in duration. In the region surrounding Mobjack Bay, the Lynnhaven and Poquoson members are undifferentiated.

The fastland directly surrounding Mobjack Bay is almost all Pleistocene deposits except for the Holocene deposits including and surrounding Guinea Marsh, Four Point Marsh, and New Point Comfort (Figure 8). While Pleistocene scarps and terraces are evident in the uplands surrounding Mobjack Bay, few Pleistocene deposits are seen in sub-bottom records. Studies done in the lower bay and bay-mouth area on the bridge-tunnel cores (Harrison *et al.*, 1965) and seismic and cores (Colman and Hobbs, 1987) showed that much of the

Pleistocene sediment that may have been deposited prior to the last glacial sea level lowstand was eroded before the latest sea level rise.

IV. METHODOLOGY

Data collection

The survey grid of Mobjack Bay consists of five sub-bottom tracklines (Figure 11), one of which was taken in 1986 as part of the Colman and Hobbs (1987) study, and one side scan sonar trackline (Figure 12). The sub-bottom profiling system used was a dual frequency Datasonics SBP-5000 set at a recorder sweep of 63 or 100 millisecs. This sweep yielded approximately 47 m and 75 m, respectively, of record assuming the acoustic velocity of 1500 m/s for shallow sediments. In order to determine bottom topography types, an EG&G SMS-960 side scan sonar system was used with the scan set at 100 m on either side of the ship track. Both systems displayed the reflections on a continuous graphic record; the data were not recorded on magnetic tape.

The closely-spaced network of seismic profiles were obtained along both north-south and east-west trending lines. In general, the Loran-C was used for navigation. The final tracklines were configured by using both latitude and longitude as derived from the Loran fixes and a Global Positioning System (GPS). Location fixes were taken primarily at three minute intervals.

Seismic Subbottom Profiling

The acoustic, subbottom profiler utilizes a sound-generating and receiving device as well as a graphic recorder to depict subsurface data. The system is designed to provide a cross-sectional display of the subbottom strata below the transceiver. Calculations of the reflection's depth are based on travel time from the source to the interface and back to the receiver and the speed of

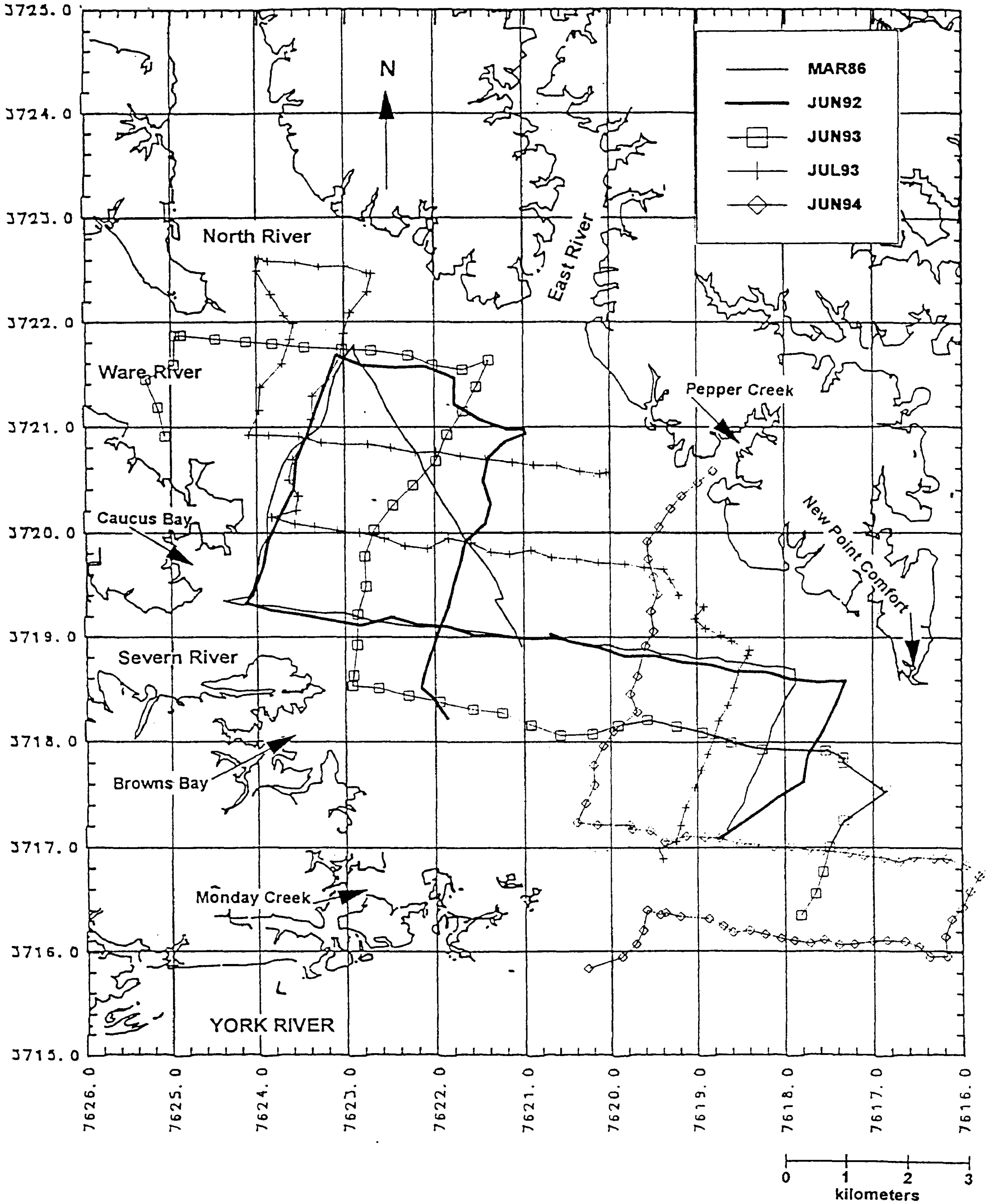


Figure 11. Sub-bottom profiling tracklines.

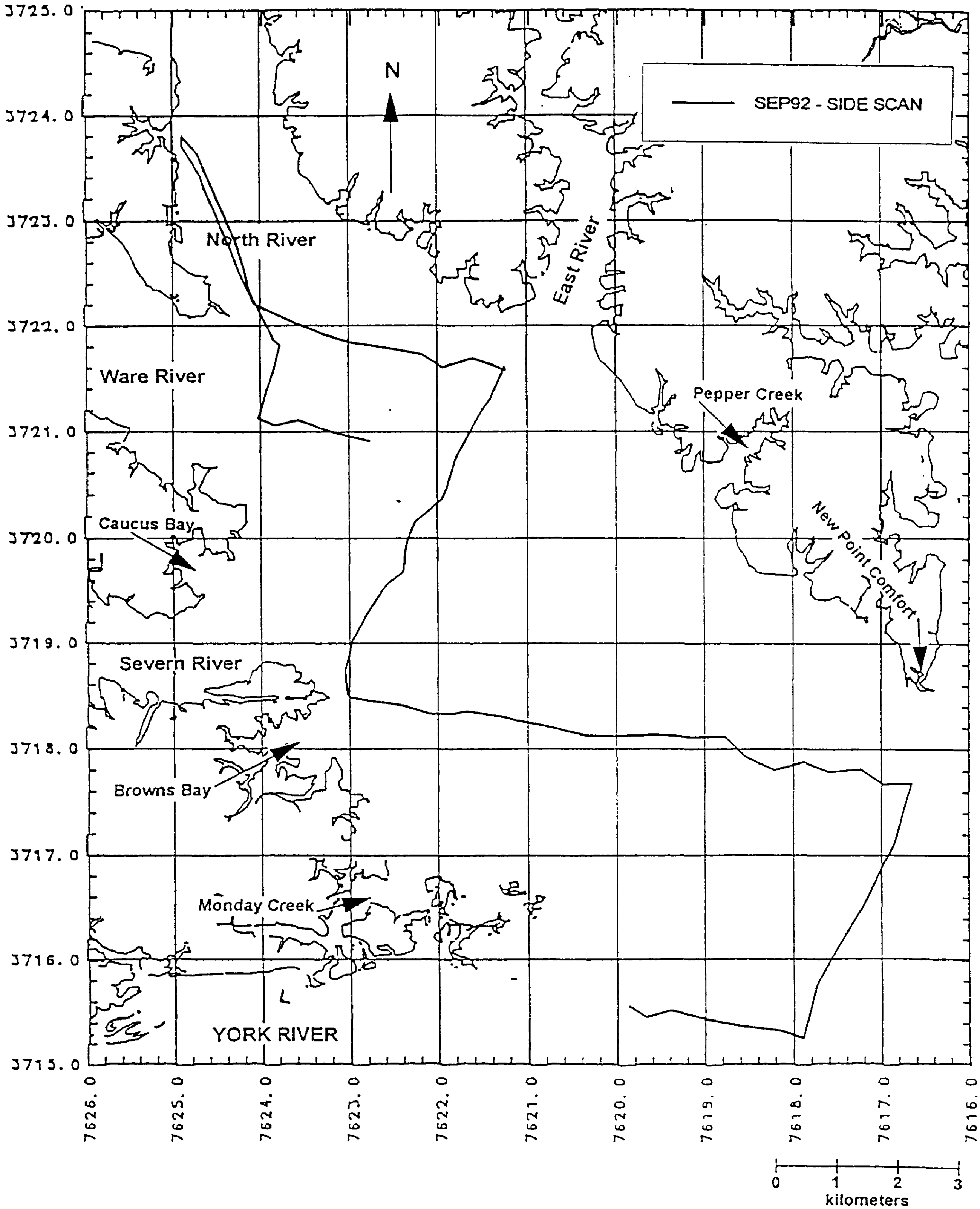


Figure 12. Side Scan Sonar trackline.

sound through the material. Most researchers assume a velocity of 1500 m/s for shallow sediments and the overlying water column. However, an important consideration is that the vertical exaggeration of reflections will be quite large since the horizontal distance traveled while profiling is greater than the vertical depth recorded by high-frequency sub-bottom systems (McQuillin *et al.*, 1984). As a result, dipping reflectors will appear much steeper in the data than they actually are.

The subbottom profiler recorder plots two-dimensional reflections that are based on acoustic interfaces. An acoustic interface occurs when the material above and below it differ in acoustic impedance. Impedance is based on the acoustic properties such as density and elasticity of the sediment (Sieck and Self, 1977). Since vertical resolution can fluctuate, the frequency of the signal can be varied in order to obtain better resolution. Higher frequency systems increase resolution of particular events but have a smaller range of depth penetration (McQuillin *et al.*, 1984).

Side Scan Sonar Surveying

The side-scan sonar system provides a planimetric image of the seafloor by transmitting and receiving sonar signals from a fish that is towed by the boat. Only signals returned from within a fixed range on either side of the track line are collected and processed; the range contains data from directly under the fish out to the horizontal range limits. The angles are converted to distances by taking into account the two-way travel time and the speed of sound through water. While the area directly under the trackline is usually unable to be resolved, the system produces a data strip that is much like an aerial photograph.

A sixteen tone gray color scale is used by the recorder to indicate the strength of the acoustic backscatter. Differences in bottom features or material will change the amount of energy returned thereby resulting in shade changes. darker tones generally indicate coarser-grained material (or rougher surfaces) or areas where the relief reflects the signal while a lighter tone may indicate finer material (or smoother surfaces) or a bottom with features that can absorb the acoustic energy (Williams, 1982). Because the transmitted pulse is so short and the frequency so high (105 kilohertz), the side scan sonar can record small objects and details of the bottom topography without penetrating the bottom. However, many variables can influence the backscattering strength of the signal; for example, the angle of the signal or the slope of the bottom will change the tone of the data strip. An accurate picture of the bottom can be obtained by tracking over the area several times.

Data reduction

Seismic reflection data were processed in several steps. The original records were reduced on a copy machine to a manageable size. This also may darken any reflectors that may be hard to detect on the original records. In addition, the reduced copies were compared to the original seismic data rolls in order ensure that no reflectors or seismic characteristics were created by the copy machine. Once seismic interpretation (discussed below) was completed on these reduced data, stratigraphic line drawings were made for each profile showing marker horizons and stratigraphic units. Since survey lines are closely spaced, the resultant data can be used to produce a three-dimensional model of seismic events as well as two-way travel time contour maps (Reynolds, 1990). The Surfer graphical software package (Golden Software, Inc., Colorado, 1989) was used to process the data and create two-dimensional maps depicting the extent of a correlated reflector over the study area.

Seismic interpretation

The interpretation of seismic data relates the reflectors shown in the data to the paleogeology of an area. Vail *et al.* (1977) suggested that researchers utilize a three-step procedure to reduce seismic data. These steps are: 1.) seismic sequence analysis; 2.) seismic facies analysis; and 3.) analysis of relative sea level change. This process is flowcharted in Figure 13, and the terminology used in this report is listed. Van Wagoner *et al.* (1988) used this process as a basis for seismic interpretation but updated the definitions of critical terminology which had evolved in scientific literature since the publication of Vail *et al.* (1977). While this process has mainly been used for shelf exploration, the same general principles can be applied to shallow marine environments.

A seismic sequence is a set of relatively similar reflections which is bounded at the top and bottom by one of the two basic types of discontinuities, unconformable and conformable (Vail *et al.*, 1977). Sequence analysis is performed on seismic records by identifying the unconformable boundaries, which represent hiatuses in deposition, and tracing them over the region to where the boundary becomes conformable. Boundaries show up in data as

Sub-bottom Tracklines

Seismic Sequence Analysis
identify unconformable boundaries

Seismic Facies Analysis
describe and interpret
internal and external configuration of sequences

Internal Configurations	External Configurations
parallel	sheet
subparallel	sheet drape
divergent	wedge
prograding clinoform	bank
chaotic	lens
reflection-free	mound
	fill

Relative Sea Level Analysis
classify reflector terminations at sequence boundaries

Reflector Terminations

- Lapout
  - Baselap
    - onlap
    - downlap
  - Toplap
- Truncation
- Concordance

Figure 13. Flowchart of seismic interpretation procedure and terminology.

reflector terminations; unconformities separate younger strata from older sediments and are defined as surfaces of discontinuity which result from erosion or non-deposition, whereas, conformities separate younger and older strata but show no evidence of erosion or a hiatus.

Seismic facies analysis is the description and geologic interpretation of both the internal configuration and external form of the seismic sequence. The geometric patterns exhibited by a three-dimensional seismic facies unit differ from adjacent units by internal parameters such as configuration, continuity, amplitude, frequency and interval velocity. Both the internal and external configuration of a unit must be delineated before environmental setting and depositional processes can be determined because similar external forms can have several different internal reflections.

A relative change of sea level is an apparent rise or fall of sea level with respect to the land surface. Change in the position of sea level is best determined in facies bounded by onlap or toplap (Vail *et al.*, 1977). Sea level rise is indicated on seismic records by progressive landward onlap whereas sea level fall is characterized by a shift of coastal onlap downslope and seaward (Figure 14). Relative stillstand of sea level is indicated on data by coastal toplap facies boundary.

The general stratigraphic model for an estuary is such that the paleo-valley is incised into the underlying strata during sea level lowstand and is separated from the overlying fluvial deposits by an erosional unconformity. As sea level rises, fluvial deposits are overlain by estuarine deposits, and the two facies are divided by a flooding surface. If sea level continues to rise, the estuary will continue to translate landward, and the drowned paleochannels will

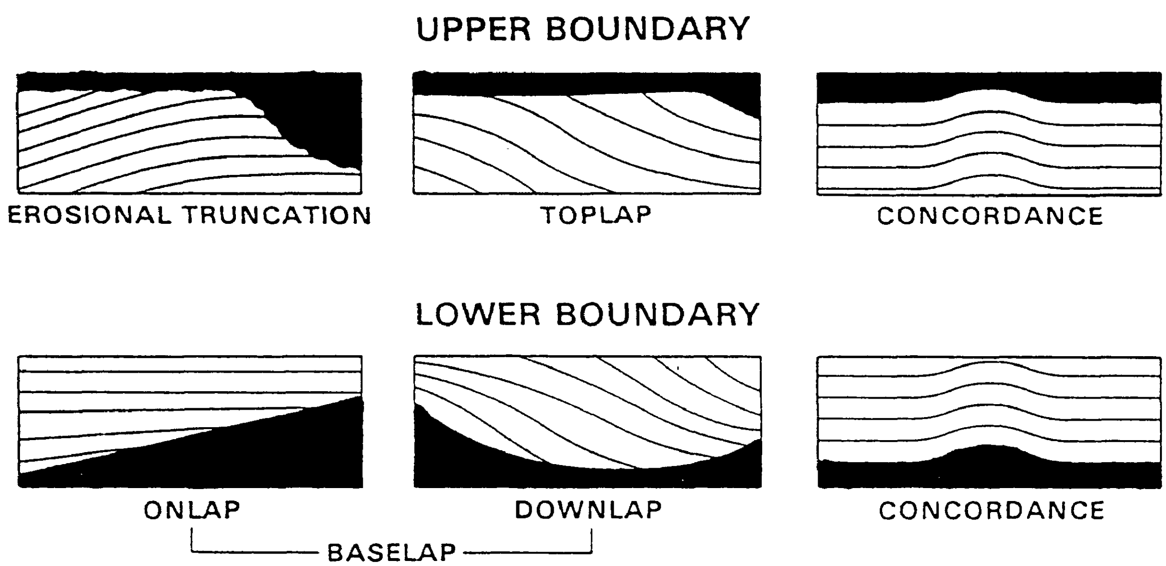


Figure 14. Relations of strata to upper and lower boundaries of a depositional sequence (Vail *et al.*, 1977).

be available to tidal and/or wave action which reworks the sediment and affects distribution and deposition patterns. When sea level reaches highstand or the rate of sediment supply exceeds relative sea-level rise, the estuary begins to fill (Dalrymple *et al.*, 1992).

Many researchers use this process to obtain information from the seismic record because inferences can be drawn concerning the dynamics of the system and the processes involved in creating the sub-surface geology (Reynolds, 1990).

Sediment Samples and Grain Size Analysis

In order to determine surficial sediment types, grab samples were taken along the side scan sonar trackline as well as along Mobjack Bay's axis and transects across the width of the bay (Figure 15). Grain size analysis consisted of pipetting and of VIMS's Rapid Sediment Analyzer (RSA). The RSA is a computerized sedimentation tube that analyzes the sand fraction of a sample to determine the grain-size distribution by measuring settling velocities. The categorization of grain size is based on Folk (1980) (Figure 16A) and classified according to Shepard's (1954) ternary classification (Figure 16B).

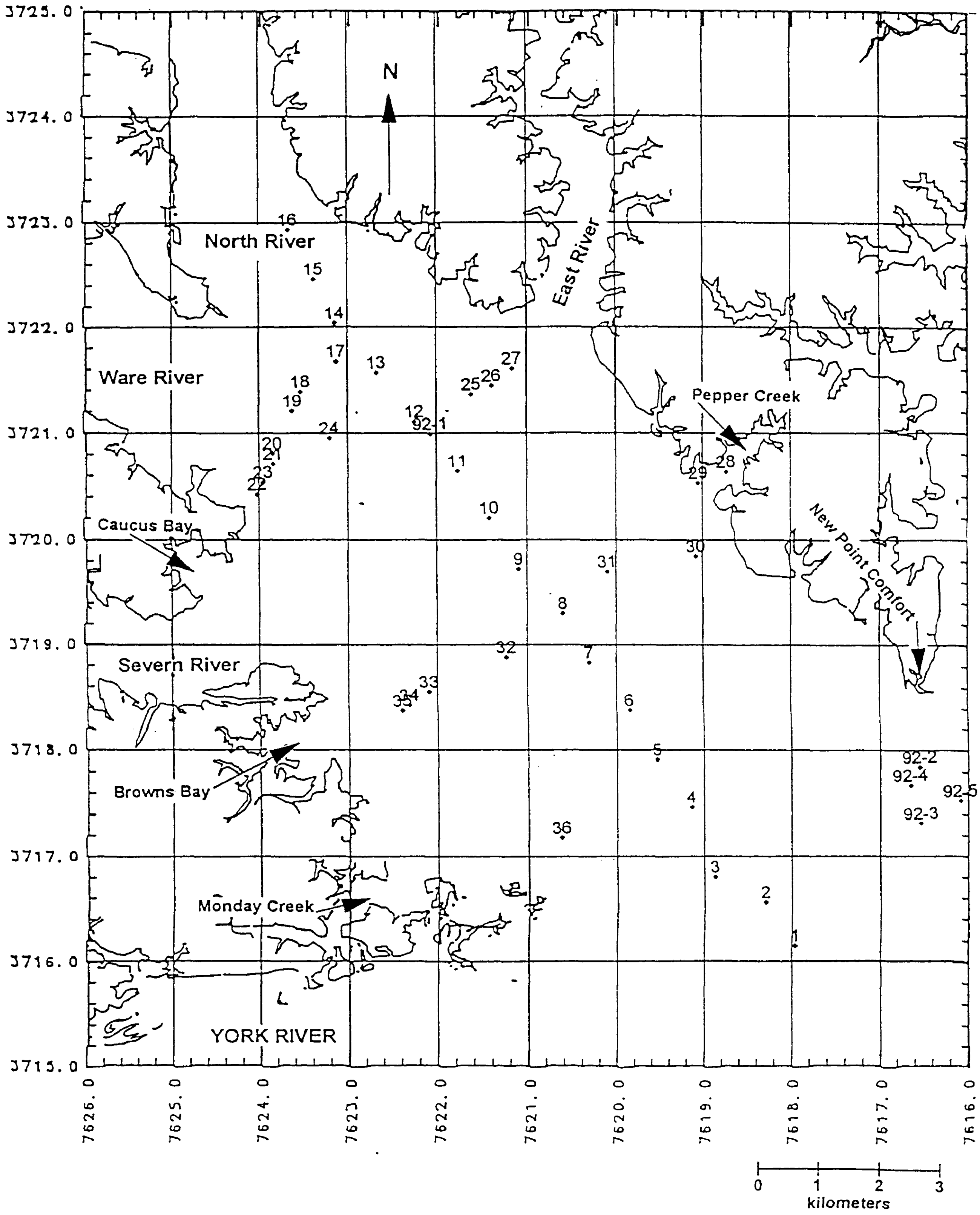
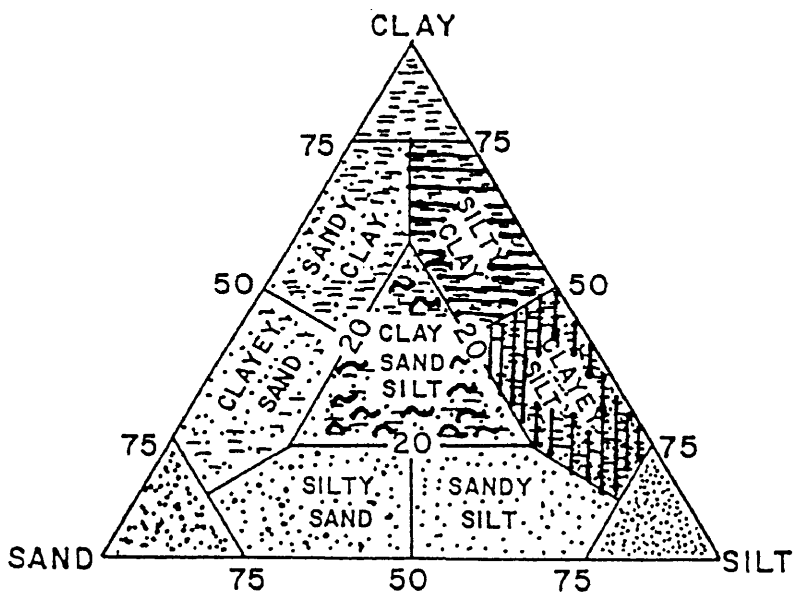


Figure 15. Sediment sample locations.

Grain Size Diameter Ø	mm	Description	Phi Size Range
-2	4	Granule	-2 to -1
-1	2	Very Coarse Sand	-1 to 0
0	1	Coarse Sand	0 to 1
1	0.5	Medium Sand	1 to 2
1.5	0.35	Fine Sand	2 to 3
2	0.25	Very Fine Sand	3 to 4
2.5	0.177	Silt	4 to 8
3	0.125	Clay	8
3.5	0.088		
4	0.0625		
4.5	0.044		
5			
6			
7			
8			

A

Sorting Value	Sorting Class
< 0.35	Very Well Sorted
0.35 - 0.50	Well Sorted
0.50 - 0.80	Moderately Well Sorted
0.80 - 1.40	Moderately Sorted
1.40 - 2.00	Poorly Sorted
2.00 - 2.60	Very Poorly Sorted
> 2.60	Extremely Poorly Sorted



B

Figure 16. Classifications for grain-size analysis. A.) Nomenclature used in analysis (Folk, 1980). B). Ternary classification of sediment grain size (Shepard, 1954.)

V. HOLOCENE DEPOSITION

While the paleochannel created by fluvial flow during the last glaciation was flooding as sea level rose, the flow of water in the deep channel gradually changed from unidirectional, fluvial flow to bi-directional, estuarine flow allowing the deposition of fluvial material that previously would have been carried out to sea. As sea level continued to rise, erosional processes within the Chesapeake Bay supplied additional sources of sediment and caused the rate of sediment supply to exceed the rate of sea-level rise. This began the infilling process.

Sediment Size Distribution

Shideler (1975) collected 200 samples in transects across the Chesapeake Bay and described the samples in terms of textural variability, which included total mud content and the size frequency distribution of the sand fractions. In general, the study found that the nearshore regions along the margins of the Bay as well as the Bay mouth region were greater than 80% sand (Figure 17). In addition, the tributaries of the lower Bay supply sediment that is greater than 80% mud while the main stem of the bay is somewhere in between. The size distribution of the sand fractions shows a texture that ranges from coarse to very fine sand. North of the York River (approximately 37°15'), the sand size generally decreases toward the center of the Bay with the very fine sand is located mostly in the bay stem. In the lower portion of the study area, there was no regional trend for sand size distribution.

Byrne *et al.* (1982) completed a much more detailed study of the Virginia portion of the Chesapeake Bay by collecting 2,172 grab samples. In general,

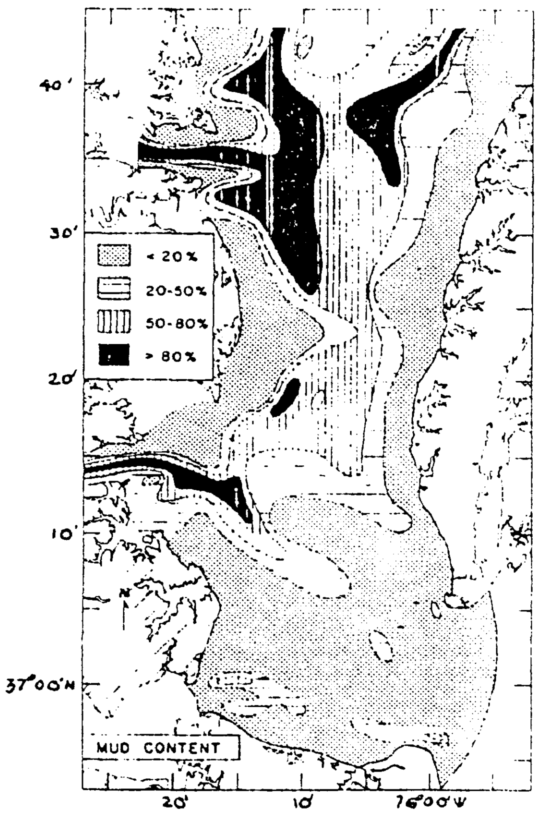


Figure 17. Isopleth map of total mud contents in the lower Chesapeake Bay bottom sediments (Shideler, 1975).

the 1982 results agree with Shideler's (1975) results. While a statistical correlation between grain size and depth could not be resolved, graphically, grain size distribution shows the medium and coarse sand primarily located in the shallow portions of the while the finer sands and muds were found almost exclusively in the central, deeper areas of the Bay (Figure 18). One of the exceptions to the general trend is Mobjack Bay and a band of fine sediments running southeast from the mouth of Mobjack Bay. This region is not much deeper than the surrounding area and yet exhibits the same pattern of deposition as the nearby York river channel. Byrne *et al.* (1982) theorized that the band is a result of the infilling of a paleochannel.

The antecedent geology of the Chesapeake Bay must play a large part in the textural distribution of the sand fraction of the samples since it influences the sources and sinks of material. The results of Byrne *et al.* (1982) indicate that the medium to coarse sand in the shallower regions could be lag deposits of eroded material with the fines winnowed out by wave action. However, certain areas of the Bay do not have sufficient sources of eroded material to explain the large sand shields present. The large sand belt on the western margin of the Chesapeake Bay adjacent to Mathews county is probably the result of erosive and transport processes, but the eroded material may not simply be the lag deposits transported to the Bay by the tributaries, but actually the reworked material of relict nearshore terraces formed during a low sea-level stand. Rosen (1976) showed that the shallow (less than 3.6 meters), flat terraces were the erosional platform created during the last 3,000 years of relatively slow sea-level rise. Sand deposits in the Bay mouth are most likely a combination of relict, palimpsest materials and modern shelf transport materials.

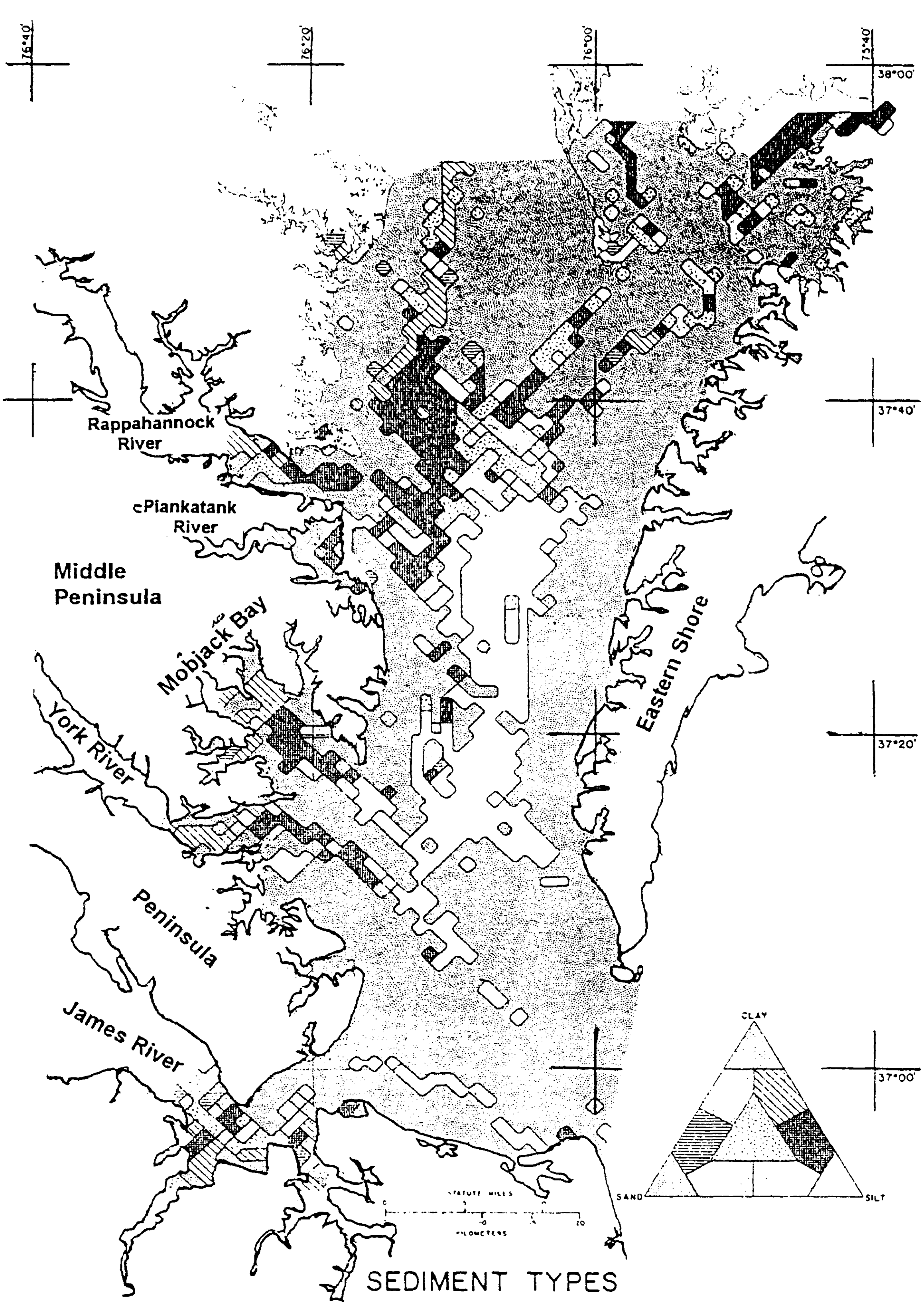


Figure 18. Lower Chesapeake Bay distribution of sediment type (Byrne *et al.*, 1982).

Sedimentation Patterns

Based on the results of his study, Shideler (1975) suggested that the Bay's main stem is a trap for fine-grained riverine input while the sand deposited on the margins of the Bay are reworked Pleistocene sediment. In the lower Bay, the textural variability of the sand fraction of the samples suggests that the origin of the sediments is not only Pleistocene deposits but also modern deposits coming into the Bay through its mouth.

Byrne *et al.* (1982) delineated three regions in the southern portion of Virginia's Chesapeake Bay to its describe sedimentation patterns. These are the upper transition belt (37°35' to 37°25'), the central farfield Bay mouth belt (37°25' to 37°15'), and the lower nearfield Bay mouth belt (37°15' to 36°55').

The upper belt is generally depositional (0-0.5 m/cent) and, because of the textural distribution of sediment, is considered a transition zone between the sandier Bay mouth region and the finer-grained region to its north. The central belt is considered a Bay mouth zone because of the deposition of sands that appear to originate from the shelf. Meade (1969) reasoned that since bottom-water moves progressively landward (Pritchard, 1952) and tends to flow into the mouths of estuaries, sediment must also be transported into the estuaries mouth. Colman *et al.* (1988) and Hobbs *et al.* (1992) confirmed that the source of the bay-mouth sand is primarily outside the Bay and that the landward net non-tidal circulation results in the deposition of sand far up the estuary.

Byrne *et al.* (1982) identified several loci of erosion or deposition within this region including the depositional nearshore terrace adjacent to Mathews county which is believed to be a composite of a relict sand feature and modern deposits accumulating there by longshore transport down the western flank of the Bay (Shideler, 1975). Just east of this nearshore terrace is a narrow erosional locus. The lower Bay mouth belt is described as a region with spatially variable patches of deposition and erosion with no clear-cut general description of sedimentation. However, Carron (1979) noted that at the mouths of the Rappahannock, Piankatank, and York Rivers and the Bay sediments tend to accumulate on the left side (looking downstream) and erode on the right.

Mobjack Bay Sedimentation

The textural distribution of sediments within Mobjack Bay is such that sand occurs along the margins, clayey silt is found in the central portion of the Bay, and silty clay is limited to the mouths of the Ware and North Rivers (Figure 18). Based on Byrne *et al.* (1982), Mobjack Bay has been accreting at up to 0.5 meters/century or more specifically, receiving 0.2 M-Tons/m^2/century of clay and between 0.2 and 0.4 M-Tons/m^2/century of silt; however, no evidence was found to indicate that sand is being deposited within the Bay.

Byrne et al. (1979) reported an interesting statistical result of plotting water depth versus the average sedimentation rate for that depth in the Chesapeake Bay main stem and Mobjack Bay. Both Bays showed high sedimentation rates in shallow (0-1.8 meters) waters as well as the deeper depths (greater than 3.7 meters). A low rate of sedimentation occurred in the 1.8-3.7 meter waters.

VI. RESULTS

Stratigraphy and Mapping of Paleochannels

In order to analyze the seismic sections, Vail *et al.*'s (1977) method had to be modified to apply it on a local as well as a short-term level. Vail *et al.* (1977) used the method on pre-Quaternary shelf and ocean basin seismic records where a seismic sequence is generally tens to hundreds of meters thick and can be traced over tens or hundreds of kilometers. Mobjack Bay is only 11 km long and 8 km wide so those are the limits to which sequences can be traced, and in general, the sequences range from 1 to 10 m thick. Also, the study area is not large enough to trace the sequence boundaries to their correlative conformities and several characteristics of seismic data, such as frequency, amplitude, and interval velocity, necessary to perform Vail *et al.*'s (1977) facies analysis are not part of the high-frequency, sub-bottom profiling system.

The quality of the seismic records varied with the bottom sediment type and the gas content of the sediments. Hard-packed sands tended to cause multiples (denoted by M on the stratigraphic line drawings) in the records while soft mud tended to obscure the sediment-water interface. Gas content in the records (denoted by G on the stratigraphic line drawings) is believed to be the result of bacterial decomposition of organic matter in the Holocene fill sediments and causes a wipe-out of seismic reflections due to increased attenuation and rapid dissipation of acoustic energy (Anderson and Bryant, 1990).

The seismic profiles of Mobjack Bay, whose stratigraphic interpretations are located in Appendix A, indicate the existence of numerous buried channels as well as complex fill sequences which can be described as three separate sequences. In addition, several buried mounds were shown in the record and are interpreted as oyster mounds due to the warping of the seismic signal which suggests a hard substance. Selected portions of tracklines, represented by both stratigraphic line drawings and a reduced copy of the original data, are used in the text of this report. Their locations are shown on Figure 19.

Based on the morphologic features of the paleochannels, their relative positions, and their fill sequences, reconstruction of the paleo-systems and their geographic distribution within Mobjack Bay have been made. During the last glaciation, a deep fluvial channel and interfluves were formed by the confluence of the paleochannels of the Ware, North, and Severn Rivers (Figure 20). The channel was incised into Tertiary material, denoted T_m, which is recognized by the series of long, strong continuous, subparallel reflectors (Halka *et al.*, 1989). It is possible that several of the interfluves present in the seismic records are actually Early Pleistocene in age, but that determination could not definitely be made so they all will be designated as T_m. The paleochannel exiting Mobjack trends eastward presumably to tie in with the paleochannel mapped by Colman and Hobbs (1987).

The East River paleochannel is small compared to the other three rivers entering the present Mobjack Bay, and even today it is not nearly as wide as the North, Ware, or Severn. In addition to the East River, small tributary paleochannels were mapped for what are known today as Caucus Bay, Browns Bay, Monday Creek, and Pepper Creek.

Seismic sequences are bounded by surfaces of discontinuity which are defined by interpreting the patterns of reflection termination. These sequences were then correlated over the entire study area. In general, three fill sequences

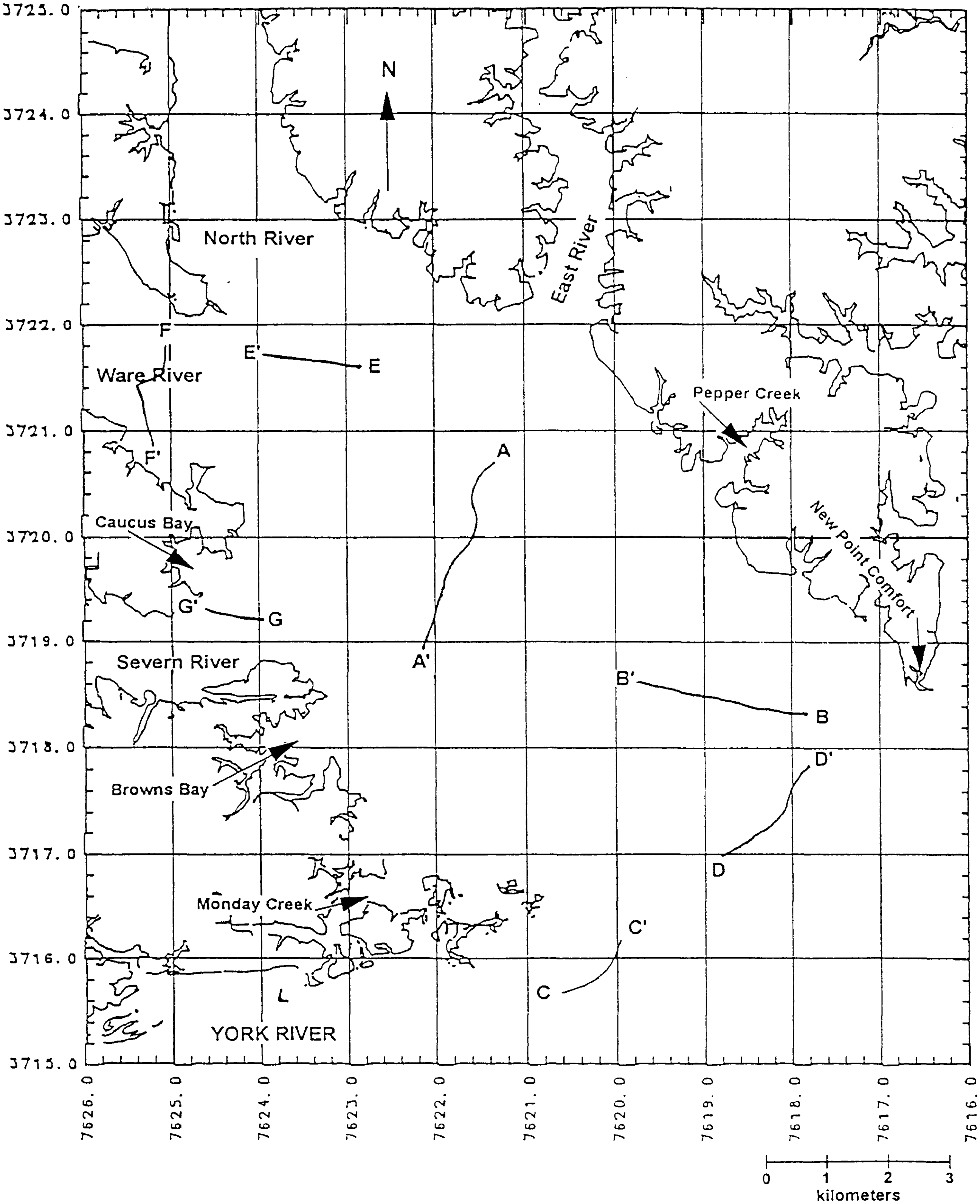


Figure 19. Locations of selected seismic lines used in the text.

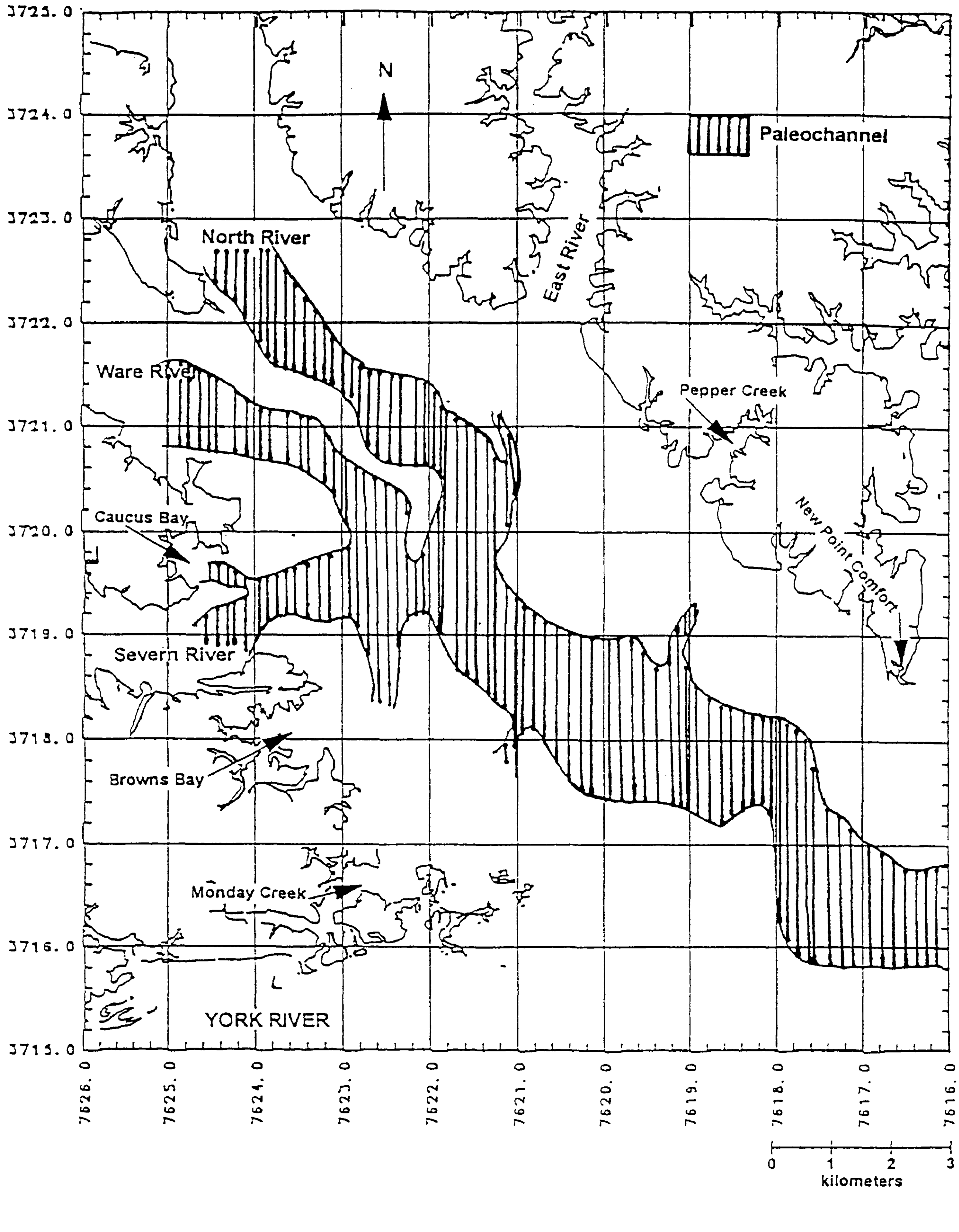


Figure 20. Map of the Late Pleistocene paleochannel system in Mobjack Bay.

were identified in the seismic record of Mobjack Bay, all of which are assumed to be Holocene in age since there was no evidence of an erosional event between sequences. If the sequences were deposited earlier than the Holocene, erosive and weathering forces acting on the exposed areas during the last sea level lowstand would have been represented in the data as an identifiable erosional truncation type of reflector termination between the sequences. Since this study did not include any cores, it may prove difficult to assign dates to the seismic facies, but relative ages can be assigned by using data from outside the study area in previously published reports. Harrison *et al.* (1965) found that the dates of the Cape Charles channel fill, representing the current sea level transgression, range from about 8 to 15 ka.

Seismic line A (Figure 21) is a south southwest trending line that crosses the middle of Mobjack Bay looking downstream and describes its main paleochannel whereas line B (Figure 22) is an east-west trending line that shows the lateral extent of the paleochannel on the eastern side of the present Mobjack Bay mouth. A break in the trackline A-A' (Figure 21) is denoted by the parallel lines. From just past mark #56 to mark #60, only gas was observed on the original record. The seismic sections are divided into seismic sequences based on the criteria of onlap, downlap, toplap, and truncation and facies have been identified using reflection configuration. Subaerial erosion of coastal plain sediments during the last sea level low stand caused the underlying unconformity in the seismic records of Mobjack Bay.

In general, three depositional sequences are identifiable. Unit Q1 is defined as a fluvial deposit that is separated from the overlying sequence by a flooding surface. This surface shows minor erosion in the paleochannel and the

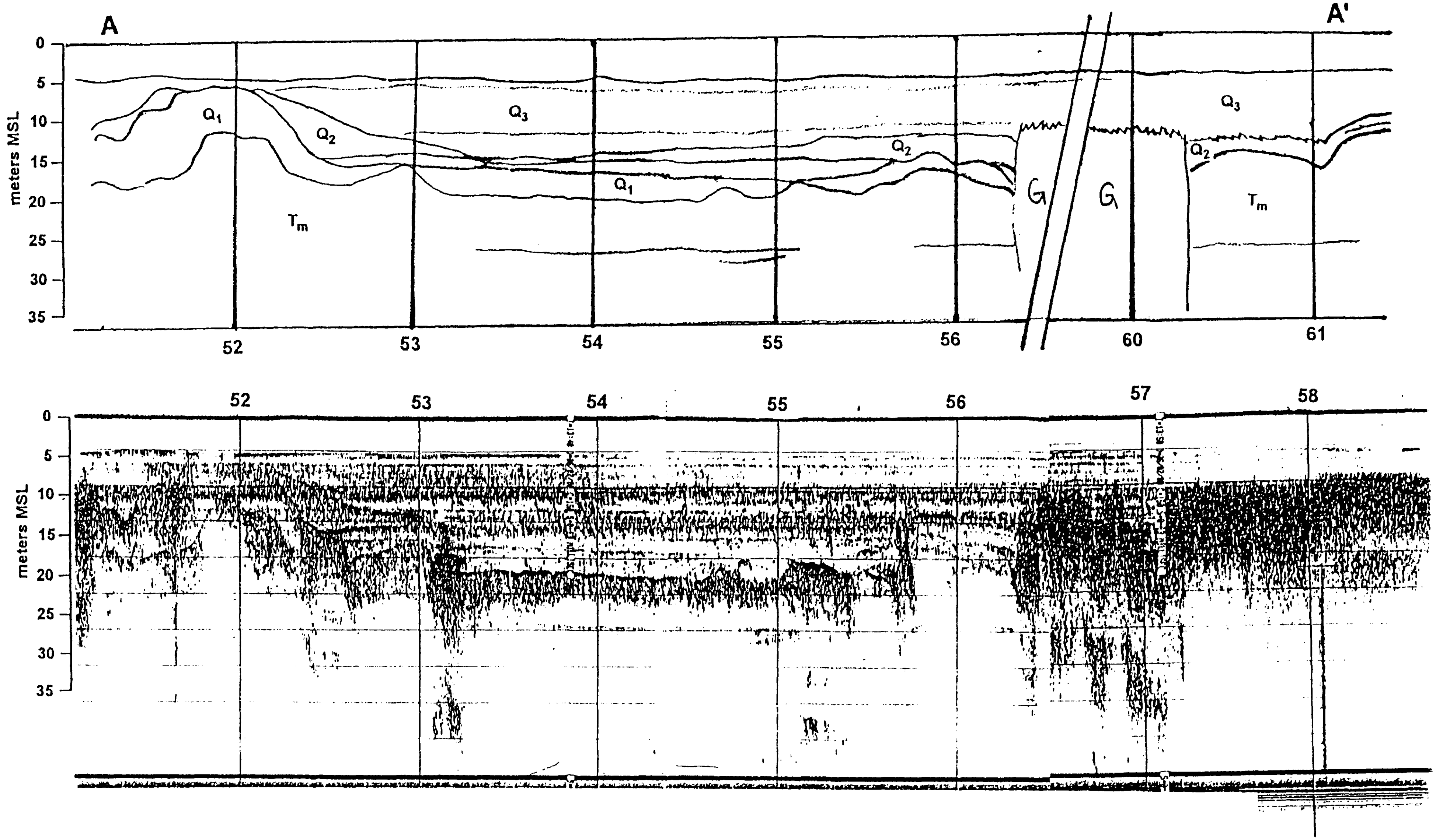


Figure 21. Seismic line A to A' crosses the middle of Mobjack Bay.

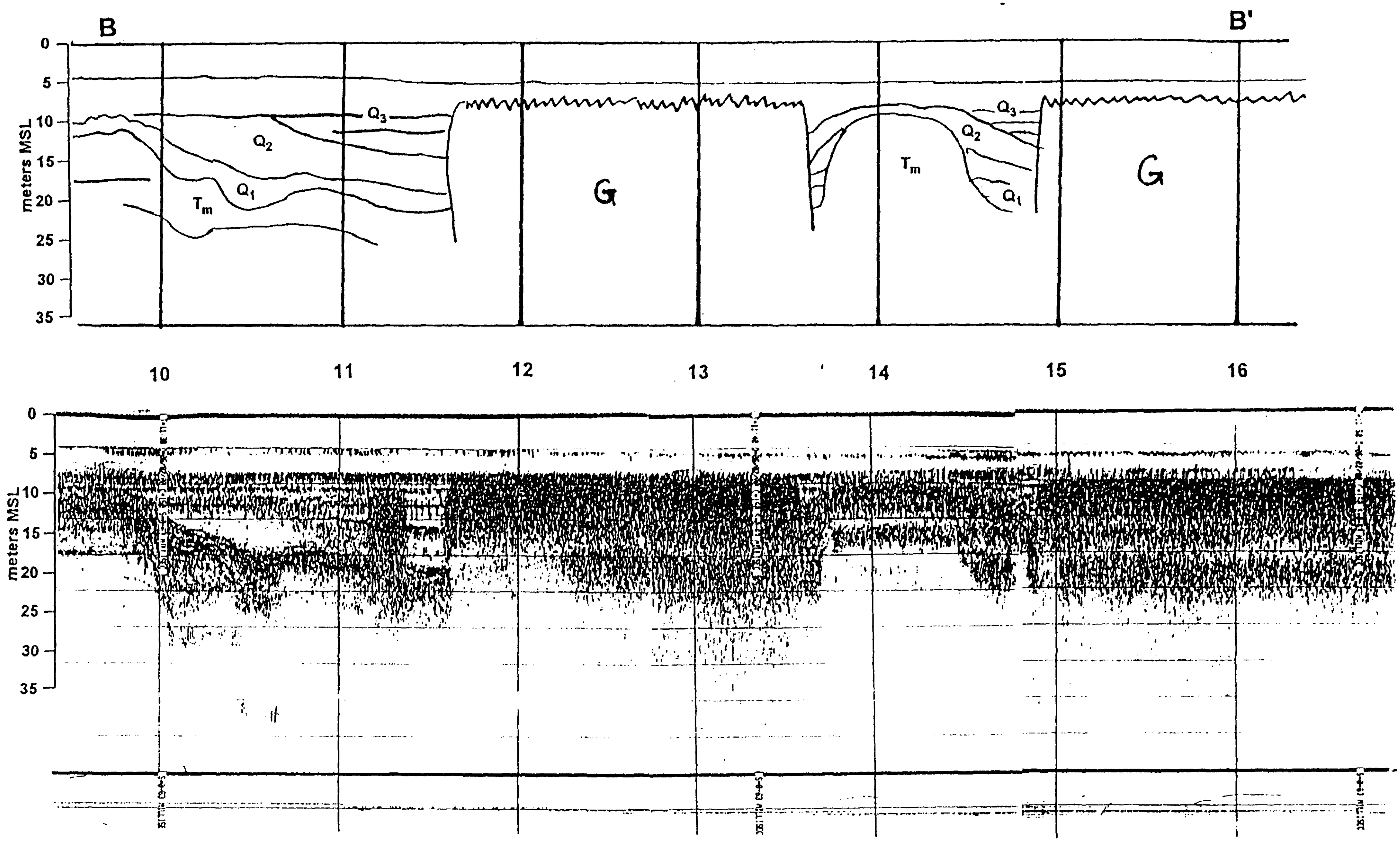


Figure 22. Seismic line B to B' describes the lateral extent of the Mobjack Bay paleochannel.

sequence itself exhibits discontinuous, relatively strong, irregular reflections. In Mobjack, particularly on the eastern side of the Bay, significant deposition occurred within this sequence on the margins of the channel (Figure 21 and 22) creating a conformable upper boundary. Based on Hack (1957), this unit is assumed to consist of sand and fine gravel. Nichols *et al.* (1991) found that this unit in the James River estuary consisted of fluvial deposits overlain by fluvial influenced estuarine deposits; however, there is no way to differentiate between the two types of deposits.

Unit Q2 generally shows gentle onlap against the underlying fluvial sequence while the upper boundary is characterized as toplap. Toplap is indicative of a nondeposition hiatus which occurs when sea level is too low to allow further deposition. Above the base level, sedimentary bypassing or even minor erosion may occur while prograding strata are deposited below (Vail *et al.*, 1977). This fill sequence is particularly evident in the three large tributary paleochannels but is not as thick in the deepest portions of the main paleochannel. The origin of Q2 can not be definitely determined without cores, but it could represent fine sands or mud originating from paludal or partially restricted estuary deposits (Nichols *et al.*, 1991).

Unit Q3 is an onlap fill sequence that is characterized by relatively weak, long smooth, continuous reflectors. Colman *et al.* (1990) found that this sequence was fine-grained, consisting of muddy sand and silt deposited in an open bay environment. In most of the study area, this layer of sediment, with different acoustic properties than the channel fill, covers the entire bay and probably represents the smooth, continuous sea level rise during the past 3,500 years. Interestingly, this present fill sequence has not yet completely covered all of the sand shoals on the margins of the bay (Appendix A1-2, A1-3, A2-2, A2-3, A3-3, A4-6).

At the western side of the mouth of Mobjack, other sequences were recorded on the seismic records but are only identified as undivided Pleistocene sequences (P_u). The difference between Tertiary and Pleistocene sediments in this area was clearly evident since a York River paleochannel (Figure 23, seismic line C) is incised into Tertiary material and covered by Early Pleistocene sediments. Farther along the trackline (Appendix A5-1), the paleochannel identified in this study as the Mobjack Bay paleochannel cuts into the Pleistocene and probably the Tertiary sediment.

The York River paleochannel (Figure 23) was mapped by Carron (1979), but the age was not determined. As the location of the channel is slightly north of the present York River, it was probably cut during the Stage 6 glaciation at the same time as the Eastville channel was formed. In addition, at least one erosional event prior to the formation of Mobjack Bay paleochannels is evident in the seismic records on the York Spit (Figure 24, seismic line D). These sediments were probably deposited and eroded during the many sea level oscillations in the Stage 5 and 3 interglaciations which created the Tabb Formation.

Channel and Fill Dimensions

Both the location and stratigraphy of the paleochannels indicate that they were formed during the last sea level lowstand. The maximum axial depth of the major river paleochannels in Mobjack and the maximum thickness of fill units were made by direct graphic measurement on the seismic profiles (Table 2) and

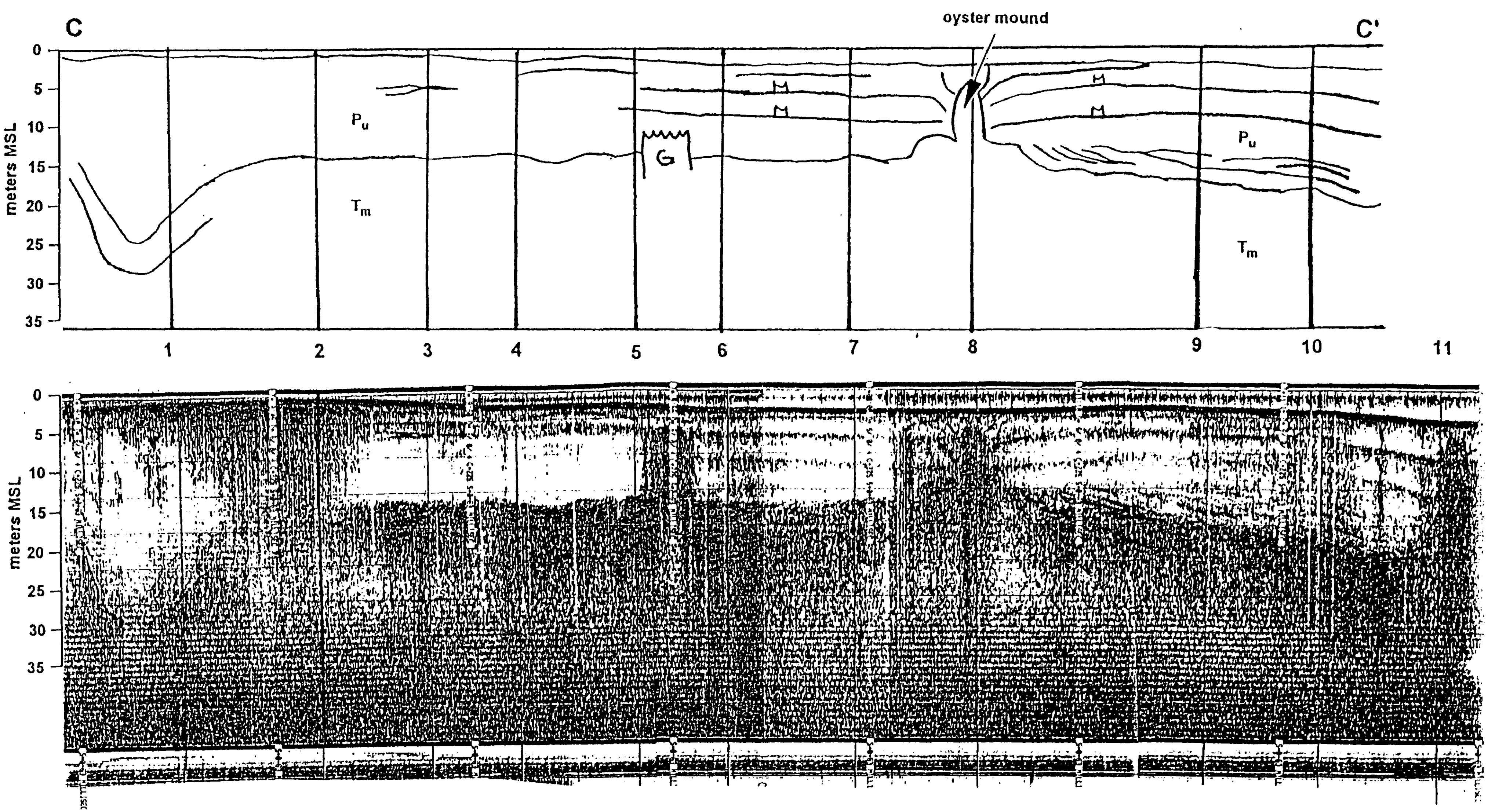


Figure 23. Seismic line C to C' is located on the western margin of Mobjack Bay.

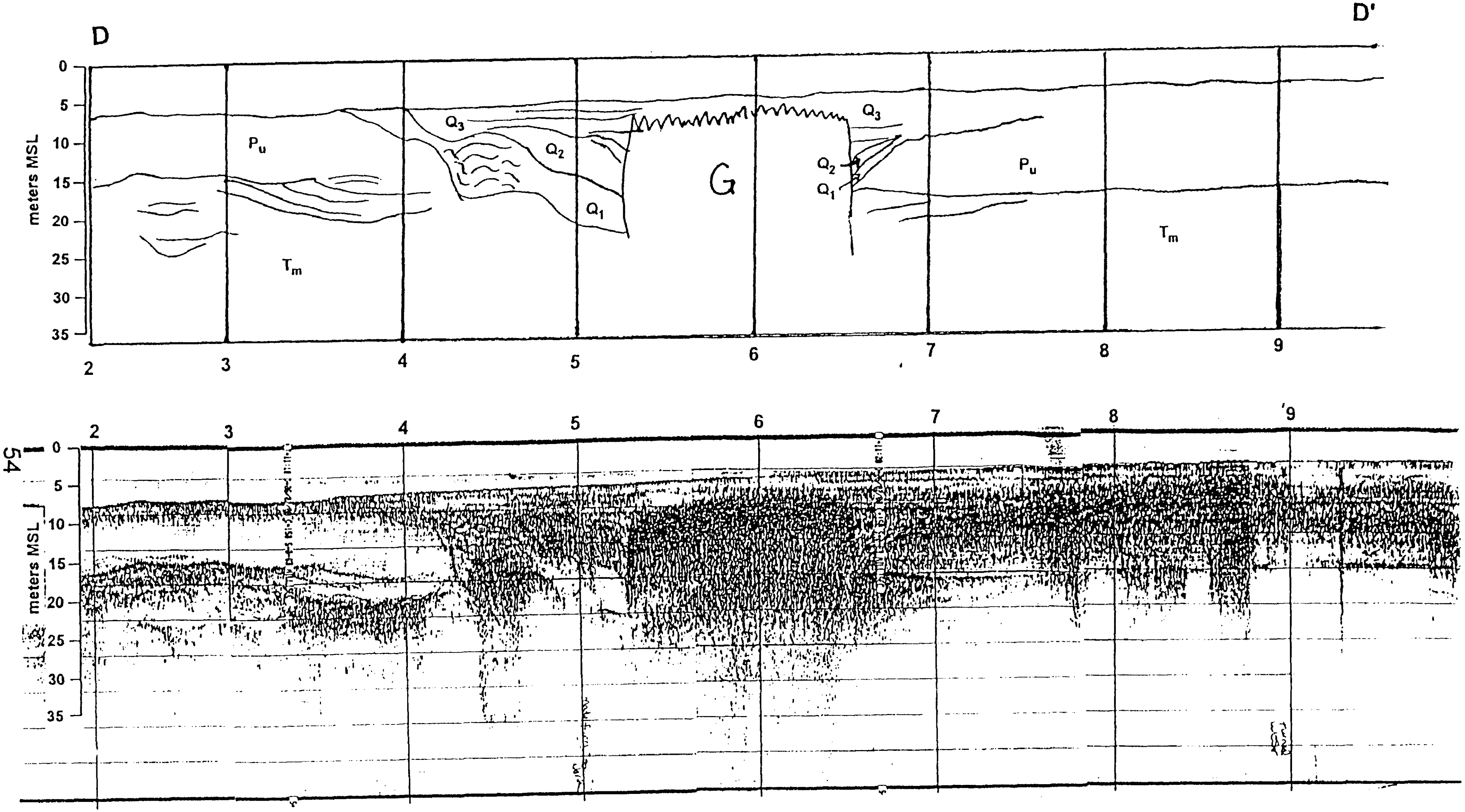


Figure 24. Seismic line D to D' shows the paleomorphology of York Spit.

are assumed to be representative of the original channels even though the channels could have been modified by erosional and depositional processes. The maximum depth of the main paleochannel exiting Mobjack Bay had to be projected downward since biogenic gas obscured the deeper portions.

Table 2. Paleochannel Depths and Fill Dimensions

		Channel Name			
		North River	Ware River	Severn River	Main Channel
Present Depth to Bottom	(meters MSL)	7	6.5	5	5
Depth to Unconformity	(meters MSL)	17.5	15	20	25-30
Width	(kilometers)	1.6	1.4	0.13	1.8
Q1 Thickness	(meters)	3.5	4	6	7
Q2 Thickness	(meters)	4.5	7	5	5
Q3 Thickness	(meters)	5	6	4.5	10

The main channel is relatively narrow at the confluence of the three rivers, only 1.3 km and at the mouth of Mobjack Bay, 1.1 km, where it constricts and turns southeast before widening again and heading east. However, the mid section of the channel is wider, measuring 3 km across. The value listed in the table is the average width along the channel. The length of the main channel from the confluence to the mouth is 7.7 km. The significantly larger amount of deposition in the Q3 sequence at the mouth is indicative of a transgressive sequence where the most seaward portion of the paleosystem will prograde sooner than the upstream constituents (Nichols *et al.*, 1991).

During the last sea level lowstand, the shoreline was on the continental shelf edge, approximately 120 m below present sea level (Fairbanks, 1989). Colman *et al.* (1990) found that the base of the Cape Charles paleochannel was at 50 meters below present sea level at the mouth of the Chesapeake Bay and had a calculated 0.0024 m/km seaward slope of the axial channel. Even though an accurate depth for the main Mobjack paleochannel could not be obtained, the estimate of 25-30 meters below present sea level (Table 2) is reasonable since this number fits with the depth given for the Cape Charles channel near the York River in Colman *et al.* (1990).

On the seismic records, the paleochannels exhibit a flat bottomed shape rather than the typical V-shaped valley of paleochannels. In addition, smaller channels were shown as part of sequences Q2 and Q3 (Appendix A3-2, A3-3, A4-5). These V-shaped valleys did not appear to be incised into the underlying sequence, but rather developed as part of the sequence when the estuarine channels began to meander due to infilling.

Sedimentation Patterns

In most areas of Mobjack Bay, Holocene deposition has completely filled the paleochannels. The smaller creeks no longer have any bathymetric expression in the bay. However, some of the interfluves created during the last sea level lowstand have not been totally covered (Appendix A1-2, A1-3, A2-2, A2-3, A3-3, A4-6) and occasionally are the present sediment-water interface. Figure 25 is a contour map of the present bathymetry of Mobjack Bay obtained from the sub-bottom records. It describes the location of the sandy interfluves (denoted as I on Figure 25) as well as the current expression of the main

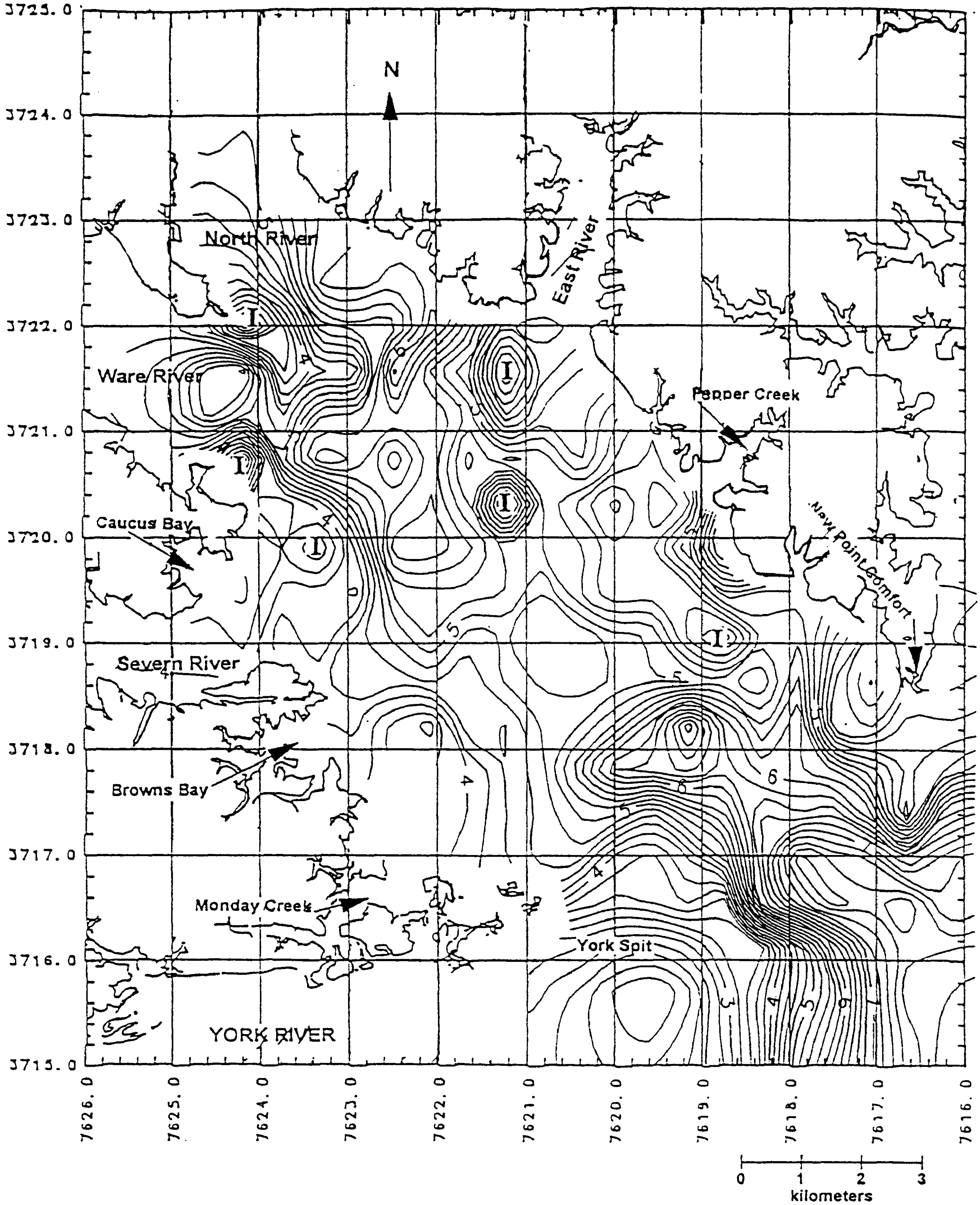


Figure 25. Contour map of the present bathymetry of Mobjack Bay.

paleochannel. Contours drawn near the shoreline are not necessarily correct; they were inferred by Surfer (Golden Software, Inc., Colorado, 1989) since the shallowness of Mobjack Bay's margins precluded sub-bottom profiling. The deepest part of Mobjack Bay is at the mouth between the two sand shoals presumably where the axial paleochannel exited.

The main channel exiting Mobjack Bay was obscured, for the most part, by biogenic gas. However, the seismic records indicate that the while the fluvial sequence, Q1, was slightly irregular, both Q2 and Q3 were characterized by long, continuous, relatively weak reflectors suggesting even deposition over the base of the channel (Figure 21). The margins of the channel, on the other hand, had significant deposition in Q1 on the eastern side of the bay.

The interfluves, located at the confluence of the Ware and North rivers in the present Mobjack Bay, are probably Tertiary and Early Pleistocene in age overlain by a thin layer of Holocene sand eroded by wave action against Pleistocene sediments. The flat between the mouths of the Ware and Severn rivers as well as the flat off the mouth of the East River are also interfluves of this age, and seismic evidence suggests the same genesis process. However, from the East River to the mouth of Mobjack Bay as well as certain portions of the river paleochannels, significant deposition of the Q1 sequence on the margins of the channel created the sand flat that is overlain with Holocene sediments (Appendix A1-4, A2-3, A2-4, A3-2, A4-5). York Spit, on the western side of the mouth of Mobjack seems to be Pleistocene in age with Holocene sediment prograding (Figure 22).

The three prominent river paleochannels can be used to illustrate the infilling of Mobjack Bay since their channels are relatively gas-free. Figures 26 (seismic line E), 27 (seismic line F), and 28 (seismic line G) are the North, Ware and Severn river paleochannels, respectively, drawn to show their morphologic expression since the last sea level lowstand. The orientation of these lines varies: E - E' travels east-west, looking south or downstream; F - F' travels approximately north-south and faces east or downstream; G - G' is an east-west line facing south or upstream. All three show similar trends in the process of infilling. The relatively flat base of the paleochannel is incised into Tertiary sediments creating steep sides. The infilling of sequences Q1 and Q2 generally made the sides of the channel less steep giving it more of a U-shape. With the deposition of Q3, the shape of the channel consisted of mounded sand flats separated by a flat, muddy bottom.

The Ware River varies from this model in that a possible sand spit developed due to the meandering of the tidal channel and occurs in both Q1 and Q2 sequences. Looking downstream, this channel appears to be infilling from the left or from the interfluve between the Ware and Severn rivers. As sea level rose, abundant material would have been available from erosion of the interfluve and deposition into both of these rivers.

The Severn River had a small part of its base somewhat deeper than the rest such that the channel was not completely flat. During the formation of the Q2 sequence, sediment appeared to be filling in the channel from both sides, but the side of the channel adjacent to the sand flat off of Guinea Neck appeared to be accreting more rapidly. This is even reflected in the present bottom of the Severn River. The paleochannel bank is nearly covered by Holocene sediments on the south bank but not on the north.

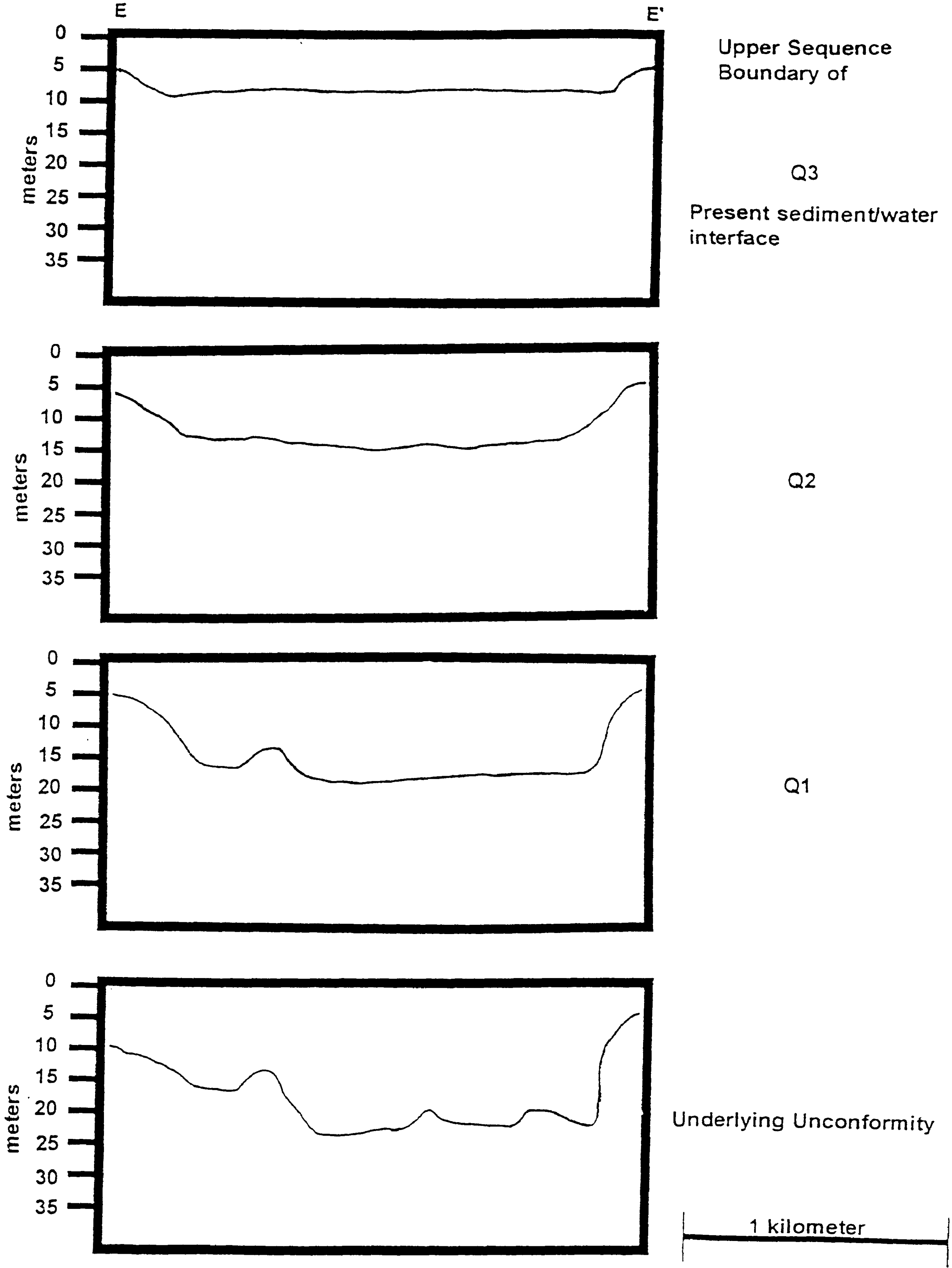


Figure 26. North River upper sediment boundary of individual sequences.

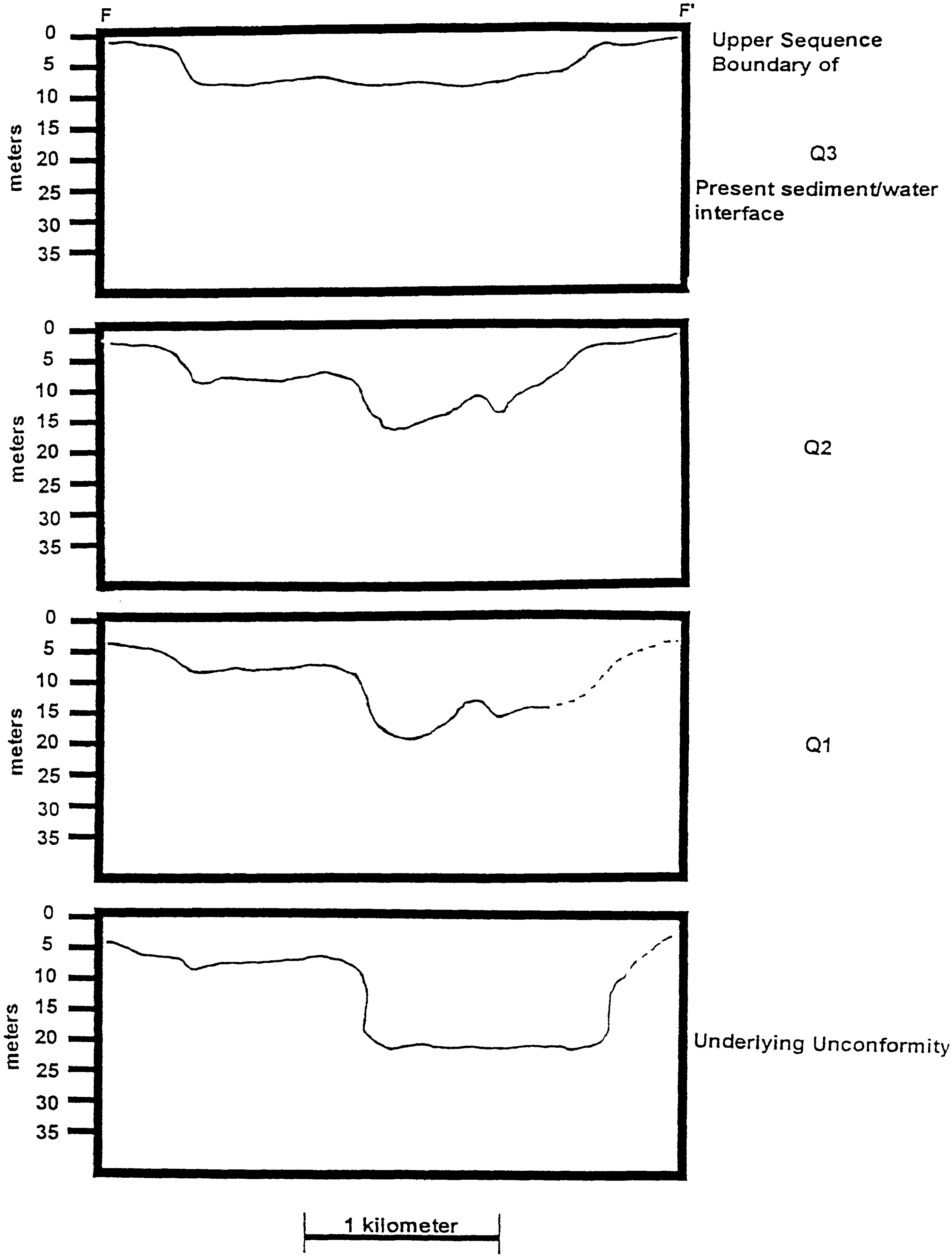


Figure 27. Ware River upper sediment boundary of individual sequences.

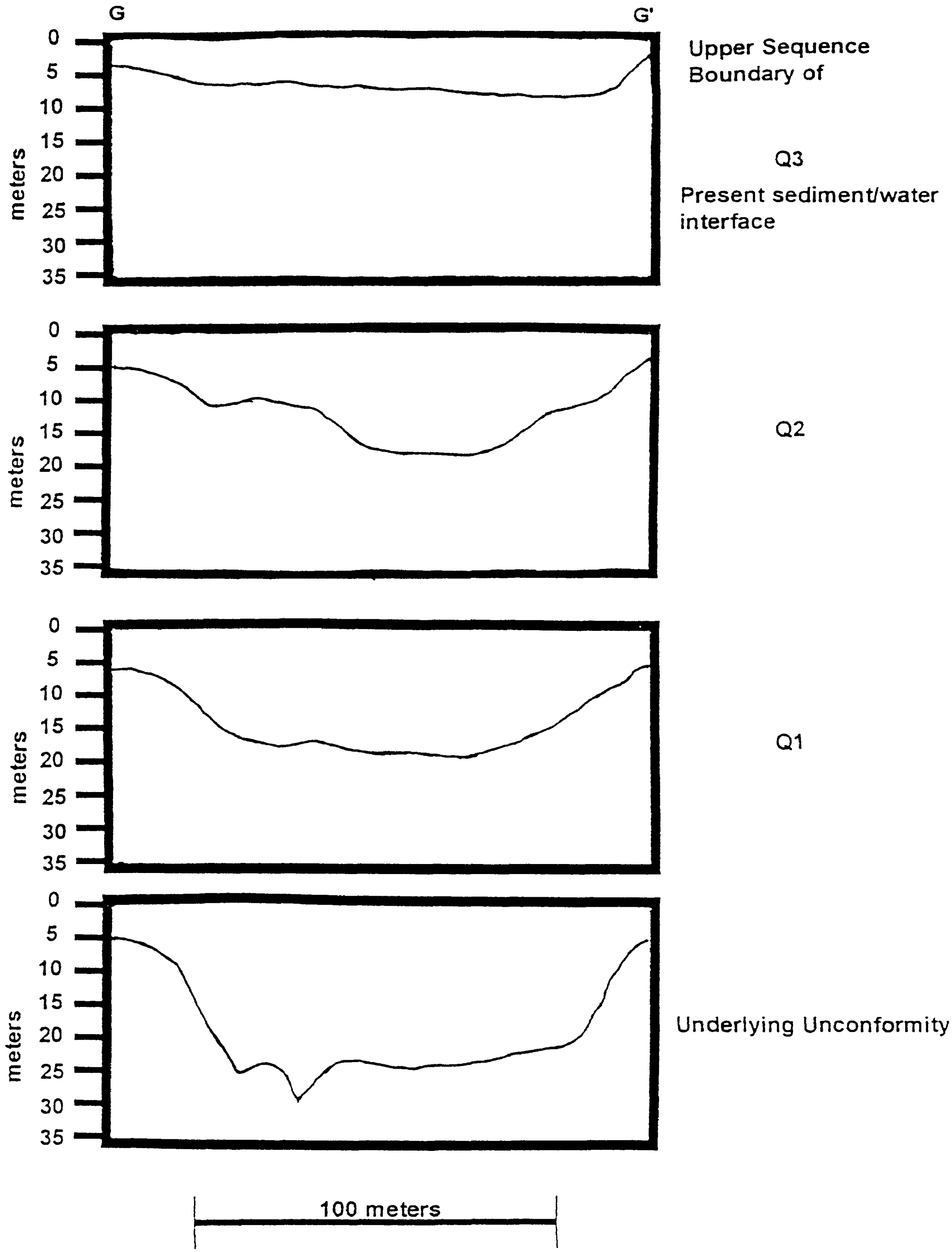


Figure 28. Severn River upper sediment boundary of individual sequences.

There is some evidence, from the sub-bottom profiles, that the mouth of Mobjack Bay has accreted more rapidly in the past 3,500 years, assuming Q3 was deposited during this time period, due to the transport of material alongshore or from the mouth of Chesapeake Bay. However, the paleochannel fill sequence Q3 (Figure 24) is slightly convex upward and had the largest maximum sequence thickness at the mouth of Mobjack Bay as compared to the fill sequence in the river paleochannels. Also, sediment appeared to prograde from the south on York spit to form Q1 and Q2 (Figure 26). On the eastern side of the mouth, the majority of the sediment seemed to prograde channelward from the north (Figure 23).

The sediment accumulated in the different sequences at various rates and in diverse patterns. Assuming that Q3 is the sequence that has been deposited in the 3,500 years of relatively stable sea level rise, the accretion rate would be approximately 0.3 meters/century in the axial channel where the maximum amount of deposition has occurred. While this is not an absolute number, it may indicate that the accretion rate has increased since Byrne *et al.* (1982) stated an accumulation rate of 0.5 meters/century.

Sediment Characteristics

The results of grain size analysis for sediments sampled in Mobjack Bay are shown in Table 3. In general, the surficial texture changes landward from coarse to fine to coarse, and as a whole, the sediments collected for this study agreed with the results of Byrne *et al.* (1982). Nearly half of the sediments analyzed for this study were classified as sand based on Shepard's (1954) ternary classification; these mostly sand samples were located on the margins of

Table 3. Grain-size analysis results.

						Sand Fraction			
	Water					Mean Phi		Sorting	
Sample #	Depth (m)	% Gravel	% Sand	% Silt	% Clay	Size	Class	Value	Class
MB 1	5.5	0.0	93.7	3.4	2.9	2.5245	Fine	0.5162	Mod Well
MB 2	6.1	0.0	87.8	5.3	6.9	2.9861	Fine	0.8001	Mod
MB 3	4.5	0.0	90.1	3.5	6.3	2.5364	Fine	0.8403	Mod
MB 4	7.9	0.0	29.9	38.0	32.1	2.8240	Fine	0.9643	Mod
MB 5	7.3	0.0	10.9	46.7	42.4	3.3852	Very Fine	0.6451	Mod Well
MB 6*	6.7	0.0	3.4	52.7	43.9				
MB 7*	6.1	0.4	1.5	51.9	46.2				
MB 8*	6.1	0.0	1.0	54.9	44.1				
MB 9*	6.1	0.0	1.2	54.9	43.9				
MB 10*	6.1	0.0	0.4	52.4	47.2				
MB 11*	6.7	0.0	0.3	43.5	56.1				
MB 12*	7.0	0.0	0.4	41.5	58.1				
MB 13*	7.9	0.0	0.9	44.1	55.0				
MB 14	8.5	0.0	76.8	7.5	15.6	2.4507	Fine	0.4313	Well
MB 15*	7.6	0.0	1.5	31.2	67.3				
MB 16*	7.6	0.0	5.8	30.4	63.7				
MB 17	3.6	0.0	96.4	1.9	1.8	2.3621	Fine	0.4733	Well
MB 18	4.2	0.0	95.2	2.3	2.6	2.0632	Fine	0.6332	Mod Well
MB 19*	7.6	0.0	6.7	40.4	52.9				
MB 20	7.0	0.0	49.0	23.5	27.5	3.1669	Very Fine	0.8516	Mod
MB 21	3.3	0.0	92.9	0.8	6.3	2.4749	Fine	0.4179	Well
MB 22	1.7	0.6	88.0	3.3	8.0	2.3594	Fine	0.8443	Mod
MB 23	2.3	0.0	93.2	5.0	1.8	2.1295	Fine	0.7509	Mod Well
MB 24*	7.3	0.0	3.2	29.5	67.4				
MB 25	5.2	0.0	91.0	1.2	7.7	2.2449	Fine	0.5042	Mod Well
MB 26	3.6	0.0	92.0	1.1	6.9	2.1626	Fine	0.7333	Mod Well
MB 27	1.8	0.0	93.3	0.4	6.3	2.6028	Fine	0.4841	Well
MB 28	2.4	0.0	81.5	7.2	11.3	2.5884	Fine	0.4697	Well
MB 29	3.3	0.0	52.6	31.5	15.9	3.4630	Very Fine	0.4851	Well
MB 30	2.9	0.0	94.3	3.0	2.8	2.4616	Fine	0.2606	Very Well
MB 31	6.1	0.0	79.4	10.0	10.6	2.1423	Fine	0.5425	Mod Well
MB 32*	5.8	0.0	2.0	52.9	45.0				
MB 33	4.2	0.0	93.5	3.1	3.4	2.2954	Fine	0.6458	Mod Well
MB 34	2.8	0.0	95.1	2.1	2.8	2.0434	Fine	0.4968	Well
MB 35	1.8	0.0	95.2	2.1	2.7	1.8682	Medium	0.7201	Mod Well
MB 36	3.3	0.0	91.4	3.3	5.3	1.6931	Medium	0.7524	Mod Well
MB 92-1*	5.5	0.0	0.9	44.3	54.9				
MB 92-2	1.5	0.0	94.5	0.2	5.3	1.9294	Medium	0.3251	Very Well
MB 92-3	3.0	0.0	89.5	0.5	10.1	2.0722	Fine	0.4430	Well
MB 92-4	4.5	0.0	87.3	4.6	8.1	2.5020	Fine	0.5154	Mod Well
MB 92-5	6.1	0.0	67.7	15.4	16.8	2.7267	Fine	0.8342	Mod

* Samples that contained less than 10% sand were not RSA'd

the bay (Figure 29) where sand is supplied predominantly by shoreline wave erosion of Pleistocene sediments or deposited by longshore currents. Clayey silt is located in the central portion of Mobjack, but the silty clay has extended further into the bay than reported by Byrne *et al.* (1982) and is not exclusively in the mouths of the Ware and North Rivers.

In the northern section of the bay, the change between bottom sediment types is abrupt. The shallow, sandy flats and shoals along the margins of the rivers quickly give way to silty clay in the channels. In the wider, middle portion of the bay, there appears to be transition zones between the clayey silt region and the sandy margins. The mouth of Mobjack Bay is a predominantly sandy area; however, it does have a transitional area between the clayey silt region and the two large sand shields on either side of the mouth. Byrne et al. (1982) reported a band of finer sediments running southeast from the mouth of Mobjack Bay, but in the current study, only sand was found. This is probably due to the locations of the sediment samples.

Only two samples contained any gravel-sized material and that was actually shell hash. The sand was classified as medium to very fine. The Rapid Sediment Analyzer (Table 3) showed that the very fine sand is limited to the deeper portions of the bay and in the river channels while the fine to medium sized sand is located in the shallows. The sand shoal on the west of Mobjack Bay may reflect a dual source of sand. Since grain size fines seaward on the shoal and the rivers transport little sand, the upper portion may be a reworked relict material from Mobjack Bay's shoreline (samples 35, 36) while the portion at the mouth may be deposition of shelf sediments (samples 1, 2, and 3).

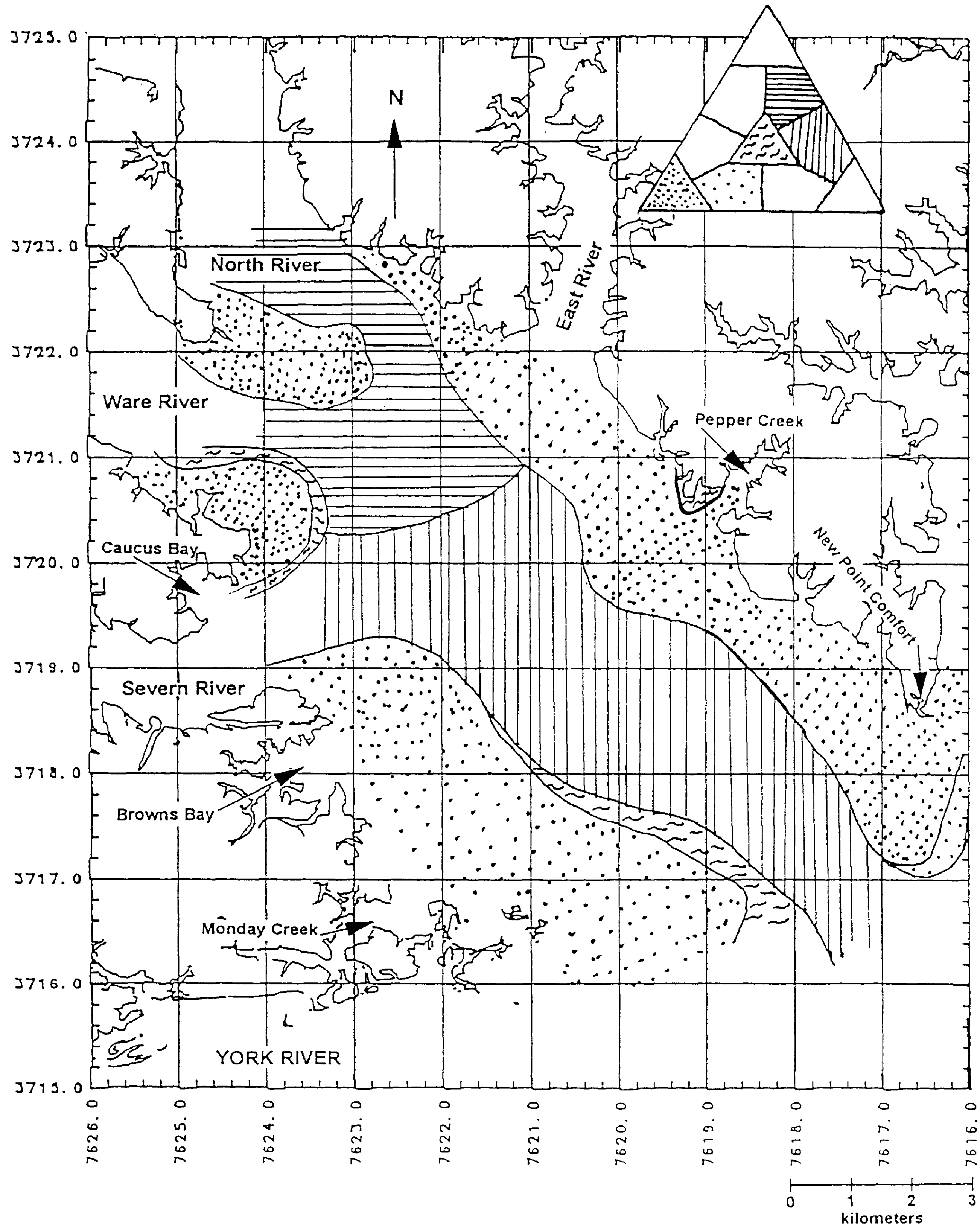


Figure 29. Map of the distribution of sediments based on ternary classification.

VII. DISCUSSION

Development of Mobjack Bay and its Paleochannels

The geologic history of the Chesapeake Bay is well documented by Hack, 1957; Meisburger, 1972; Colman and Hobbs, 1987; Colman *et al.*, 1990; and others. From these studies, three Quaternary paleochannels and their associated fill sequences have been reconstructed from seismic profiles, and their ages determined by radiocarbon dating. Each channel and fill sequence represents the fluvial channel and subsequent infilling of the Susquehanna River during sea level lowstands and highstands, respectively. These paleochannels are identified as the Exmore, Eastville, and Cape Charles.

Coastal plain sediments are exposed to erosional forces during a marine regression, and river channels are incised into older sediments to transport water to the ocean creating the underlying unconformity shown in seismic records. As sea level rises, sand and gravel accumulates in channels. Eventually the flow becomes partially restricted estuarine flow and finally estuarine. At the limit of sea level highstand, an erosional scarp or beach forms and seaward deposition of eroded sediments creates a terrace feature.

Approximately 187 ka, sea level was 14 meters above present mean sea level (Peebles, 1984), and during this sea level highstand the Shirley Formation, whose landward limit is the Hazelton and Big Bethel scarps, was deposited. Based on the location of these scarps, Peebles (1984) suggested that the York River was situated slightly north of its present course while the Piankatank River was located somewhat south. About 30,000 years later, with the onset of the Stage 6 glaciation which lowered sea level, the Eastville paleochannel was carved into the underlying sediments. Evidence of a York River paleochannel which would correspond to this time was found in the seismic records (Figure 23) supporting Peebles (1984) hypothesis. With the onset of the Stage 5 and 3 interglaciations approximately 80 ka, several cycles of sea level oscillations created the three members of the Tabb Formation. The formation of the scarps associated with the Tabb Formation as well as successively lower sea level highstands caused the York and Piankatank Rivers to move to their present position. When the latest glaciation began, the configuration of the Middle Peninsula had been so altered by the movement of the rivers and the development of scarps that a new drainage channel formed in Mobjack Bay.

There was no evidence in the seismic records that the four rivers entering the present Mobjack Bay existed prior to the last glacial maximum so the Mobjack fill sequences can not be related to the Early Pleistocene Exmore and Eastville paleochannel fills shown to exist in the Chesapeake Bay. The confluence of the North, Ware, and Severn paleochannels formed during the last sea level lowstand created a channel exiting the mouth of today's Mobjack. This paleo-river presumably flowed southeastward to become a tributary of the ancient Susquehanna River expressed in seismic records as the Cape Charles channel.

Seismic records support this claim since only one underlying conformity was observed in the records overlying a sequence consisting of subparallel, relatively weak, fairly continuous reflectors which is widely recognized as Tertiary material (Shideler *et al.*, 1972; Colman *et al.*, 1988; Colman *et al.*, 1989; Halka *et al.*, 1989). In addition, only fill sequences are observed in the records suggesting that the sediments were deposited after the end of the last glaciation.

Sequence Q2 did show minor erosion in isolated areas, but the extent of sea-level fall during the last glaciation would have resulted in much greater erosion if the sequence had been deposited before it.

At the end of the last glaciation, sea level was approximately 120 meters lower than it is today (Fairbanks, 1989). As it began to rise 18 ka, coarse sand and gravel accumulated in the channels creating sequence Q1. Between 9,500 and 6,000 years ago, the Chesapeake Bay as well as Mobjack began to be influenced by tidal and wave energy. Since sequence Q2 is bounded by toplap, sea level had generally not risen over the banks of the paleochannel when this sequence was deposited in a restricted estuarine environment. About 3,500 years before present, Mobjack probably reached its present configuration as sea level rise slowed but had already risen to such a height that the confluence of the Ware and North Rivers is now the head of Mobjack Bay and the Severn River is a tributary. Since that time, sequence Q3 was deposited under estuarine conditions.

Application of the Facies Model

The application of a facies model to paleochannel fill sequences of a marine transgression is appropriate and useful as sediment preservation potential is high because of its location in a paleovalley (Kraft, 1971). How the sediments accumulate relate to many factors including the antecedent geology upon which the sequences form as well as the relative importance of forces (tides, waves, and riverine flow). By applying a model to the information gathered from a seismic study to determine the development of an estuary, we can learn what forces have been primarily important in the formation of the system and how the system has responded to modern conditions.

Presently, the Chesapeake Bay and Mobjack Bay are affected by low to moderate intensity tidal and wave processes (Colman *et al.* 1988). Tidal forces extend all the way up the rivers, but no modern tidal channel exists. Due to its exposure and relatively wide mouth, waves from the south, southeast, and southwest impact the Bay (Hardaway *et al.*, 1982). Riverine energy and sediment input is minimal to Mobjack Bay from its tributaries.

Without cores, it is difficult to determine the lateral succession of transgressive facies since the type of facies (*i.e.* sandflat, mudflat, or marsh) are not known. However, specific information gathered from seismic profiles can be interpreted and applied to a model to classify an estuary. Due to the relatively small scale of Mobjack on which the model is applied, some of the facies described in the model may not be represented.

The main axial channel exiting Mobjack Bay as well as the river paleochannels tended to accrete channelward and vertically. Large sand deposits accumulated on the margins of the channel in Q1 (Figure 21) while Q2 was limited to the channel except for a few areas where it overtopped relatively low interfluves (Appendix A1-1, A2-3). In these two sequences, there was no longitudinal trend; however, Q3 was much thicker in the axial channel than in the river paleochannels (Table 2). Subaqueous shoals appeared to develop near the confluence of the three rivers and up the river paleochannels from processes occurring during the deposition of Q1 and Q2, but not in Q3. The slight convex upward shape of Q3 at the mouth of Mobjack may indicate that, in this area, the sediment supply is external.

Based on the model described earlier, only two possible classifications, wave-dominated and tide-dominated, exist for the description of facies development within Mobjack Bay. However, in reality, the bay is influenced by both wave and tidal energy, and its shape is a compromise between the two possible end-members as well as its inherited geometry. Wave dominated estuaries tend to develop in irregularly shaped paleochannels, such as in Mobjack, since tidal amplification does not readily occur (Nichols and Biggs, 1985). However, based on the Dalrymple *et al.* (1992) synthesis of a tide-dominated estuaries, sand tends to occur in the tidal channel whereas muds accumulate on the margins. The existence of several shoals (Figures 27 and 28) as well as migrating tidal channels (Appendix A3-2, A3-3, A4-5) suggests that tidal forces were probably more important than waves during the formation of Q2. In addition, overtopping of lower interfluves probably created mudflats or marshes along the edges of the paleo-Mobjack estuary.

Finkelstein and Hardaway (1988) studied Late Holocene estuarine and marsh sediments deposited along the York River. They found that the rapid sea level rise during the mid-Holocene resulted in the deposition of estuarine sediments creating a wide expansive marsh system. However, as sea level continued to rise, estuarine waters would have overran the banks of Mobjack Bay's paleochannels and spread over the flat subaerially eroded coastal plain overtopping the marshland. In the York River, fringing marshes developed under moderate estuarine water levels and reduced sea level rise in the Late Holocene (Finkelstein and Hardaway, 1988).

When sea level overran the paleochannel banks, the tidal wave would no longer be confined. At the same time, fetches would have increased throughout the bay allowing the generation of larger waves and the development of a wave-dominated estuary. This is evidenced by the even deposition of fines in the less energetic central portion of the Bay while sands are deposited at the mouth where waves encounter the sand shoals and flats located on either side of the Bay mouth. The bay-head delta does not exist in Mobjack as is the case when tributaries supply little sediment to the system (Honig and Boyd, 1992).

Comparison of the facies located in Mobjack Bay to the facies present in examples of the two end-members can help determine the usefulness of the facies model. The South Alligator River in Northern Australia is a macrotidal estuary with a spring tide range of 5-6 meters at the mouth (Woodroffe *et al.*, 1989). The three facies in this river consist of the characteristic "straight-meandering-straight" morphology of a tidally-dominated estuary. The funnel zone at the mouth has elongate tidal bars which make up the marine sand body, and is banked by mangroves which are analogous to the mudflats and marshes in Dalrymple *et al.*'s (1992) model. The sinuous meandering region contains no point bars but is completely surrounded by mangroves. Woodroffe *et al.*, (1989) identified the upriver straight zone as two separate facies, cuspate meandering and upstream; however, the two facies are similar in that they both have limited mangrove growth but point bars and shoals are well-developed.

Lake Macquarie is located on the southeastern Australia coast in New South Wales. Along this coast, the wave climate consists of swell and wind waves which frequently exceed four meters, and the tide range averages 1.6 meters (Roy *et al.*, 1980). Riverine input is considered low. This river has three distinct facies. A marine sand body consisting of a modern barrier sediments overlying Pleistocene barrier sand as well as a prograding, flood-tidal delta is located at the mouth. The central portion consists of a muddy, prodelta basin, and a small delta exists at the head of the estuary.

Mobjack Bay varies significantly from both end-members. It is a microtidal estuary with low wave energy and limited riverine flow. While the bay is affected by sea swell coming through the mouth of Chesapeake Bay, it does not open directly to the ocean. The mouth of Mobjack Bay has a somewhat limited sand body consisting of two shoals on either side the mouth region. The central axis of Mobjack consists of muddy sediment and is flanked by subtidal and intertidally sand flats. No bay-head delta exists since river flow is negligible.

The comparison between these three sites reveals that Mobjack is influenced by relatively low intensity waves and tides, but its present morphology is probably determined more by wave energy. During the mid-Holocene, it is reasonable to assume that tidal energy was more important since amplification of the tidal wave within the paleochannel, due to shallowing and narrowing of the channel from sedimentation, would have increased the tidal range. However, it is very unlikely that characteristic "straight-meandering-straight" morphology of the tide-dominated estuary ever developed.

Modern Sedimentation, Source or Sink

Many of the modern sand flats and shoals located along the margins of Mobjack have been shown to be reworked Pleistocene material derived from shoreline erosion deposited upon Tertiary interfluves or Q1 fluvial deposits. Also, Byrne *et al.* (1982) determined that Mobjack Bay is in the "central farfield Chesapeake Bay mouth region" since it receives sands tidally transported from the shelf (Meade, 1969; Colman *et al.*, 1988); in addition, sediments are transported alongshore down the northwestern flank of Chesapeake Bay. The sediment analysis was not conclusive as to the origin of the spit on the eastern side of the mouth; however, mean grain size was similar between the shoals inside Mobjack, which receive reworked relict material, and the shoal surrounding New Point Comfort. Fining seaward of mean sand size on the shoals within the Bay indicates that the material eroded by waves is not transported out of Mobjack. It may also indicate that York Spit is receiving sediment from an external source.

The abrupt change is grain size from the sand flats to the river channels suggests that little sand is being deposited in the deeper portions of Mobjack, particularly in the tributaries. The transition zones in the central bay indicate that the sand flats are probably prograding towards the axis of the bay.

The main paleochannel in Mobjack has been completely filled by sediments, and Q3 is even beginning to take on a convex upward shape at the mouth of Mobjack Bay. The highest interfluves of the river paleochannels have not yet been topped by Q3 deposition indicating that a major source of sediment to Mobjack is external and that the bay itself is a sink. Wave and tidal energy transports sediment down the western flank of Chesapeake Bay and from the continental shelf. These forces encounter the large shoals at the mouth of Mobjack causing the sands to be deposited, but the fines are kept in suspension and distributed to the central basin of Mobjack by the tide. Shore erosion within Mobjack also contributes to the sediment supply as indicated by the bayward prograding sand flats on the margins of the bay. The rivers contributing to Mobjack mostly carry silty clay that also is deposited in the less energetic central portion of the Bay.

VIII. Summary and Conclusions

While the Chesapeake Bay has had several incarnations during the Pleistocene as evidenced by the formation of the Exmore, Eastville, and Cape Charles paleochannels and their subsequent infillings, Mobjack Bay is a relatively young section of the Chesapeake since it did not exist prior to the last sea level lowstand. The system of paleochannels and interfluves created by erosion during the last glaciation unconformably overlies material of Tertiary or Early Pleistocene age. Three paleo-river channels converged inside the present Mobjack to form a main axial channel exiting the bay that joined with the previously mapped Cape Charles paleochannel.

The three separate fill sequences observed in the seismic records within the paleochannels of Mobjack are depositional in nature with only Q2 exhibiting minor erosion in isolated areas. Q1 consists of fluvial fill material that was deposited when stream gradients decreased as sea level rose. Q2 is assumed to be paludal in origin, deposited in a restricted marine environment when water flow was in transition from uni-directional fluvial flow to bi-directional estuarine flow. Based on facies analysis, the upper boundary of Q2 generally shows a toplap relation indicating sea level had only risen to the tops of the highest paleochannel banks and not overrun them. Q3 is a fine-grained depositional sequence that accumulated in an estuarine environment over the past 3500 years while sea level rise was relatively consistent and can be considered fairly stable.

In most areas of Mobjack Bay, Holocene sedimentation has completely filled the incised paleochannels. Sequences Q1 and Q2 are generally limited to the paleochannels themselves except in a few areas where overtopping of low interfluves occurred. The largest amount of deposition was taking place on the margin of the paleochannels while these sequences were forming, presumably from erosion of material by wave action against the shore. This is supported by the channelward deposition within the sequences. Q3, however, was deposited under less energetic conditions as evidenced by the relatively smooth, weak reflectors within the sequence. The extent of this sequence is bay-wide indicating that Mobjack Bay had reached its present form while it was being deposited. In Mobjack's bay mouth region, Q3 appears to have a convex upward shape which could indicate that a large amount of sediment is being deposited here.

Analysis of surficial sediments within Mobjack Bay revealed several trends. The deeper portions of Mobjack Bay are accumulating fine-grained material, and the shallower margins are receiving sand. Silty clay seems to be carried into Mobjack from the four small rivers entering it, but clayey silt may be transported into Mobjack from the Chesapeake. The sand flats located on western side of Mobjack's mouth, adjacent to the York River, appears to be prograding channelward from sediments supplied by the York River and/or the Chesapeake Bay mouth.

The application of a facies model to the seismic analysis of Mobjack indicates the relative importance of the three different types of energy, wave, tidal, and riverine, during the formation of the estuary. Riverine flow is generally considered to be low in the present Mobjack Bay and was assumed to be the same during the Holocene marine transgression. The migration of the tidal channels seen in Q1 and Q2 as well as the possible development of subaqueous shoals and mudflats or marshes along the margin indicate that tidal forces were important during the deposition of these two sequences. However, the deposition of sand on the margins and the development of shoals at the mouth of the bay in addition to the fine-grained sediment accumulation in the central portion are characteristic of a wave-dominated estuary.

Even though evidence exists for the relative importance of different types of energy presently and during the formation of Mobjack Bay, the end-members described by Dalrymple *et al.* (1992) for wave- and tide-dominated estuaries do not and probably never existed in Mobjack. The semi-enclosed nature of the bay within the Chesapeake Bay modifies the energy of tides and waves; in addition, the deposition of sediment from several sources leads to complex sedimentation patterns.

IX. FURTHER INVESTIGATIONS

The most obvious avenue for further investigation would be to take cores within Mobjack Bay in order to confirm the ages of the paleochannel and its fill, to differentiate between Tertiary and Early Pleistocene deposits of the interfluves, to determine the depositional environment of Q1, Q2 and Q3, and to quantify sedimentation rates. Additional data on wave and tidal currents would prove useful in further analyses performed in Mobjack.

The application of the facies model to Mobjack Bay was not entirely successful. Facies models exist for river estuaries within the Chesapeake, but are not particularly applicable to semi-enclosed bays, such as Mobjack or any other small bay within the Chesapeake, since riverine flow as well as fluvial sediment input is so important. A need exists for a facies model that could be used to predict stratigraphic development of shallow bays in a low energy environment with muddy sediment supply and limited access to the ocean.

As sea level continues to rise, the relatively low topography of Mathews and Gloucester counties surrounding Mobjack will be significantly impacted. Much of the Gloucester side is flanked by marshes while the Mathews side by subtidal sand flats. How will erosion of these sediments affect the depositional patterns within Mobjack? Since the bay is a sink for sediment, what processes and sediment sources will most affect it's infilling? A study of accumulation rates would determine if Mobjack is really accumulating sediment faster than sea level rise.

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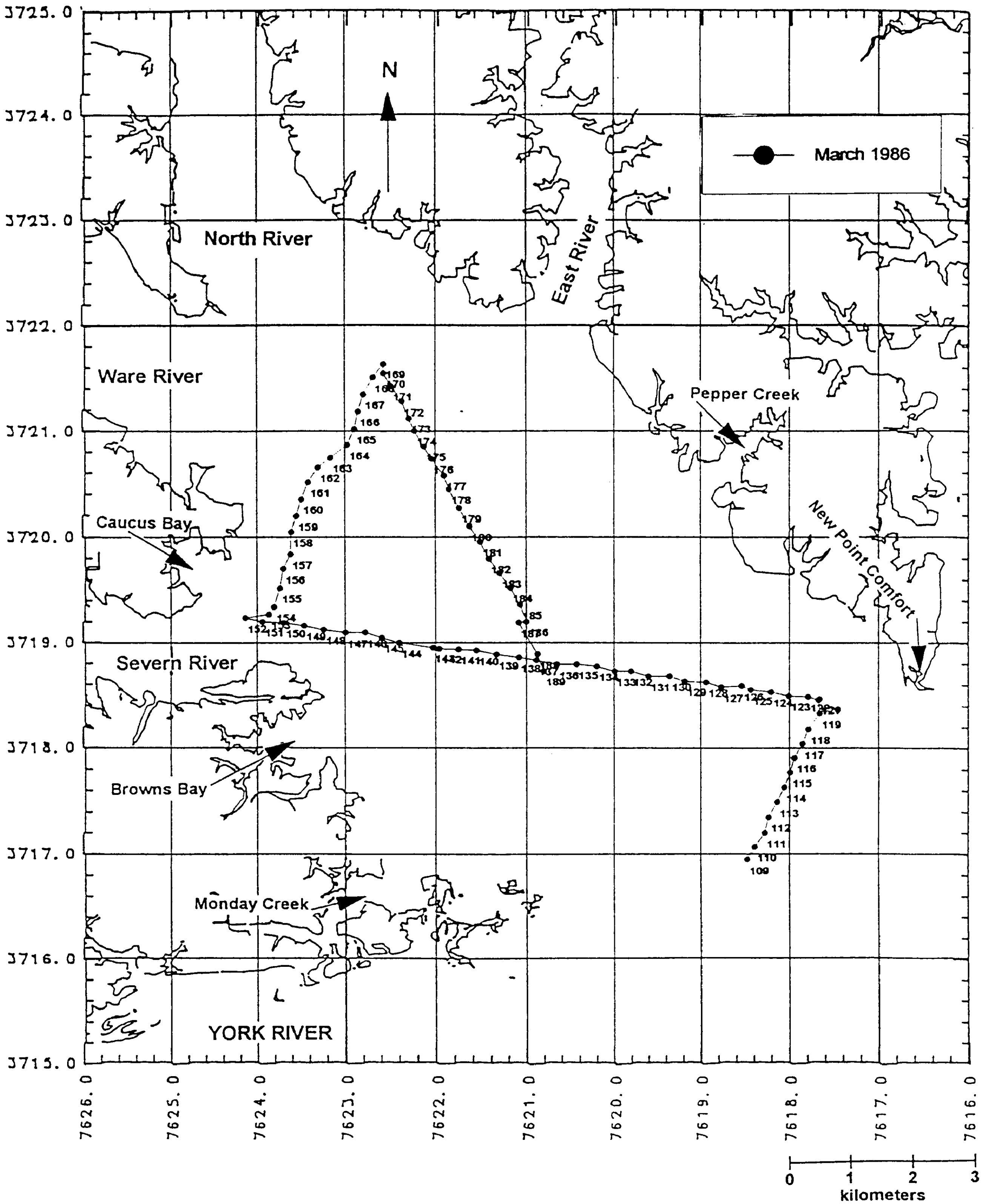
APPENDIX A

1.) March 1986
2.) June 1992
3.) June 1993
4.) July 1993
5.) July 1994



N
March 1986
North River
East River
Ware River
Pepper Creek
Caucus Bay
New Point Comfort
Severn River
Browns Bay
Monday Creek
YORK RIVER
3725.0
3724.0
3723.0
3722.0
3721.0
3720.0
3719.0
3718.0
3717.0
3716.0
3715.0
7626.0
7625.0
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7616.0
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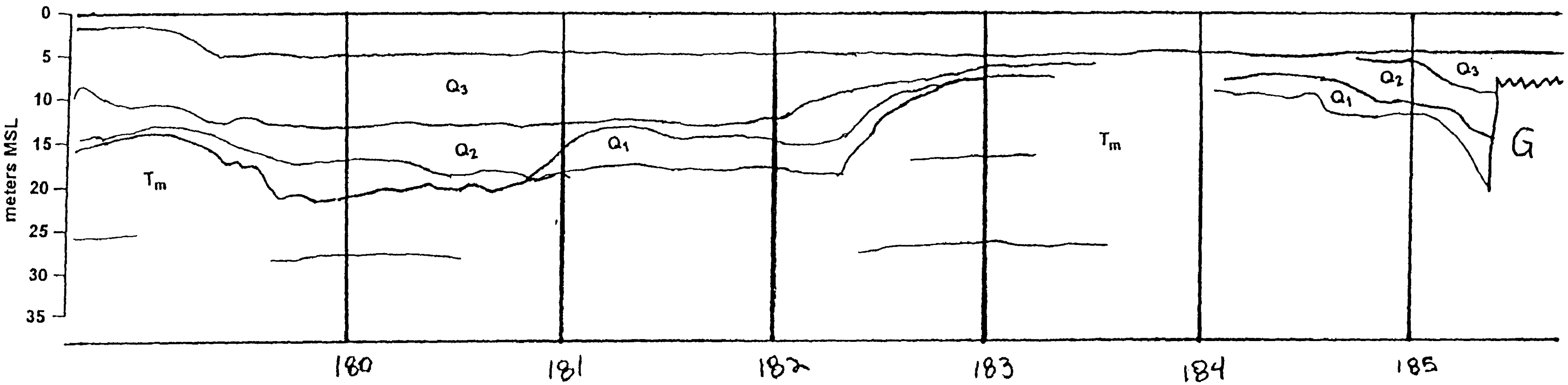
kilometers



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meters MSL
Q3
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Tm
Q3
Q2
Q1
Tm
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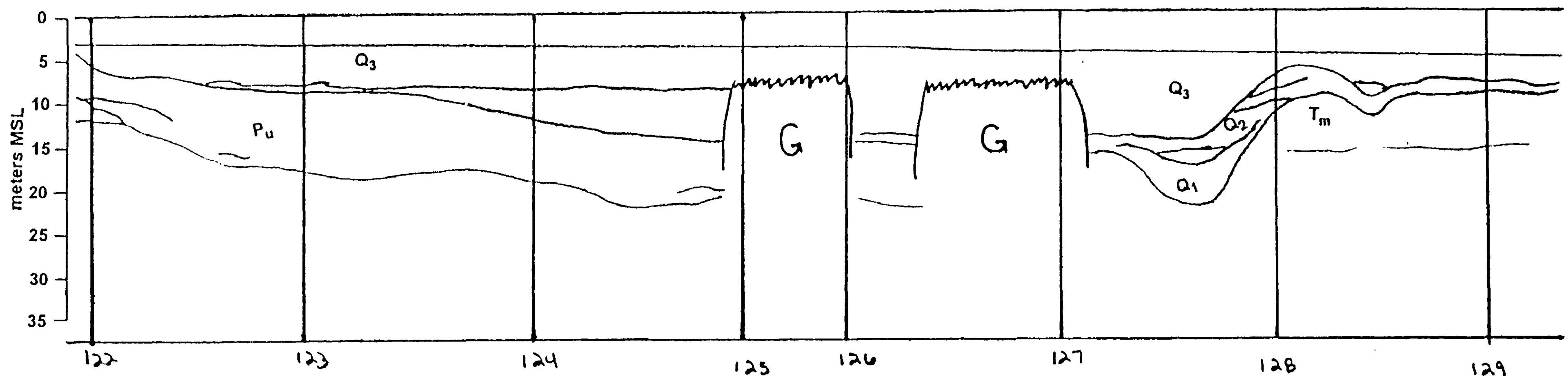
180
181
182
183
184
185

A1-1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meters MSL
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G
Q3
Q2
Tm
Q1
122
123
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125
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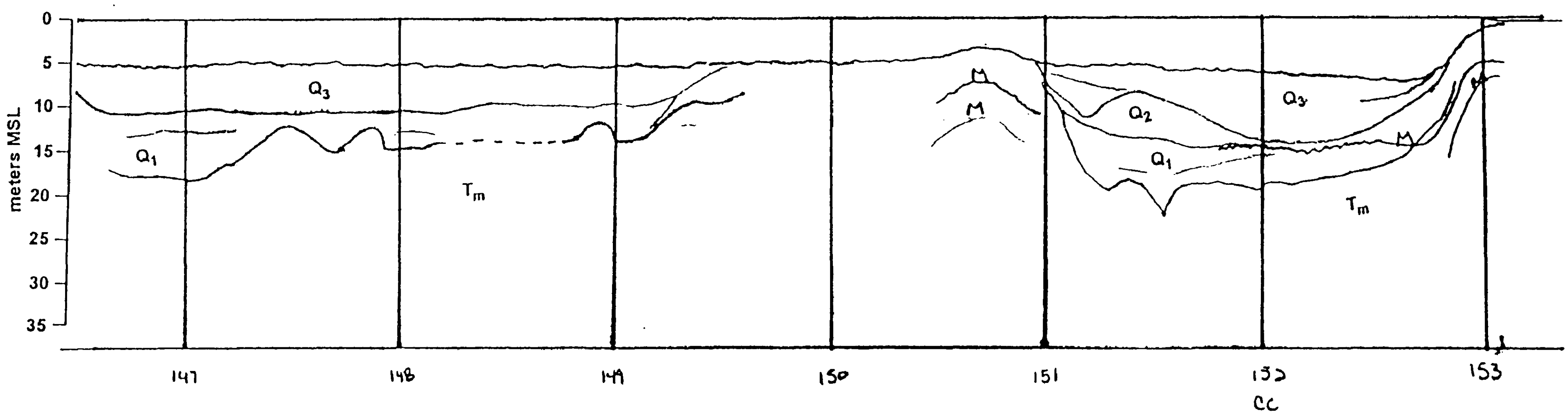
127
128
129

A1-2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meters MSL
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Tm
147
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150
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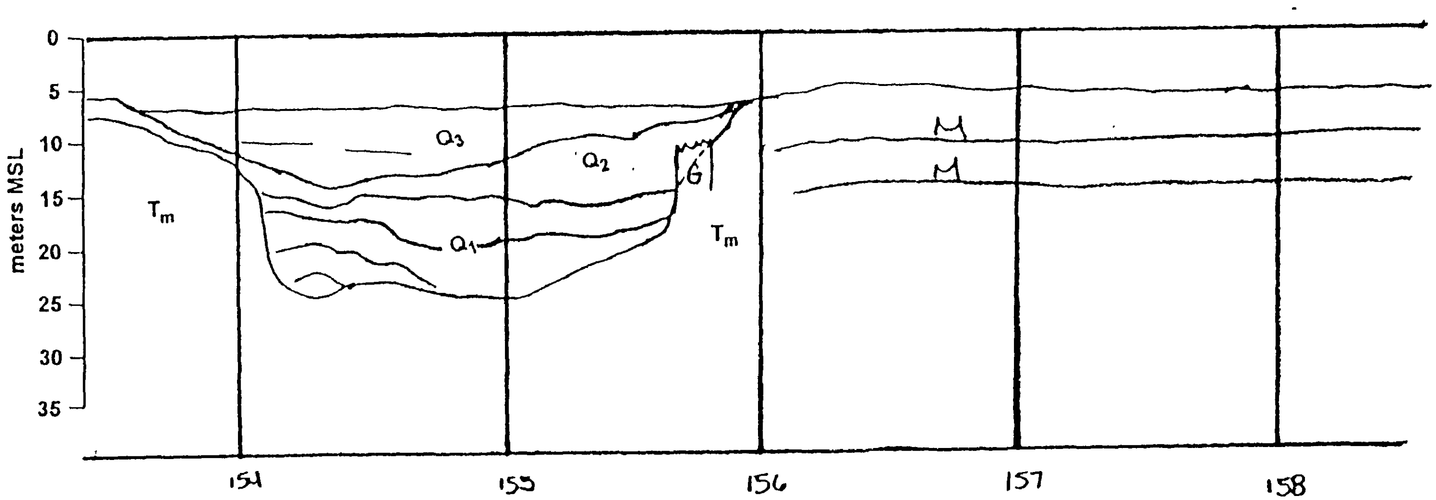
152
CC
153

A1-3



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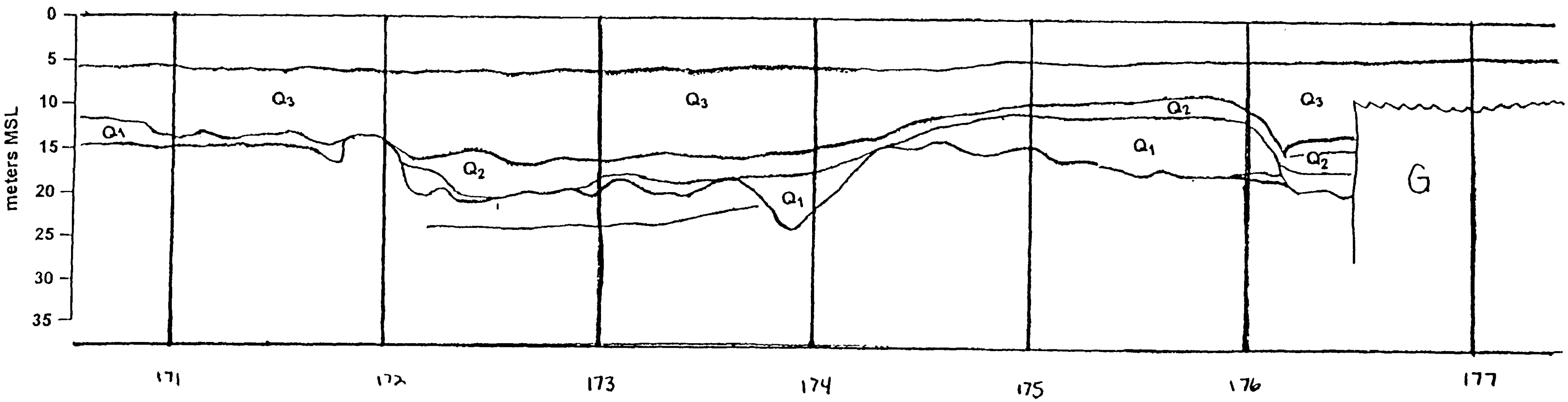
35
meters MSL
T_m
Q_3
Q_2
Q_1
G
T_m
M
M
154
155
156
157
158

A1-4



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meters MSL
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Q_2
G
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172
173
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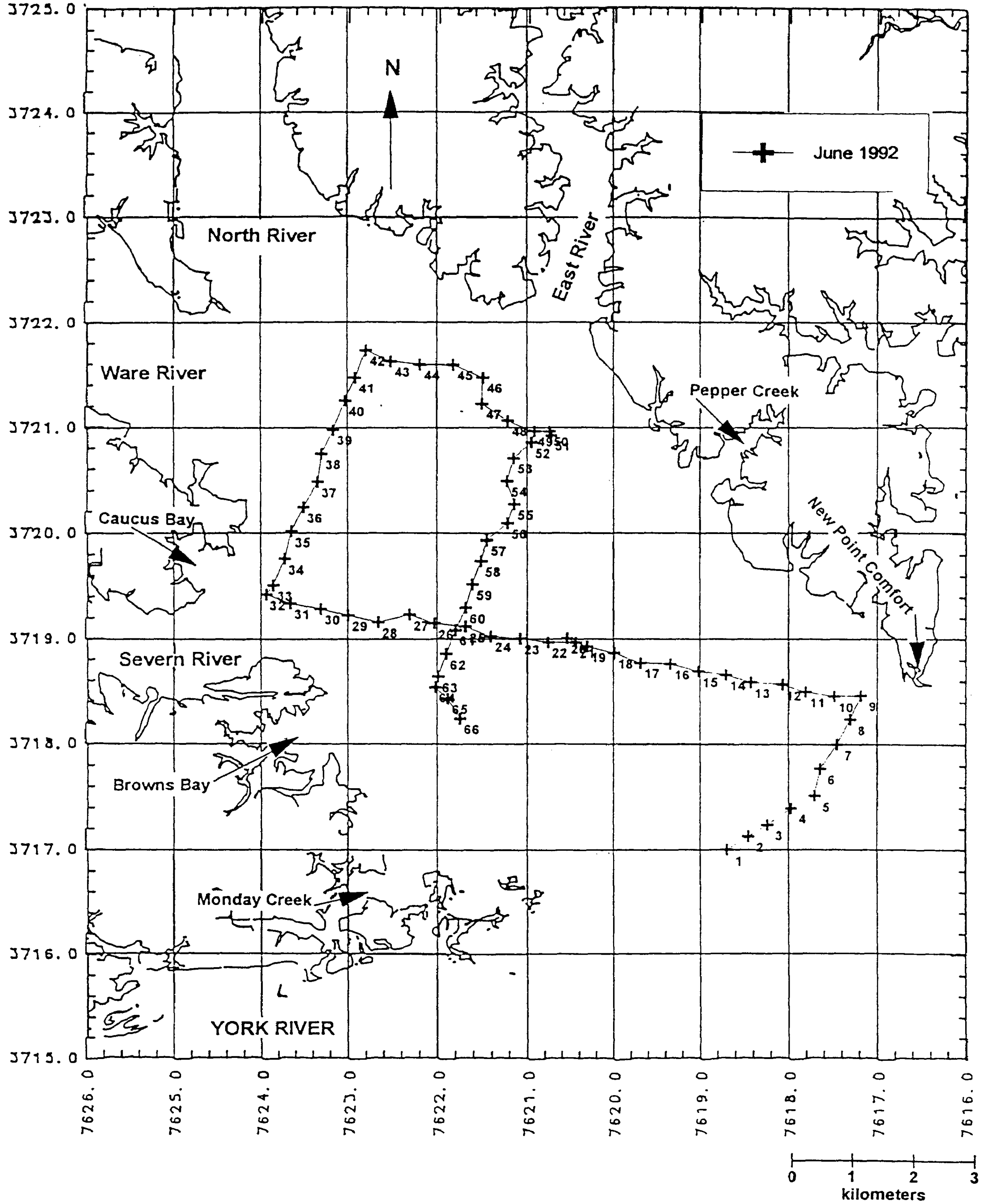
177

A1-5



N
June 1992
North River
East River
Ware River
Pepper Creek
Caucus Bay
New Point Comfort
Severn River
Browns Bay
Monday Creek
YORK RIVER
3725.0
3724.0
3723.0
3722.0
3721.0
3720.0
3719.0
3718.0
3717.0
3716.0
3715.0
7626.0
7625.0
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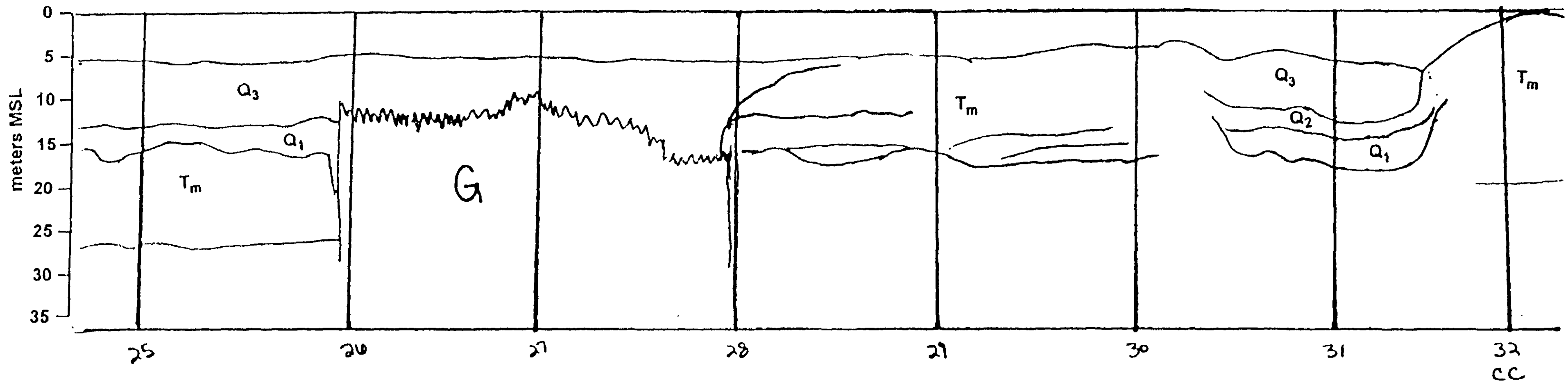
kilometers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Q3
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Q3
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Q1
Tm
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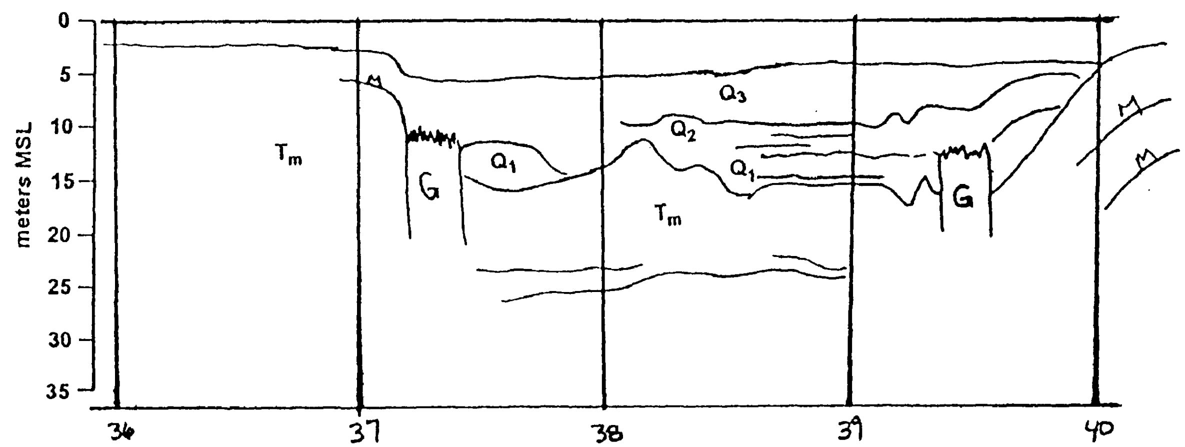
31
32
CC

A2-2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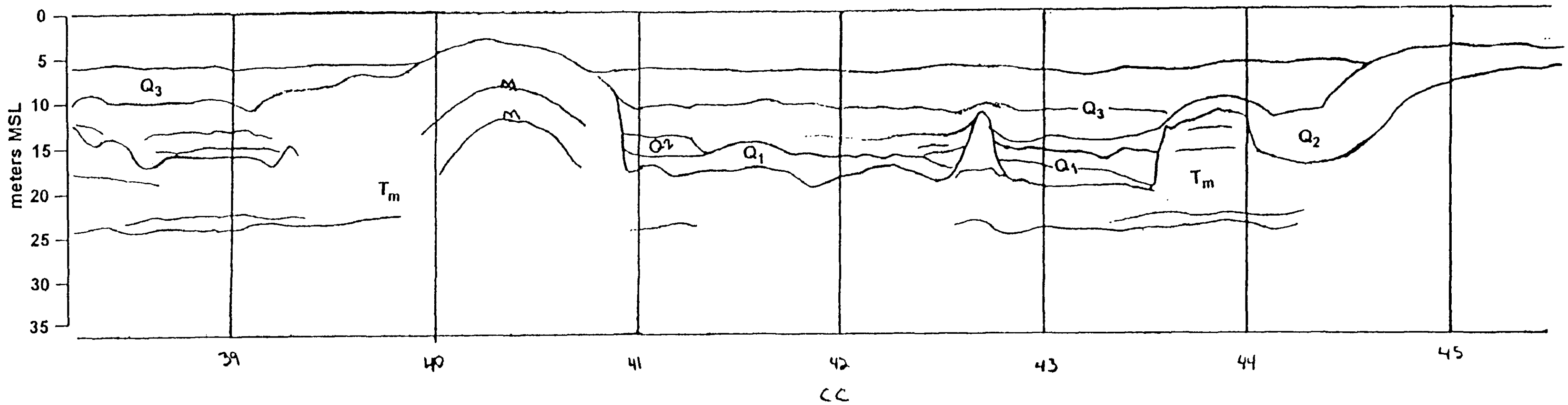
A2-1



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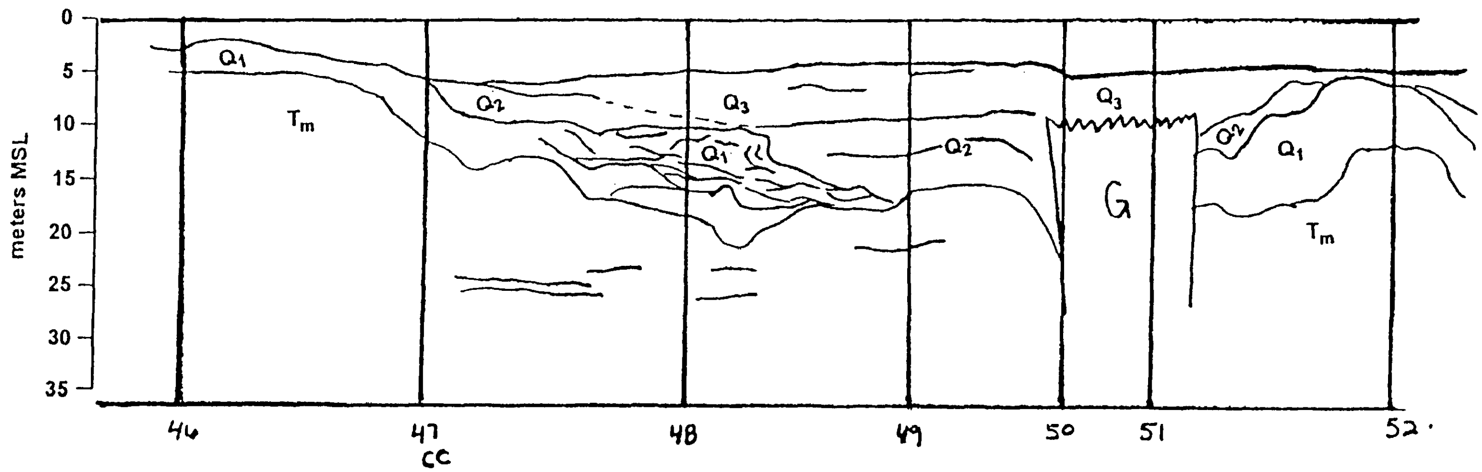

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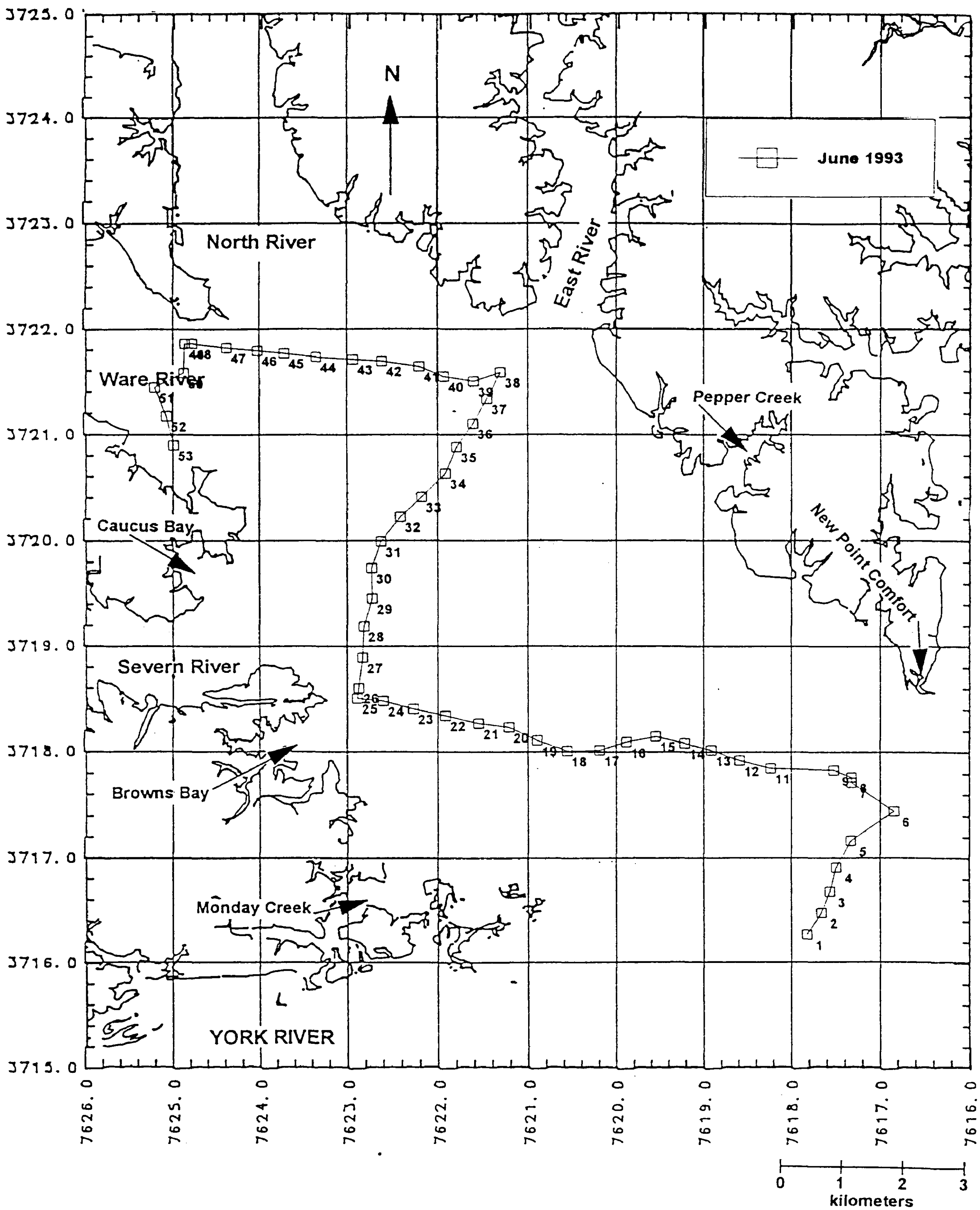
A2-4



N
June 1993
North River
East River
Ware River
Pepper Creek
Caucus Bay
New Point Comfort
Severn River
Browns Bay
Monday Creek
YORK RIVER
3725.0
3724.0
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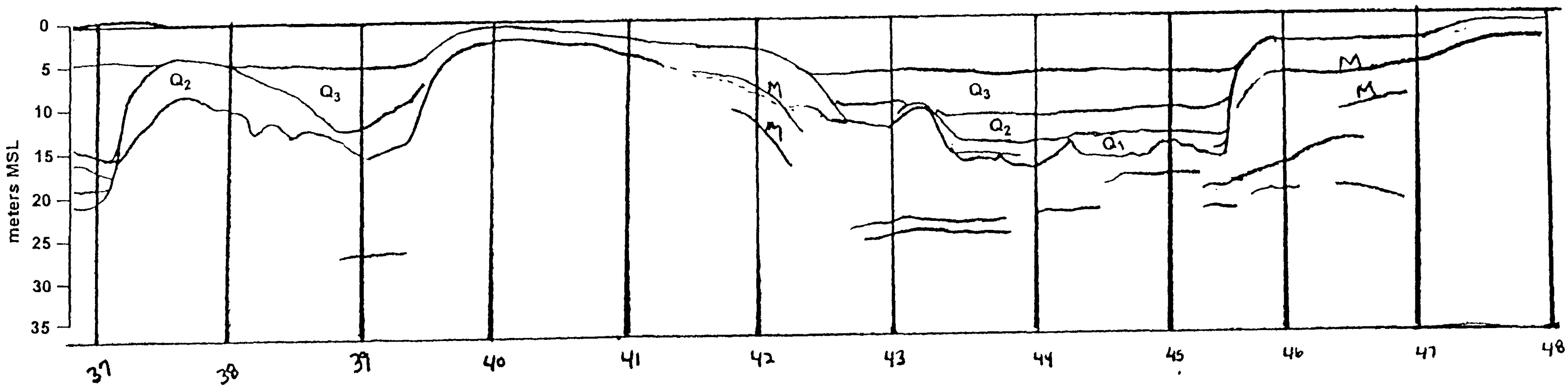
kilometers



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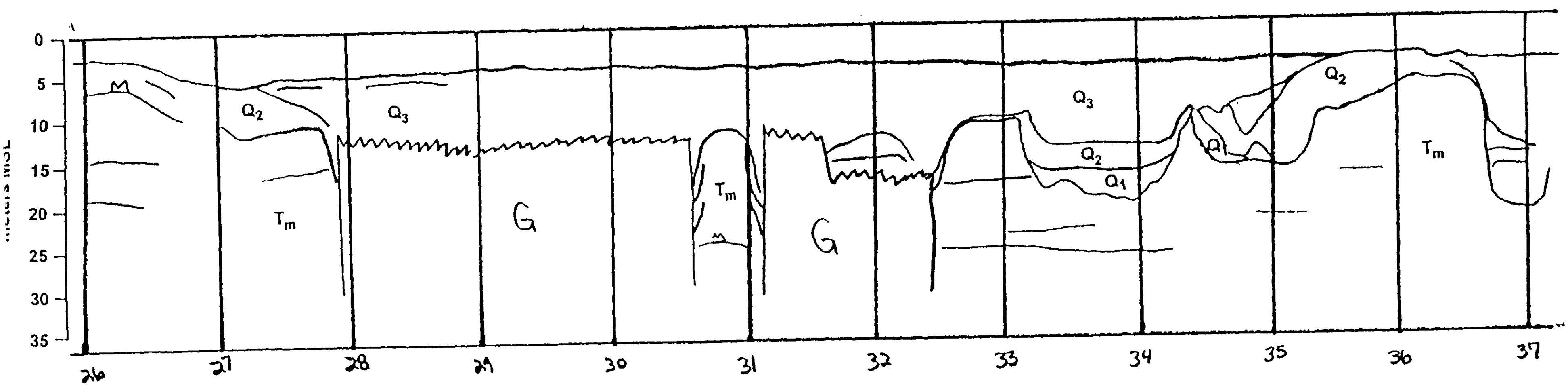
A3-1



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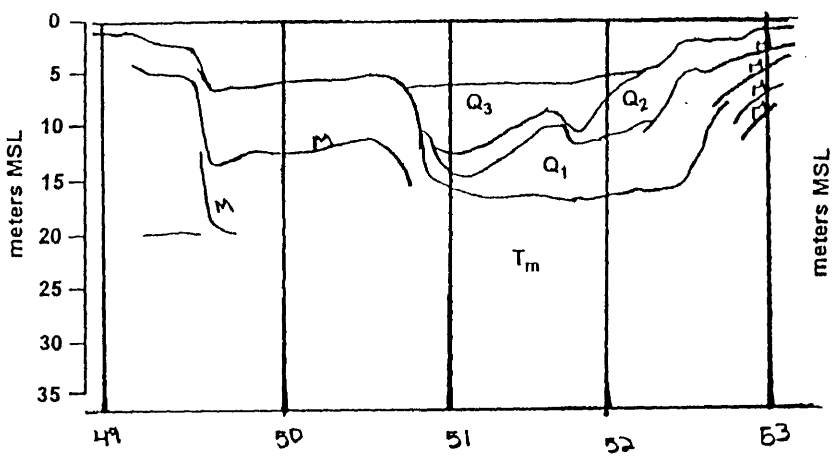
A3-2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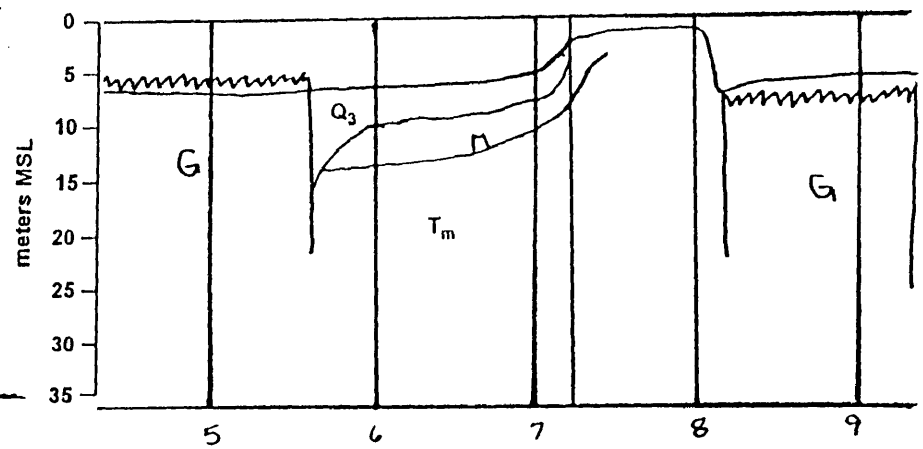
A3-3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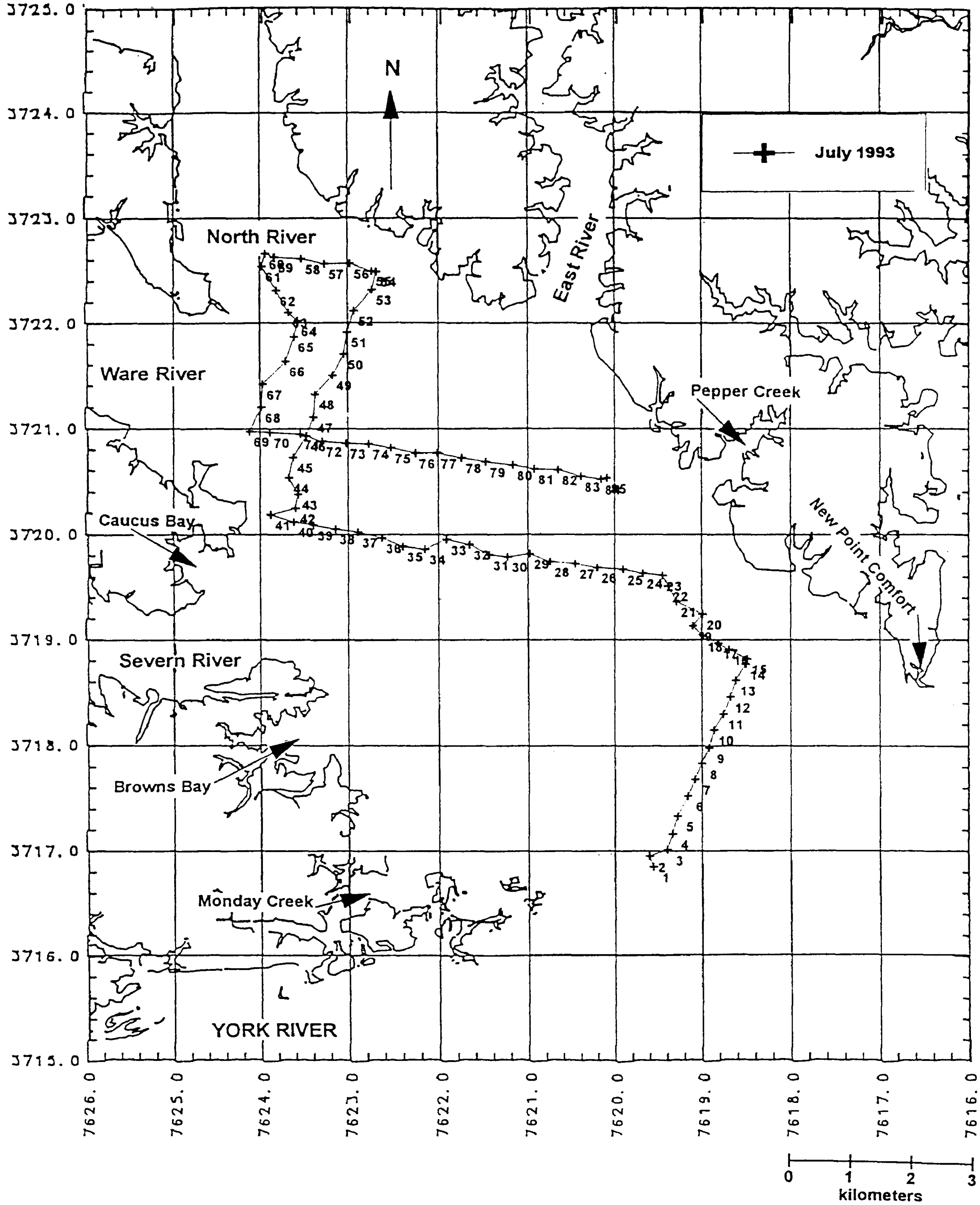
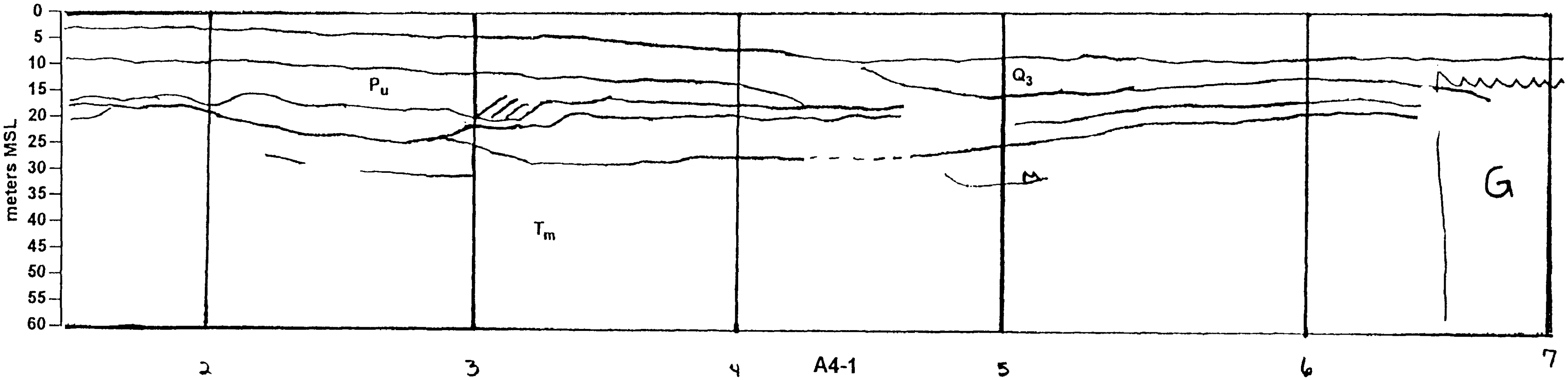
A3-4



North River
Ware River
East River
July 1993
N
Pepper Creek
Caucus Bay
New Point Comfort
Severn River
Browns Bay
Monday Creek
YORK RIVER
kilometers



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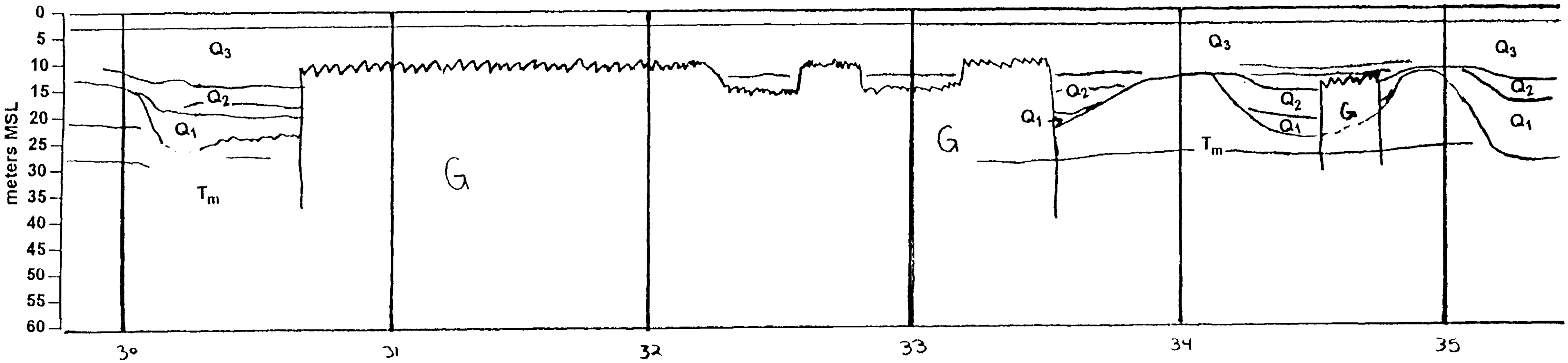
A4-1



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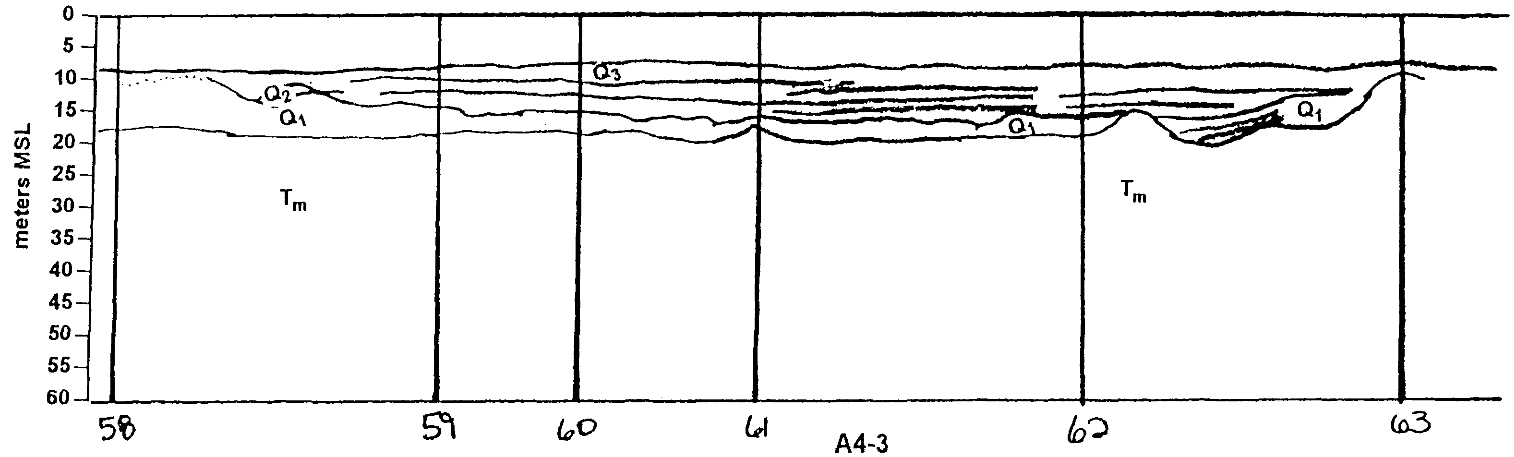
A4-2



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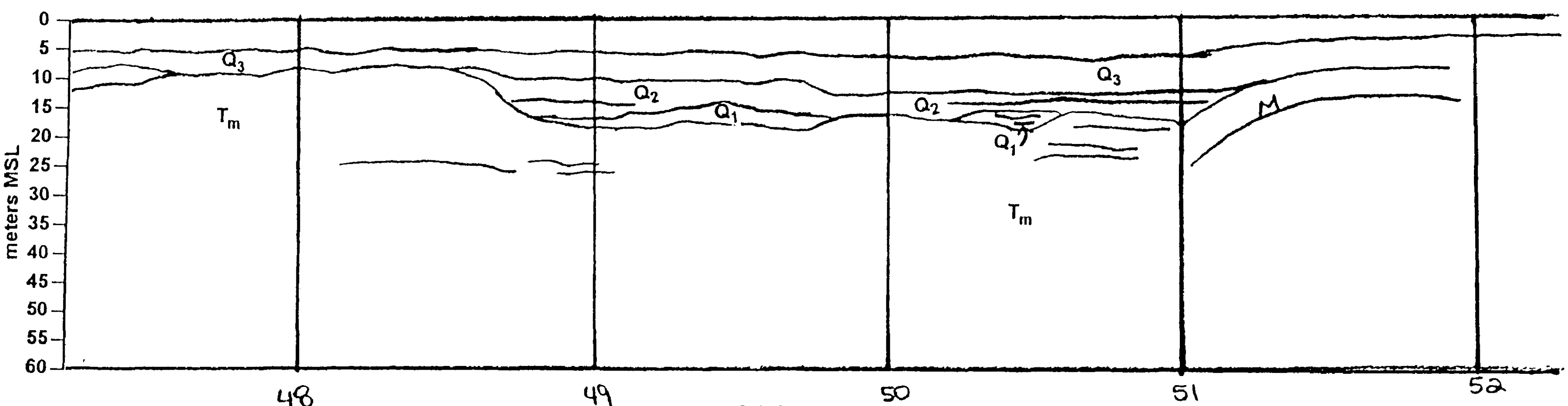
A4-3



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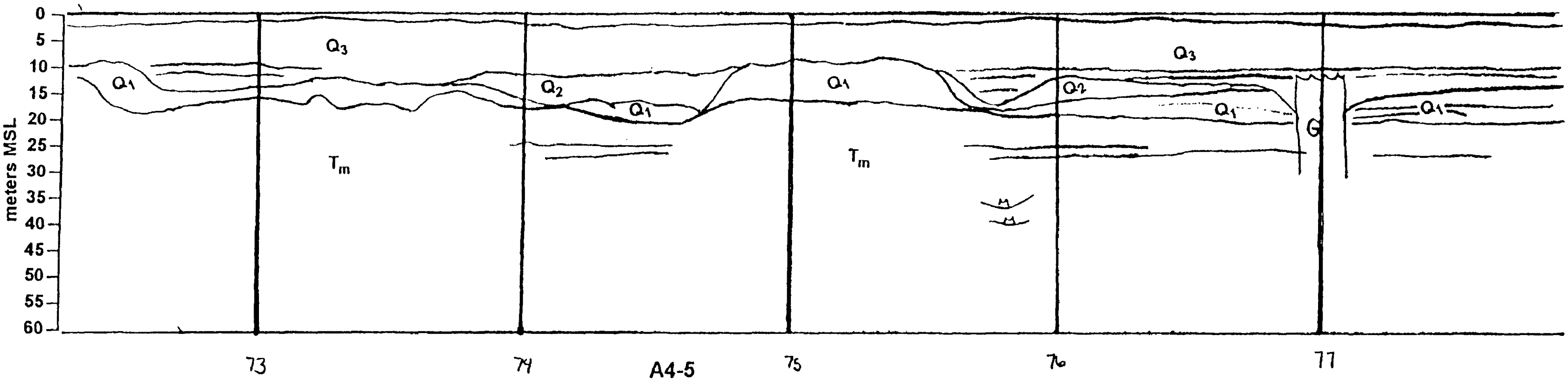

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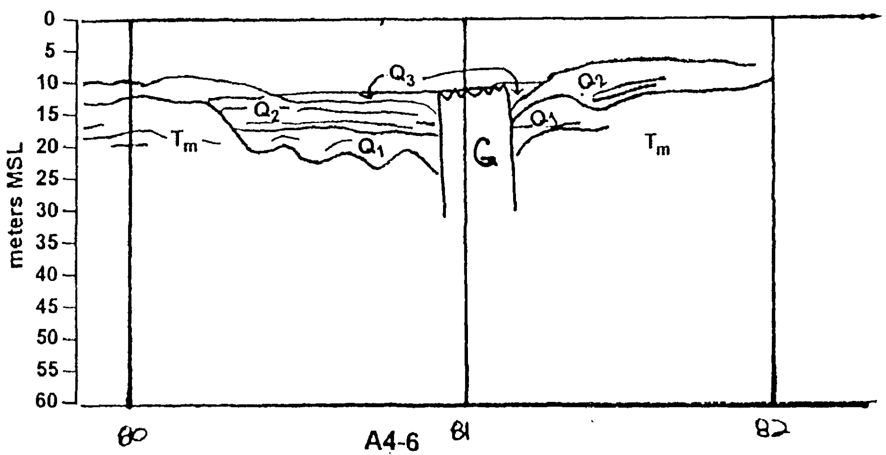
A4-5



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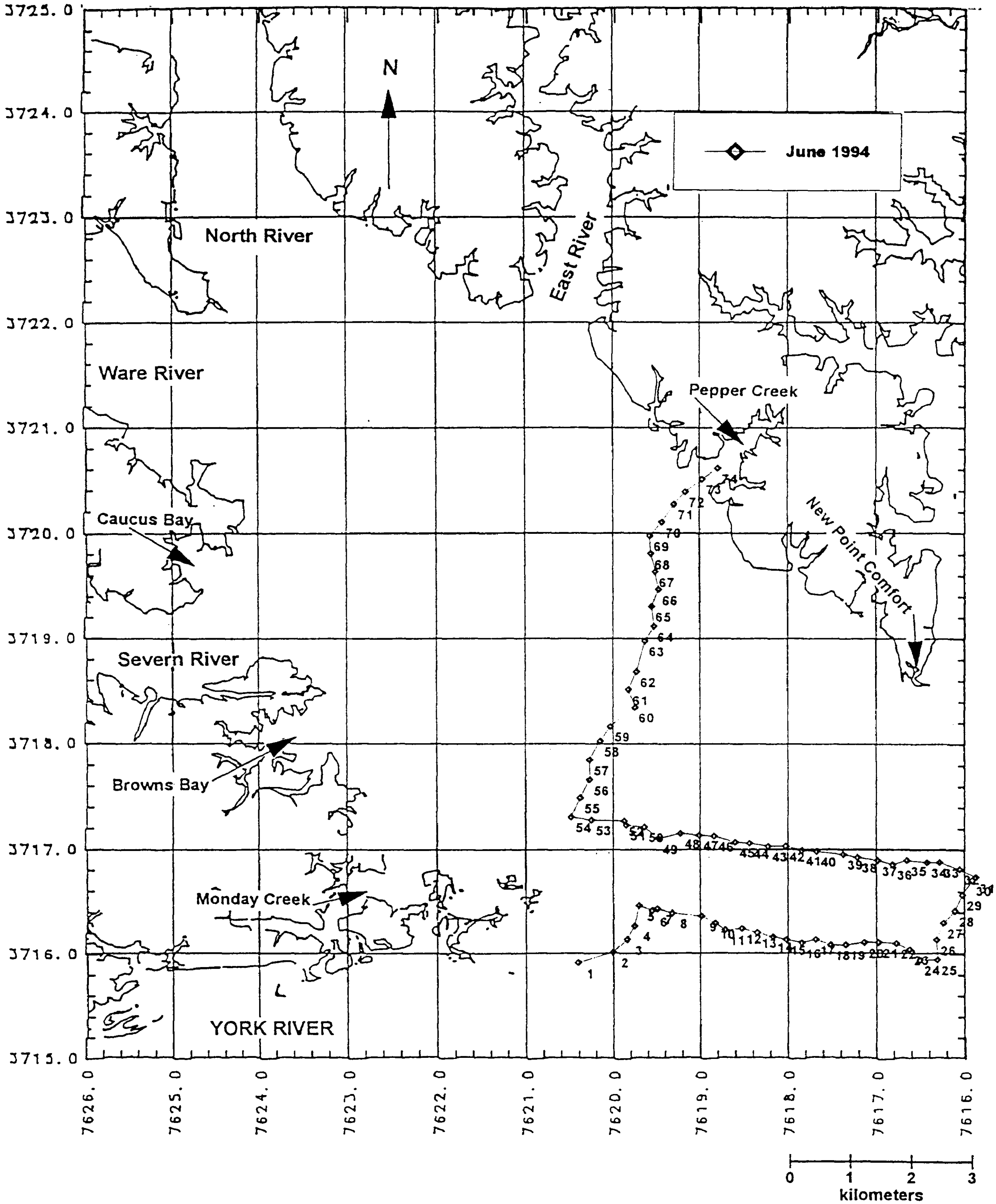
81
82

A4-6



June 1994
N
North River
East River
Ware River
Pepper Creek
Caucus Bay
New Point Comfort
Severn River
Browns Bay
Monday Creek
YORK RIVER
3725.0
3724.0
3723.0
3722.0
3721.0
3720.0
3719.0
3718.0
3717.0
3716.0
3715.0
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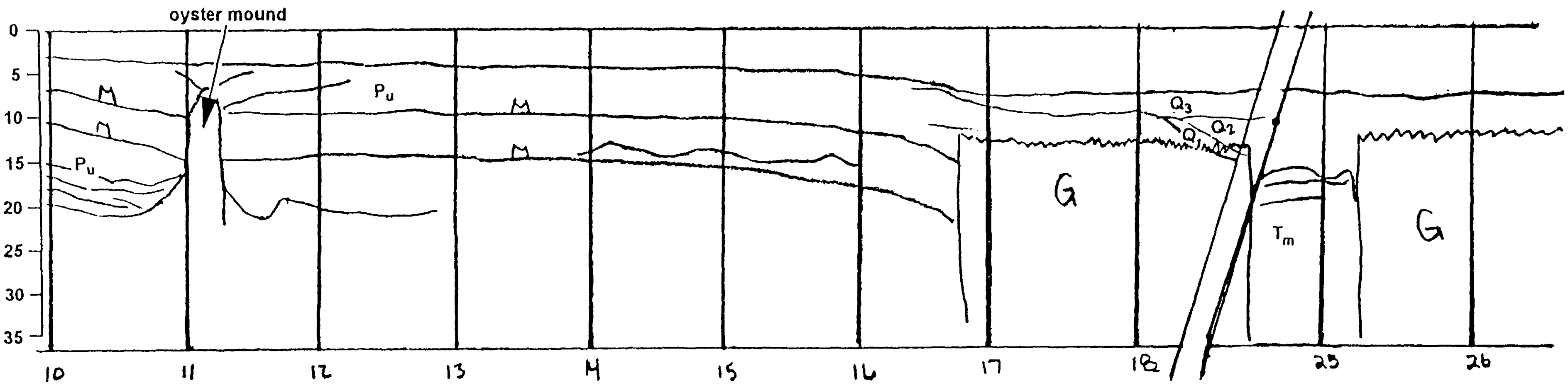
kilometers


oyster mound
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P u
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Q 2
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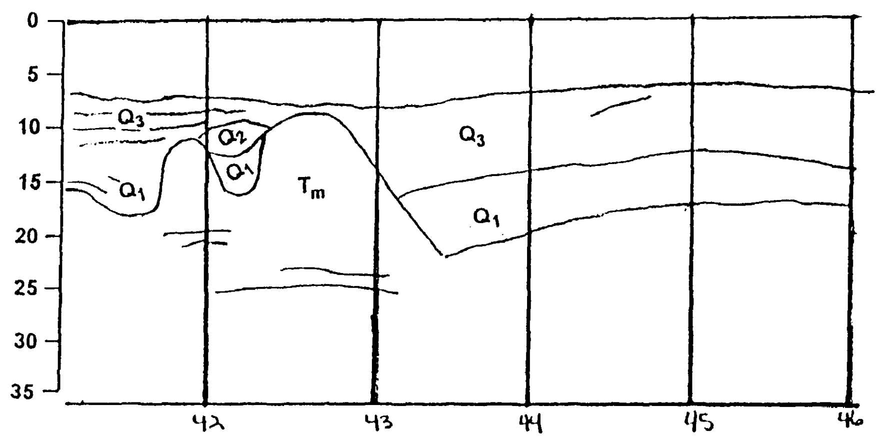
A5-1


Q 3
Q 2
Q 1
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A5-2