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Origin of a Solitary Sand Shoal offshore of Sandbridge Beach, Virginia

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Archives

ORIGIN OF A SOLITARY SAND SHOAL
OFFSHORE OF SANDBRIDGE BEACH, VIRGINIA

A Thesis

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In Partial Fulfillment

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James Knox Dame, II

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APPROVAL SHEET

This thesis is submitted in partial fulfillment

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ABSTRACT

Offshore of Sandbridge Beach, Virginia, the surface of the inner continental shelf is a featureless, gently sloping plain with the exception of a solitary sand shoal. This shoal, referred to here as the Sandbridge Shoal, is located approximately 5.5 km from the shoreline in 10 to 12 m of water. This study uses stratigraphic relationships to evaluate six models of shoal origin. Because the shoal is situated over a large paleochannel system, the models represent depositional environments ranging from completely fluvial conditions to completely marine conditions.

Correlation of seismic data with vibracores and surface grab samples indicate the Sandbridge Shoal is roughly 6x8 km in areal extent, and has a barcan or horseshoe shape in map view. The Sandbridge Shoal contains approximately 80 million cubic meters of clean, well-sorted, medium to coarse sand. The shoal is best described as a wedge of sand, with the thickest amounts of material occurring in the southwest quadrant. Its surface tapers and thins to the north and east.

Stratigraphically, the Sandbridge Shoal is composed of two distinct units. The surface morphology and character of the surficial sediments suggest the sands of the upper unit have been transported landward or to the southwest. Both the upper and lower units contain shell material which indicate they were deposited in marine environments. However, geochronology data indicate the upper unit is modern, and the lower unit is late Pleistocene in age. Furthermore, the age relationships suggest the lower unit is more closely related to the underlying strata which lies within the paleochannel system. Stratigraphic relationships and faunal analyses indicate the upper portion of the paleochannel system represents an estuarine environment.

Therefore, a two-stage formation is believed to have occurred. The lower unit of the Sandbridge Shoal represents the relatively thin remains of a relict barrier or submerged bar which survived marine transgression. The upper unit of the Sandbridge Shoal was then deposited over the lower unit by a landward transport of material from the shelf during the Holocene transgression. Thus, the traditional theories of linear shoal origin (i.e. either an entirely relict or an entirely modern feature) do not apply in the case of the Sandbridge Shoal.

ORIGIN OF A SOLITARY SAND SHOAL
OFFSHORE OF SANDBRIDGE BEACH, VIRGINIA

INTRODUCTION

This study explores the origin of isolated linear shelf sand bodies by examining a feature located on the southern portion of Virginia's inner continental shelf. The major objectives of the study are to give a better understanding of shoreface sand bodies as their use as a sand resource increases in the future, and to help unravel the Quaternary history of Virginia's inner shelf.

Occurrence and Description of Linear Shoals

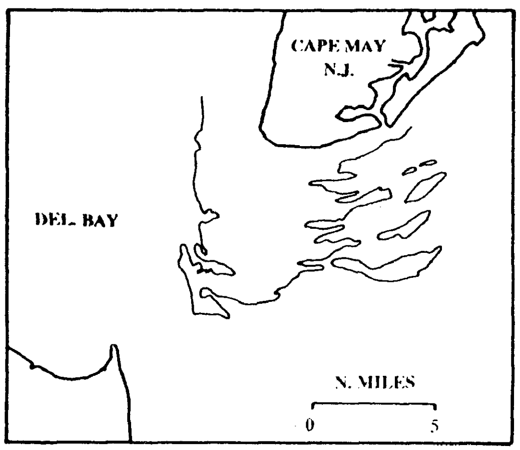
The Middle Atlantic Bight is characterized by numerous linear sand shoals which are present from the shoreface to the shelf break. Along the inner portions of the shelf, these sand bodies normally occur within shoal fields. These shoal fields may be present as secondary features on arcuate inlet or cape associated shoals, or may exist along the open coast (Fig. 1). Those shoals on the open coast may be described further as either shoreface connected or isolated.

Duane et al. (1972) noted the presence of linear shoals along the inner continental shelf offshore of New York, New Jersey, Delaware, Maryland, and Virginia. Their analysis of several hundred shoals indicated these features exist at two to three discrete depths; 10 m, 15 m, and 24 m. Most of these shoals, with the exception of those offshore of Long Island, New York, have an axis whose azimuth is

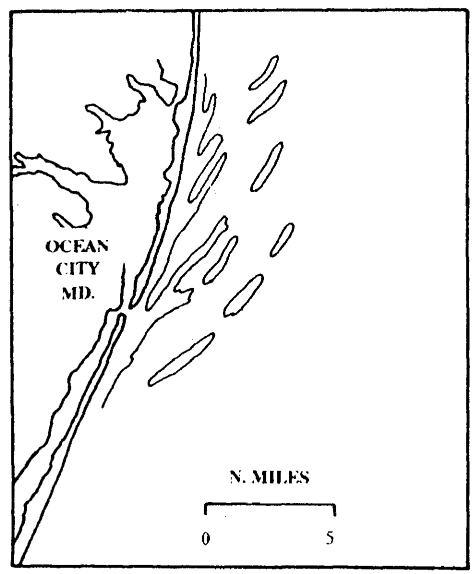
FIGURE 1

Schematic diagram of major shoal types.
(after Duane et al., 1972)

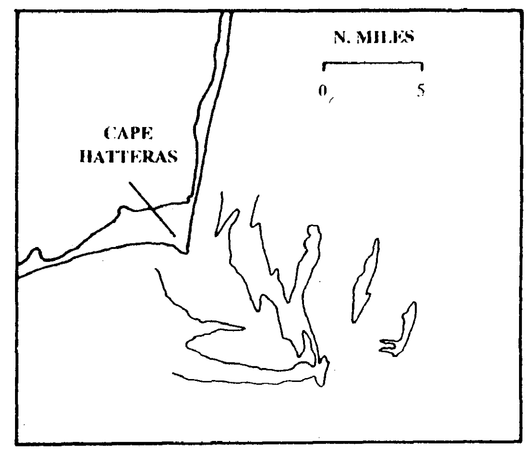
SCHEMATIC DIAGRAM OF MAJOR SHOAL TYPES



INLET ASSOCIATED SHOALS



LINEAR SHOREFACE CONNECTED AND ISOLATED SHOALS



CAPE ASSOCIATED SHOALS

oriented to the northeast. This orientation is prevalent regardless of the direction of net littoral drift. Futhermore, this axis normally forms an oblique angle, which is generally less than 35 degrees, with the axis of the coastline.

Seismic reflection profiles and vibracore data have been used in studies of shoals offshore of Beach Haven Inlet, New Jersey (Stahl et al., 1974), the Central Delmarva Peninsula (Field, 1979), and False Cape, Virginia (Swift et al., 1972). These and other studies describe linear inner shelf shoals as planoconvex in cross-section with some internal stratification. They normally have crests at least 3 m above the surrounding shelf surface, and are separated from the underlying strata by a strong horizontal reflector. These shoals are composed of clean, medium to coarse sand, whereas the underlying deposits are usually made up of silty clay or silty fine sand.

Genetic Interpretations of Linear Shoals

The genesis of these linear features is not completely understood. However, various interpretations have been presented in the literature, and two general hypotheses stand out among them. The first explains the sand shoals as remnants of Pleistocene beach ridges or barrier islands which became stranded, and then drowned by the Holocene transgression. Curray (1960), working in the northwest Gulf of Mexico, interpreted a number of elongate sand ridges on the east Texas shelf as being drowned barrier islands. In a study of the ridge field off of False Cape, Virginia, Sanders (1962) tentatively suggested these features represent a coastal dune and beach complex which formed at various Pleistocene still stands. However, he noted that a change in orientation of the shoreline subsequent to formation would have had to occur. Kraft (1971) explained the shoreface connected linear shoals of Delaware and New Jersey as relict coastal barriers. He showed a surprising parallelism of these offshore features with adjacent onshore pre-Holocene barrier ridges near Bethany Beach, Delaware. In general, this hypothesis regards these sand bodies as relict features, and suggests their presence across the shelf represents successive steps of a transgressive sea.

Another hypothesis, which was first suggested by Moody (1964), explains linear sand bodies as modern features. He studied sand ridges on the Delaware shoreface, and determined that they migrated during the Ash Wednesday storm of 1962. He concluded that their formation is a result of the modern hydraulic processes working on the shoreface. Field (1979), who advocates this hypothesis, noted that the mechanism which initiates shoal formation is unknown; however, he stated it is probably some shoreline irregularity which allows for accretion of nearshore sediments. Swift et al. (1972) support a modern origin by proposing that the most significant process responsible for the growth and development of a shoreface shoal is storm-generated coastal currents. The dominant storm waves on the middle Atlantic shelf are from the northeast, and tend to cause headward erosion of the troughs and accretion on the crests and seaward flanks of the shoals. This results in shoal elongation which, coupled with shoreline retreat due to a relative rise in sea level, results in a transition from a shoreface connected to an isolated shoal. Large scale, storm-generated, rip currents may cause saddle development across the shoal, and then the eventual detachment and isolation occurs (Fig. 2). Moody (1964) postulated that the shoals became isolated on the shelf as the shoreface retreated, and this ultimately gave rise to an offshore ridge system. In their survey of linear shoals along the central and southern inner Atlantic continental shelf, Duane et al. (1972) agreed with this explanation, and noted that a strong similarity between all the shoals in their study suggests a single mode of formation for most linear shoals.

However, it is possible that not all isolated shoal features can be explained by a single-mode formation. Therefore, the general purpose of this study is to examine a solitary sand body relative to possible mechanisms of formation.

CONTINENTAL SHELF HISTORY

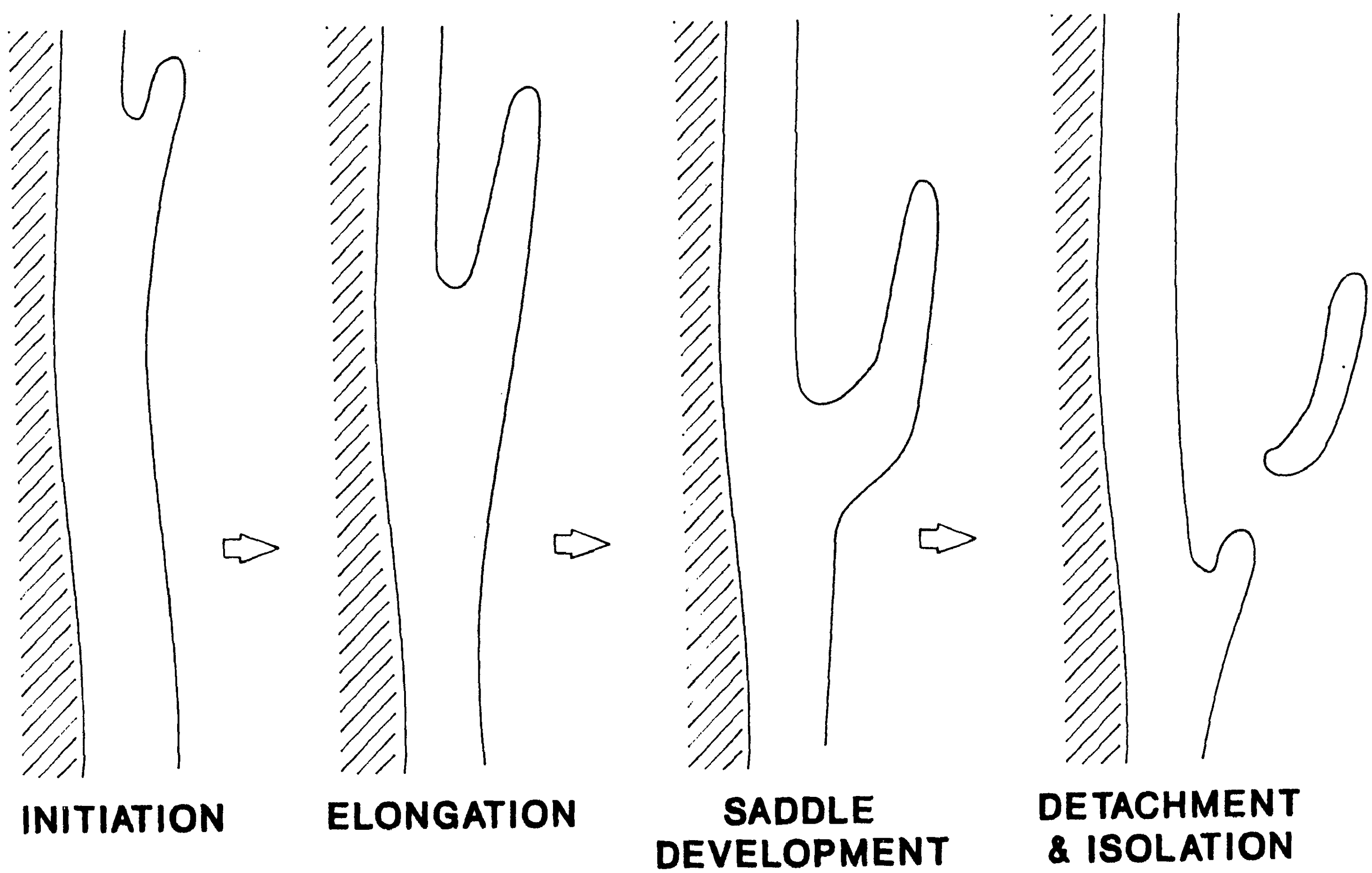
Sea-Level Fluctuations

The continental shelf is a submerged extension of the coastal plain province. Its width and landward boundary are defined by the shoreline, the location of which changes with variations in sea level. Thus, it is likely that changes in sea level have played some role in the history of linear shoals on the shelf.

FIGURE 2

Idealized evolution of a detached shoreface shoal.
(after Duane et al., 1972)

IDEALIZED EVOLUTION OF A DETACHED SHOREFACE SHOAL



Sea-level oscillations which accompanied Pleistocene glacial activity have been well documented. Shackelton and Opdyke (1973), using oxygen isotope analyses of deep sea cores, defined isotopic stages which represent fluctuations in sea level (Fig. 3). These stages are given by variations in the $^{18}O/^{16}O$ ratios found in foraminifera tests, and represent alternating glacial and interglacial episodes. Odd numbered stages represent interglacial episodes, and are characterized by higher amounts of the ^{16}O isotope. Even numbered stages contain more of the heavier isotope, and represent glacial periods.

Other studies have used radiocarbon and uranium series dating to estimate the age of these sea-level oscillations. Chappell (1974) and Chappell and Shackleton (1986), using both radiocarbon and uranium series dates from terrace reefs in New Guinea, defined sea level maxima for the past 240,000 years. Cronin et al. (1981) used uranium series dates from corals along the U.S. Atlantic coastal plain coupled with paleoclimate data in documenting five relatively high stands of sea level during the past 200,000 years. Working in Barbados, Fairbanks (1989) used radiocarbon dates from the depth sensitive coral Acropora palmata to give a detailed record of sea level for the past 17,000 years, while Bard et al. (1990) obtained uranium series dates by mass spectrometry from samples of the same collection. They compared their results to normalized ^{18}O data from Labeyrie et al. (1987) to determine sea-level history for the past 130,000 years.

These and other studies show the same general trends of sea level even though the exact dates and elevations may not be in total agreement (Fig. 3). Variations in these trends are most likely due to regional differences in tectonic activity, sediment loading, and isostatic and hydrostatic crustal adjustments due to glacial activity.

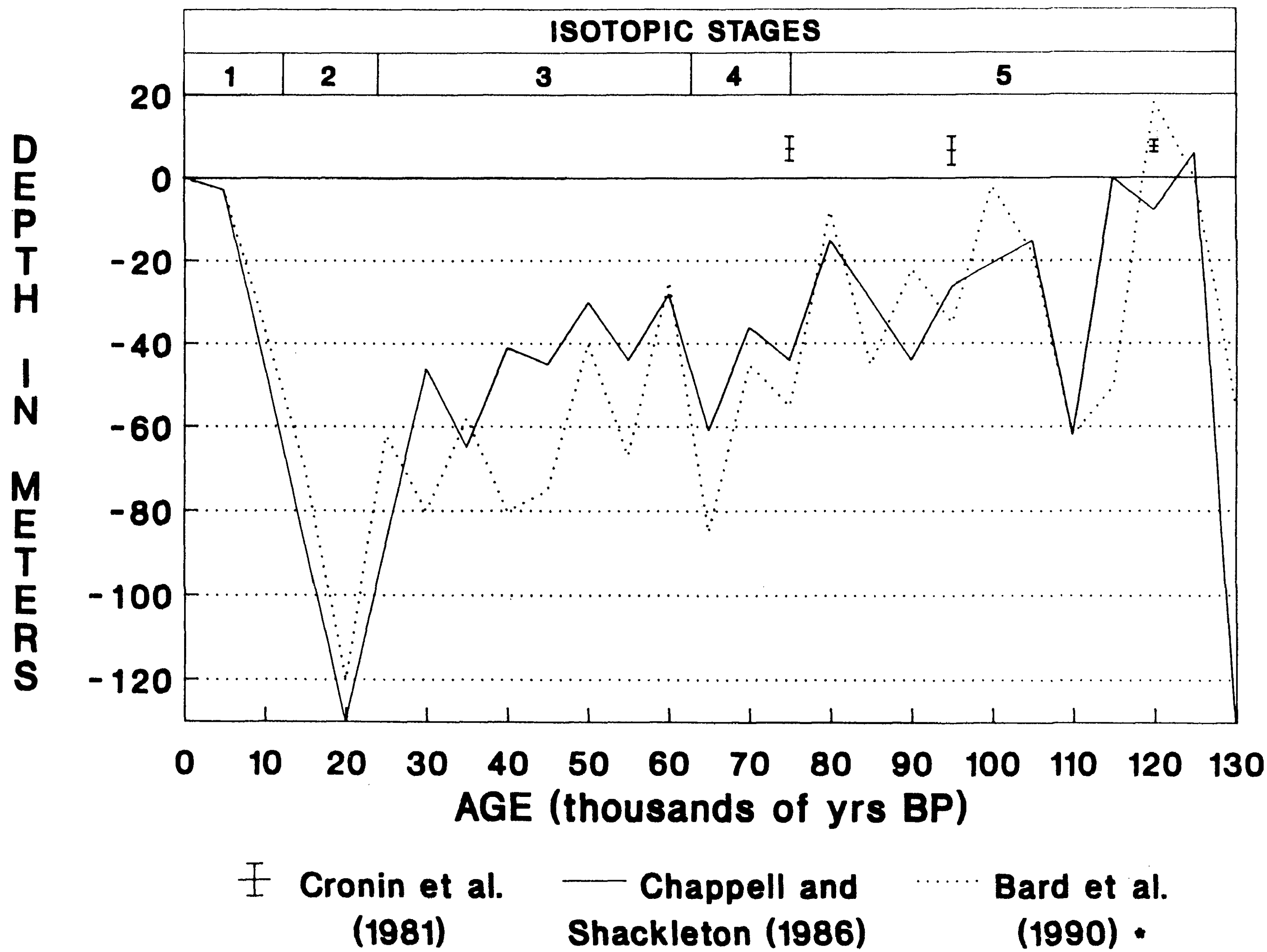
The general trends in sea level are marked by the following: (a) A high stand of sea level approximately 120,000 years ago which was at or above present day levels. This is followed by two cycles of fluctuations where sea level maxima is increasingly less than the 120,000 year high stand. This period is identified as isotopic Stage 5, which is believed to have ended around 75,000 years ago. (b) Following this period is a low stand (representing isotopic Stage 4) which climaxed approximately 65,000 years ago. This low stand precedes a series of decreasing sea level highs, labelled isotopic Stage 3. (c) Stage 3 ended around 25,000 years ago, and is followed by another low stand which marks the end of the Pleistocene. This low stand is identified as isotopic Stage 2. Its maximum depths are not well-defined, but sea level is believed to have been approximately 120 m below present day levels (Bard et al., 1990). This event reached its maximum around 18,000 years ago. (d) The most recent major event in sea level history is the Holocene transgression. This transgression immediately follows isotopic Stage 2, and represents an extremely rapid change on a geological time scale (a sea level rise of over 100 m in approximately 20,000 yrs).

Throughout all of these sea level oscillations the rate of

FIGURE 3

Late Pleistocene sea-level curves showing isotopic stages.
* Bard et al. (1990) used normalized oxygen isotope data from Labeyrie et al. (1987)

LATE PLEISTOCENE SEA-LEVEL CURVES



change in sea level was not constant. Minor fluctuations in the rate of sea level rise or fall are believed to have occurred. These differences in the rate of sea level change are better defined for the Holocene transgression because of the larger number of data points available. Fairbanks (1989) and Bard et al. (1990) have identified a total of three instances when the rate of sea level rise slowed during the Holocene transgression: approximately 14 ka, between 11-11.5 ka, and between 4-6 ka (Fig. 4).

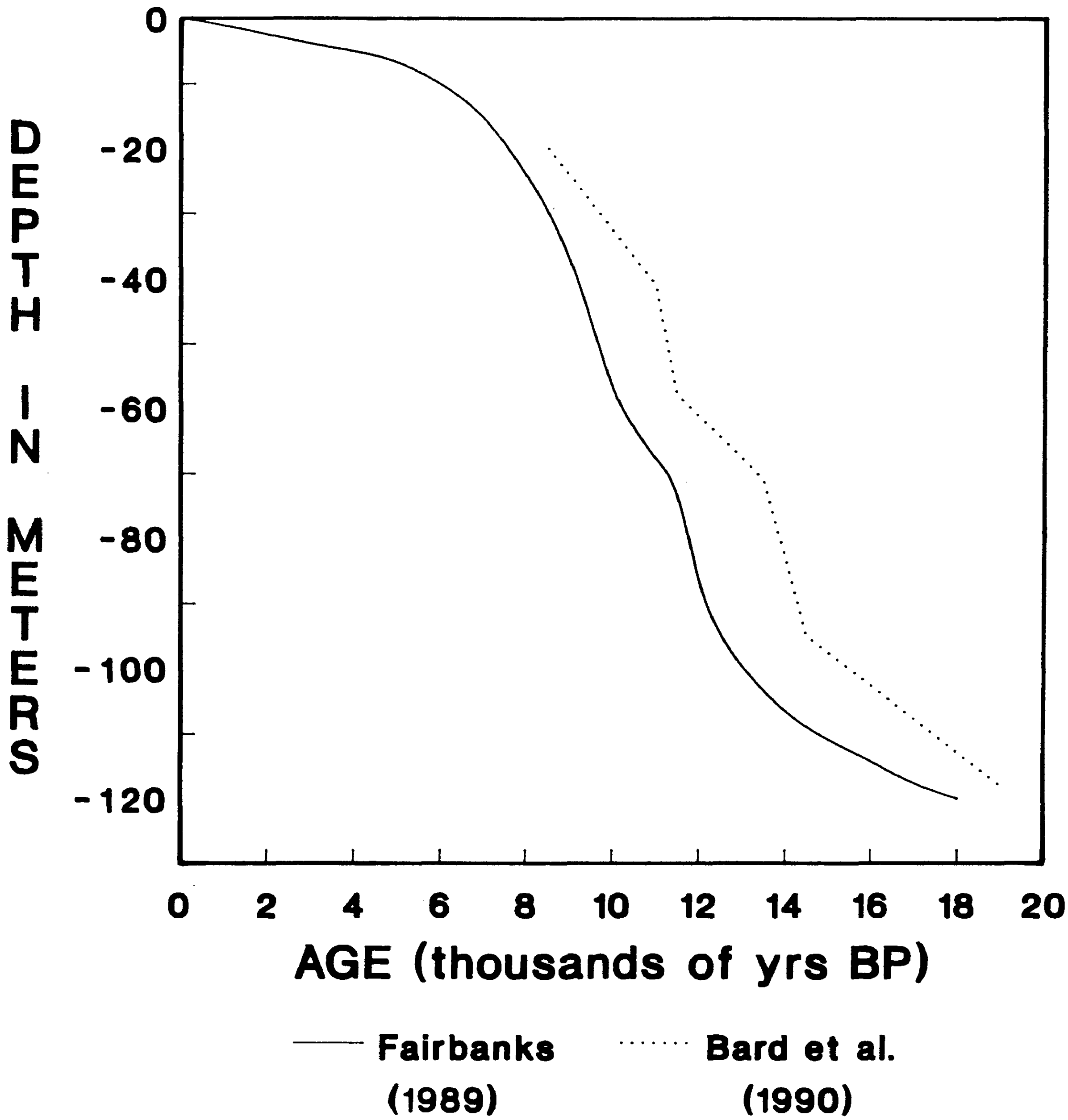
Effects of Sea-Level Fluctuations

The effects of these sea-level oscillations on the middle Atlantic continental shelf are best understood by considering the period since the last major glacial advance. About 18,000 years ago sea level was approximately 120 m below its present level, and the present day continental shelf was subaerially exposed with a shoreline near the modern slope break (Bard et al., 1990). During this lowstand, fluvial processes became the predominant mode of morphologic development on the shelf. Large fluvial channels and related sedimentary deposits were located many miles to the east of the modern shoreline. The lowstand allowed widespread erosion of the coastal plain, and the fluvial systems delivered an abundant amount of sediment to the late Pleistocene coastline. Coastal hydrodynamics during the subsequent Holocene marine transgression molded these sediments into groups of submarine shoals and barrier island complexes.

FIGURE 4

Holocene sea-level curves based on radiocarbon ages (Fairbanks, 1989) and U-Th ages obtained by mass spectrometry (Bard et al., 1990) using Acropora palmata samples from Barbados. Note the rate of sea-level rise decreased up to three separate times (14 ka, between 11-11.5 ka, and between 4-6 ka).

HOLOCENE SEA-LEVEL CURVES



Large scale arcuate shoals are believed to be formed by the progressive landward migration of shoreline depositional centers during a marine transgression (Swift et al. 1977a). However, the origin of barrier islands has been the subject of periodic debate since the early 1800's. Schwartz (1973) compiled a series of classical and contemporary articles which detail four hypotheses: (1) the upbuilding and emergence of offshore bars (Otvos, 1970), (2) development and extension of spits with eventual breaching and inlet cutting (Fisher, 1968), (3) partial submergence of coastal dunes and beach ridges (Hoyt, 1967), and (4) a multiple causality origin, where each of the above causes may occur independently or in concert (Schwartz, 1971).

Sedimentary records of the middle Atlantic shelf indicate precursors to present barrier systems existed throughout the Holocene transgression (Field and Duane, 1976). The evolution of these features is a function of sediment supply and the rate of sea level rise (Kraft, 1971). Theoretically, barrier islands can respond to a rising sea level by: (1) building upward and seaward, (2) being overstepped or drowned, or (3) migrating shoreward. Stationary barrier growth requires an accelerating increase in the amount of sand needed to maintain shoreface equilibrium (Dillon, 1970). If the effects of sea level rise dominate the increasing supply of sediment, then either barrier drowning or migration will occur.

At this stage, the evolution of barrier islands during the Holocene transgression is of some debate. One theory, based mostly on studies of the Long Island shelf, states that the barrier remains relatively stationary while the back-barrier lagoon deepens and widens during sea level rise (Sanders and Kumar, 1975; Rampino and Sanders, 1981). As sea level continues to rise, the breaker zone eventually reaches the dune crest, and the barrier is ultimately overstepped. Subsequently, the breaker zone skips landward to form a new barrier at the mainland boundary of the former lagoon. Thus the surf zone moves across the shelf in successive jumps, and a major portion of the transgressive sequence (ideally represented by dune or barrier sands overlying lagoonal or fringing marsh muds) is likely to be preserved (Rampino and Sanders, 1981). This type of evolution occurs where there is a moderate to low sediment supply, and relatively rapid pulses of sea level rise during an overall upward trend. In addition to these studies offshore Long Island, New York, Penland et al. (1986) have interpreted Ship Shoal in the northern Gulf of Mexico as an overstepped barrier.

A second and more widely accepted theory states that a continuous landward migration of barrier systems has been occurring throughout the Holocene transgression (Leatherman, 1983; Kraft, 1971; Swift, 1975). This theory does not imply that all barrier islands formed at the same time and place, or that the same barriers have existed throughout the Holocene epoch (Field and Duane, 1976). Their formation and migration on the shelf is believed to have been intermittent in both space and time. Mechanisms of shoreward migration include washover deposition and inlet cutting and filling

(Leatherman, 1979). In this theory the surf zone progresses across the entire shelf, and back barrier sediments are exposed to continuous reworking on the shoreface. Belknap and Kraft (1981) predicted that the rate of sea level rise is the main factor governing sequence preservation because it controls the amount of time an area is exposed to shoreface erosion. Also, they state that transgressive facies deposited in stream valleys and topographic lows are more likely to be preserved with this type of evolution because they are more likely to be below the depth of shoreface erosion. Conditions that favor the landward migration of barrier systems include low sediment supply during a steady moderately rising sea level.

REGIONAL STRATIGRAPHY

The sea level fluctuations described above are evident in the stratigraphy and subbottom structure of the Virginia/North Carolina inner shelf. The sediments reveal a complex geologic history of marine regressions and transgressions (Shideler and Swift, 1972). Downcutting by ancestral fluvial systems during low stands of sea level resulted in widespread erosional surfaces and fluvial channel deposits. Subsequent marine transgressions are expressed by the presence of estuarine and nearshore sedimentary sequences overlying the fluvial deposits. The stratigraphy of the Virginia inner continental shelf has been well documented in some areas through the analysis of seismic records and sediment core logs. The most notable investigations are reported in Shideler and Swift (1972), Shideler et al. (1972), Meisburger (1972), and Swift et al. (1977b). These studies indicate four distinct sedimentary sequences were deposited in this region on the present day continental shelf since the Pliocene. Hobbs (1989) confirms the stratigraphic relationships of these units.

Unit A

Shideler and Swift (1972) correlated the deepest and oldest of these sequences, termed Unit A, with the Yorktown Formation. This formation is unconformably overlain by younger sediments throughout much of Virginia's coastal plain, and its uppermost strata is likely Pliocene in age (Oaks et al., 1974). Williams (1987) used a "boomer" system in the area between Cape Henry and Virginia Beach. This system gives greater penetration to the seismic record as compared to the system used in this study. He noted that the contact between the Yorktown and the overlying sediments was represented as only a faint and discontinuous trace on the seismic records.

Unit B

The next youngest sequence, Unit B, consists of fluvial deposits overlain by nearshore deposits. It is characterized by lenticular to planar stratification within well developed local channels (Shideler and Swift, 1972). These buried channels trend to the southeast, and have considerable relief. Shideler et al. (1972), using radiocarbon dating and stratigraphic position, correlated this unit with the Great Bridge Formation - Sandbridge Formation sequence of the adjacent coastal plain. This sequence is believed to be of Sangamon or middle Wisconsin age (Oaks et al., 1974). More recently, this sequence has been assigned to the Sedgefield and Lynnhaven members of the Tabb Formation (Johnson, 1976; Peebles, 1984).

Unit C

Unit C lies above Unit B, and differs in both composition and character. This sequence is composed of homogeneous, horizontal layers of silt and clay that thicken slightly in an eastward direction. The deposit was formed in a low energy environment, such as an estuary or back barrier lagoon, during a late Pleistocene highstand of sea level (Williams, 1987). This unit has not been correlated with any onshore sequences.

Unit D

The uppermost and youngest sedimentary sequence, Unit D, makes up the majority of modern surficial inner shelf deposits except for local outcrops of Units B and C. Unit D is considered by Swift et al. (1977b) to represent a discontinuous Holocene transgressive sand sheet. It is composed of fine to medium sand or muddy sand with shells of modern marine fauna. Little internal stratification is visible (Williams, 1987). The sand sheet is the result of rising sea level over an eroding shoreface. The eroded material is redistributed by modern shelf currents.

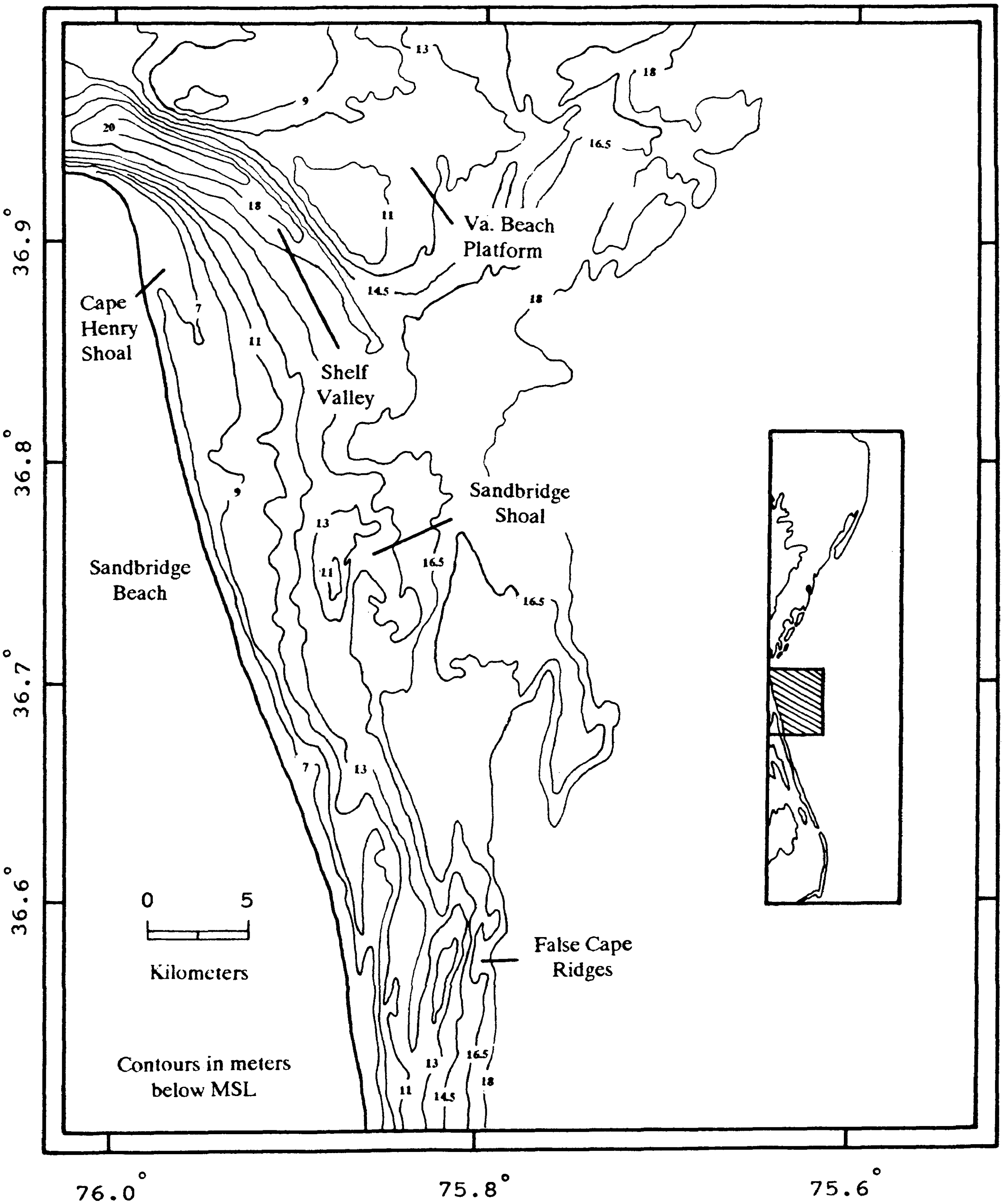
REGIONAL SETTING

Virginia's inner continental shelf is a submerged extension of the Virginia Coastal Plain Province. Between Cape Henry and the North Carolina state line, an overall seaward dipping trend of the shelf surface is interrupted by several major morphological features (Fig. 5). One of these is a well-defined shelf valley that extends southeastward from the mouth of Chesapeake Bay. This valley is believed to be a modern, topographic representation of a relict, fluvial channel that was active during the last major glacial advance (Meisburger, 1972). It is bounded on the east by the Virginia Beach Platform, which is a large shoal that makes up a portion of the Virginia Beach Massif. Swift et al. (1977b) term this feature a shoal retreat massif, which marks the retreat path of littoral drift deposition on the northern side of an estuary during a marine transgression. The valley's position corresponds to the Atlantic Ocean Navigation Channel.

Another prominent feature is the Cape Henry Shoal, located on the west flank of the shelf valley. This shoal is attached to the shoreface at the bay mouth and projects southward, paralleling the present shoreline, to a point seaward of Dam Neck. Williams (1987)

FIGURE 5

Virginia's inner shelf morphology
between Cape Henry and False Cape.
(adapted from Goldsmith, 1973)



Va. Beach
Platform
Cape
Henry
Shoal
Shelf
Valley
Sandbridge
Shoal
Sandbridge
Beach
0 5
Kilometers
False Cape
Ridges
Contours in meters
below MSL
36.9°
36.8°
36.7°
36.6°
76.0°
75.8°
75.6°

described the Cape Henry Shoal as a modern depositional feature that is a product of ebb tidal sedimentation processes occurring at the Chesapeake Bay mouth.

Located on the southern extreme of Virginia's inner shelf, a third distinct morphological regime is present in the form of linear shoals, or ridges. The False Cape Ridge System is composed of a series of northeast trending, shoreface attached shoals that have a length of up to several kilometers.

Seaward of the reach between Dam Neck and False Cape, the shelf surface is a generally featureless gently sloping plain, with the exception of a solitary sand shoal situated approximately 5.5 km offshore of Sandbridge Beach. This moderately sized feature (hereafter referred to as the Sandbridge Shoal) has not been described in the literature despite being a prospective source of sand and gravel.

OBJECTIVES

Because of the presence of large relict fluvial systems in the study area, the traditional theories of relict barrier or modern shoreface shoal are not the only interpretations possible for the origin of the Sandbridge Shoal. Therefore, the specific objectives of this study are to evaluate six models of shoal origin which represent depositional environments ranging from completely fluvial conditions to completely marine conditions. A schematic diagram of all six is given in Figure 6. The question of shoal origin is addressed by comparing the characteristics of the shoal and its surroundings with those which would be expected from each of the following models:

Model A: remnant of a point bar system

The paleochannel system (likely the ancestral James River system) in this region during the late Pleistocene could have evolved into a meandering stage before the effects of the Holocene transgression took over. Evidence for this model would require this sand body to be associated with a change or bend in the orientation of the paleochannel. A point bar is located on the inside bend, and is a part of the channel boundary. Thus, for the relict point bar to outcrop, the crests of the paleochannel sides should be at or near the present day shelf surface. Further evidence should indicate a progradation of the sediments toward the center of the paleochannel. Also, the sands of the shoal should show cross-bedding, fine upwards, and a lag deposit should be found at the base of the channel.

Model B: remnant of a fluvial or tidal delta

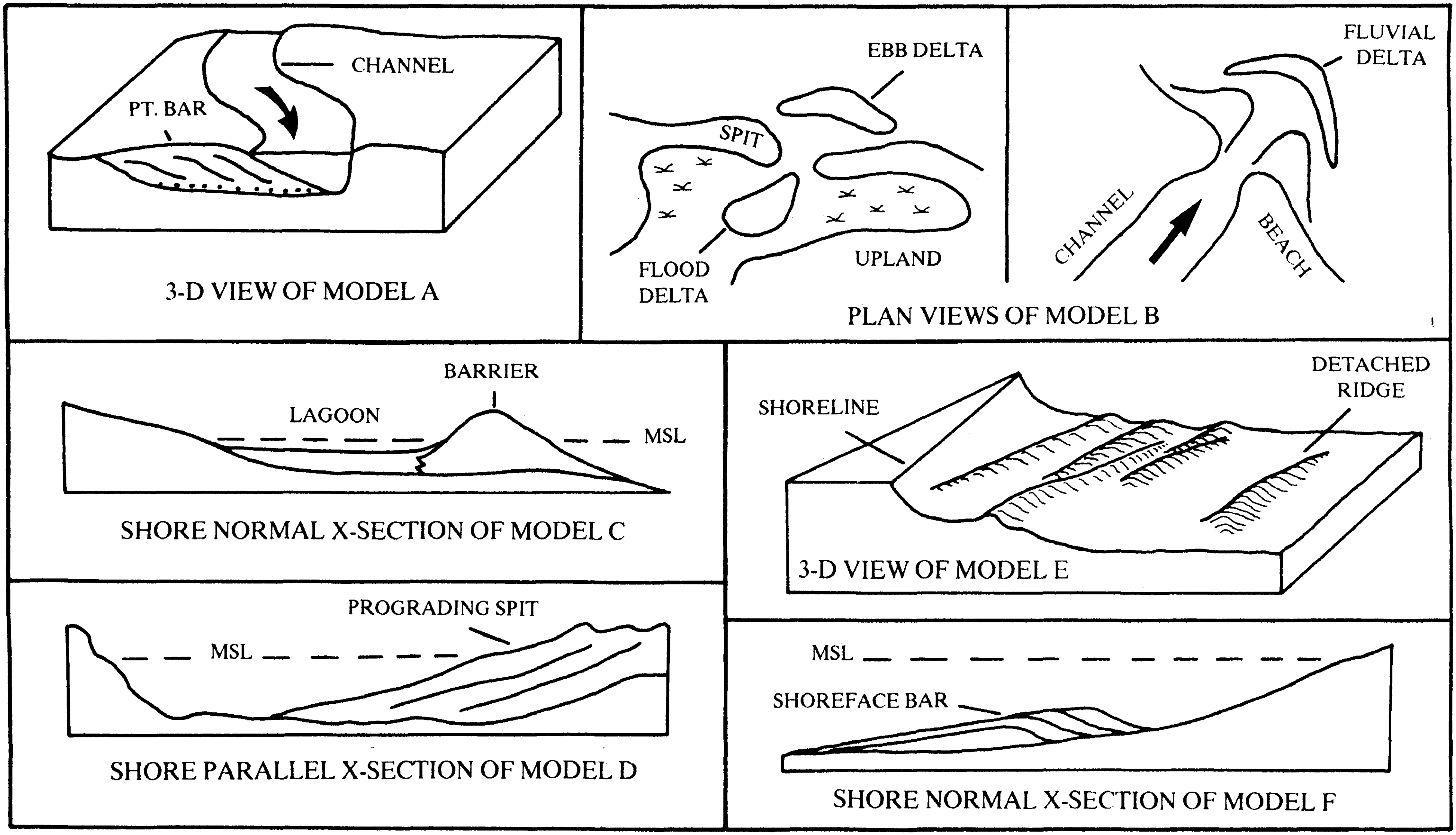
The large quantities of sediment being transported onto the shelf during the late Pleistocene probably resulted in the formation of fluvial and tidal deltas. For this feature to be considered a relict delta, its position should be within the paleochannel at an elevation below the channel sides. Its orientation should be along

FIGURE 6

Schematic diagram of models proposed for the origin of the Sandbridge Shoal.

A: after Blatt et al. (1980)
B: after Walker (1984) and Wright (1977)
C: after Walker (1984)
D: after Walker (1984)
E: after Swift et al. (1972)
F: after Van Straaten (1973)

SCHEMATIC DIAGRAM OF PROPOSED MODELS



inferred flow directions, showing a landward progradation for a flood-tidal delta or a seaward progradation for an ebb-tidal or fluvial delta. A flood-tidal delta would be made up of crossbedded sands, and surrounded by mud flat and marsh deposits. An ebb-tidal delta would also contain crossbedded sands, possibly interbedded with fine material. The fluvial delta would contain coarse crossbedded sands towards the surface, and would gradually become finer with depth until prodelta clays are reached.

Model C: drowned or overstepped barrier

The presence of a body of clean sand seaward and at least partially overlying silty clay points to a transgressing barrier system. Evidence for this model would include the presence of thick lagoonal deposits shoreward of the barrier sands. Moreover, evidence of previous inlet cutting and filling may exist seaward, and possibly within the shoal while being absent on its shoreward side. The shoal should contain crossbedding and excellent sorting as a result of former aeolian processes. Also, evidence of former sea level positions may be present; and if a source is present, an abundance of heavy minerals are likely to be found because they are commonly concentrated along the shorelines of barriers. A typical transgressive sequence may exist as a result of barrier migration which preceeded drowning.

Model D: remnant of a spit complex

The presence of a paleochannel filled with silts and clays shoreward of a moderately sized sand body indicates the possible existence of an estuarine system. On the seaward side of the sand body, littoral currents carrying material alongshore would lose their competence once they intersect the estuary mouth and result in spit growth. Similar evidence used to support Model A can be used to support this model. However, there also should be an indication of spit accretion and progradation in the stratigraphy. Moreover, a vertical transgressive sequence is not necessary, because the spit possibly could overlie a much older substrate.

Model E: detached shoreface ridge

As outlined by Duane et al. (1972), shoreface attached shoals follow an evolutionary sequence from being completely attached, through various degrees of saddle development, to complete truncation and isolation. This is then followed by the initiation of a new shoal inshore and down current from the previous segment. Therefore, this shoal could be a precursor of the False Cape Ridges. Evidence for this model would indicate that the shoal has no relation with the underlying stratigraphy (i.e. its bottom contact would be an unconformity). Internally, upward fining sequences and cross-strata would indicate storm events. These would be separated from fair weather periods evidenced by massive to slightly laminated sequences of invariant grain sizes (Swift et al., 1972). Textures and composition of the sediments should match or be very similar to the False Cape Ridges.

Model F: modern development of a shoreface bar

The development of an offshore bar may occur during a rise in sea level when there is a gently sloping nearshore bottom and an onshore supply of sediment (Leont'yev and Nikiforov, 1973). Van Straaten (1973) hypothesized that during a rapid sea level rise, erosion on the upper shoreface occurs more rapidly than on the middle and lower regions. Equilibrium is restored with a slowing of sea level rise, resulting in onshore transport. Evidence for this model would be similar to Model E. However, the textures and composition of the shoal's sediments may differ from those of the False Cape Ridges. Moreover, the morphology would indicate that material is being pushed landward from the shelf. This could be shown by a truncated shoreward side, and a seaward side gradually sloping offshore.

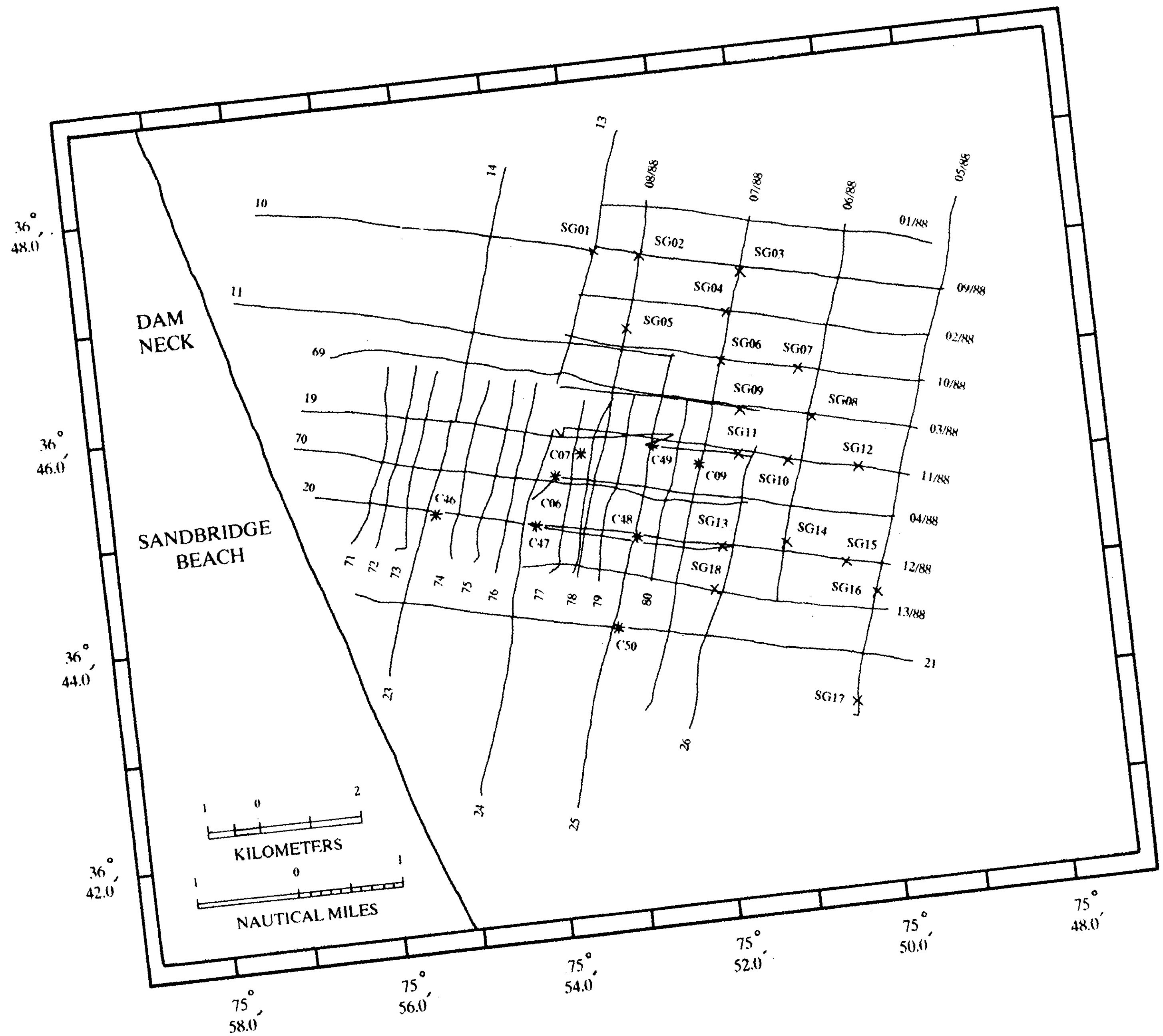
METHODS

Determination of the shoal's morphology, sedimentology, and its relationship with the surrounding stratigraphy has been achieved by correlating geophysical data with vibracores and surface grab samples. Data from sedimentary samples including geochronology, grain size analysis, petrologic analysis, and paleontologic analysis were evaluated to help in the determination of shoal origin. The initial data for this study were obtained as a part of two related studies along Virginia's inner continental shelf. Shallow seismic reflection and side-scan sonar records were obtained during the summer of 1987 as a part of an evaluation of sand resources offshore of Virginia Beach (Kimball and Dame, 1989). Vibracoring operations, also held during the summer of 1987, were performed for a reconnaissance of heavy minerals on the Virginian inner shelf (Berquist and Hobbs, 1988). After preliminary analyses of these data, a second, shallow, seismic survey was performed in the fall of 1988, and grab samples were obtained in the spring of 1990. This was necessary in order to more clearly delineate the northern and eastern boundaries of the shoal. An additional set of vibracores were obtained in the fall of 1989 from the U.S. Army Corps of Engineers.

The seismic surveys were carried out in a grid pattern (Fig. 7), and conducted aboard the Virginia Institute of Marine Science's R/V Bay Eagle. Navigational fix marks were taken every two minutes on the short tracklines and every five minutes on the longer tracklines. During the 1987 survey, the subbottom reflection and side scan sonar data were taken concurrently. The 1988 survey consists of subbottom profile data only. Navigation was carried out using a standard loran-C system for both surveys, and a Del-Norte positioning system was used for a portion of the 1987 survey.

FIGURE 7

Map of study area showing location of:
1987 seismic tracklines
1988 seismic tracklines (number followed by /88)
vibracores (number prefixed by C)
surface grab samples (number prefixed by SG).



DAM NECK
SANDBRIDGE BEACH
KILOMETERS
NAUTICAL MILES
36° 48.0'
36° 46.0'
36° 44.0'
36° 42.0'
75° 58.0'
75° 56.0'
75° 54.0'
75° 52.0'
75° 50.0'
75° 48.0'
01/88
02/88
03/88
04/88
05/88
06/88
07/88
08/88
09/88
10/88
11/88
12/88
13/88
SG01
SG02
SG03
SG04
SG05
SG06
SG07
SG08
SG09
SG10
SG11
SG12
SG13
SG14
SG15
SG16
SG17
SG18
C06
C07
C09
C46
C47
C48
C49
C50

Shallow Subbottom Reflection

An overview of the principles involved in this technique can be found in Williams (1982). Both sets of subbottom data (1987 and 1988) were obtained using a Datasonics SBP-5000 subbottom profiler. This system consists of a two channel, dual frequency transceiver that is connected to a towfish carrying the transducers. The primary profiling channel was set at 3.5 kHz while the second channel was fixed at 200 kHz. These frequencies were used because they gave the best combination of penetration and resolution to the seismic record for the conditions that were experienced. The profiler emits acoustic pulses at regular intervals from the towfish. The acoustic pulses are reflected from the contact between substances of different densities. Because of the relatively low frequency, these pulses not only reflect off of the air-water and water-sediment interfaces, but have enough energy to penetrate the sea bottom and reflect off the interfaces between different sedimentary layers. Reflected acoustic pulses are intercepted by the transducers in the towfish, and the acoustic pressure waves are converted into electrical signals. Energy attenuation of the transmitted signal occurs with depth, and a trade off is made between energy input and resolution of the reflected signal. In general, penetration and record quality is better in the 1988 data set. Up to 30 m of penetration is not unusual with excellent resolution.

The profiler was used in conjunction with EPC Model 3200 and EPC 4800 graphics recorders. The recorders produced hard copies of the converted electrical signals on electrostatic paper. The sweep rate of the recorder, which gives the vertical scale on the hard copy, was set at either 1/8 or 1/16 second. Because of the small depths involved, a travel time of 1500 m/s was assumed for all media. Interpretations of the data were made primarily from the EPC 3200 data, and the EPC 4800 data was used only to resolve the complicated areas because of a more expanded horizontal scale. The interpretations were made by tracing acoustic horizons (inferred sedimentary horizons) from the electrostatic paper onto vellum tracing paper. These tracings were then reduced to a more manageable size and redrafted into a report quality form.

Side-Scan Sonar

The side-scan data were obtained from an EG&G SMS 960 seafloor mapping system. This system consists of a processor/graphics recorder and a transducer-carrying towfish. The side-scan sonar provides information on the surficial characteristics of the seabed by giving a map view of the area directly below and to either side of the survey vessel. The transducers emit acoustic pulses of 105 kHz in a narrow fan shaped beam on each side of the towfish. The swath width of this survey was normally 100 m on either side. Backscattered and reflected acoustic signals are received by the transducers, and then sent to the processor/graphics recorder in the form of electrical signals where they are displayed on electrostatic paper. A side-scan record represents the acoustic energy which is returned from the seafloor. The amount of energy backscattered is a function of the bottom roughness: the rougher the bottom the more energy returned (Williams, 1982). Bottom roughness includes seafloor topography (sand waves, ripples, etc.) as well as sediment composition (muds reflect less energy than coarse grain sediments). The returned energy shows up on the record as sharp outlines or patterns with shadows for large scale roughness, and as shades of varying intensity for small scale or compositional roughness.

Sediment Cores and Grab Samples

The 1987 vibracores were obtained by contract with Alpine Ocean Seismic Survey Inc., aboard the R/V Atlantic Twin, and the 1988 vibracores were obtained by Exmar Inc., through the Geotechnical Division of the Norfolk District of the U.S. Army Corps of Engineers. Recoverable lengths of both sets of cores reached a maximum of just over 6 m; however, jetting often was necessary to achieve this limit. The 8.9 cm (3.5 in) inside diameter cores were split in half and described (Appendix A). Channel samples (continuous samples from the middle of the core half) were taken from sediments between each major textural change. Core locations were plotted on a map containing the seismic tracklines (Fig. 10). From this map, the cores were located on the subbottom cross-sections and correlated to the interpreted stratigraphic horizons.

Surface grab samples were obtained with a Smyth-McIntyre sampler, which gives a disturbed sample of the top 15-20 cm of sediment. These samples were correlated with the geophysical data in order to delineate the shoal's boundaries.

Geochronology

Amino Acid Dating

Geochronologic data are essential in determining which model best describes the origin of the Sandbridge Shoal. Twelve samples of shell material were collected from the vibracores and analyzed by two different dating methods. The principal method of analysis used amino acid techniques because of the low cost per sample and the relatively small sample size required. Amino acid dating is based on the diagenesis of proteins in an organism (Miller and Hare, 1980). In the living state, an organism integrates proteins into its shell material as growth continues. After death, the breakdown of peptide bonds, which hold amino acids together in the form of proteins, results in the freeing of amino acids. In addition to this, some amino acids undergo racemization after an organism dies. This process involves the conversion of l-isomers of the amino acid to d-isomers (l- and d-isomers of a particular substance have the same composition but different structures which yield different optical properties). Geological dating can be applied to these processes because the racemization ratios (D/L) and the ratios of free to bound amino acids increase with time. Since racemization data have proven to be more reliable, the "free to bound" ratios are used in support of the D/L data (Miller and Hare, 1980). This technique has been found to be very reliable when shells from the same genera are compared (Wehmiller et al., 1988).

The fundamental limitation of this method is the temperature dependence of both the rate of protein breakdown and the rate of racemization. For chronological purposes, uniform temperature conditions would be assumed to exist throughout time. Given Quaternary glacial history, this assumption is obviously invalid. However, the dependence of this method on temperature can be dealt with by assuming uniform climatic conditions within the spatial domain, instead of in the temporal domain. In other words, it can be assumed that similar paleoclimatic changes have occurred within specific geographical regions (Wehmiller et al., 1988; Belknap and Wehmiller, 1980; Miller and Hare, 1980). The shell material within a particular region would be subjected to similar temperature variations.

With this assumption, a relative dating of material within each of these geographical regions can be performed (i.e. A older than B, or B younger than C). Keeping in mind that different genera racemize at different rates, this is accomplished by comparing the D/L ratios of each sample; the greater the ratio, the older the sample. However, amino acid D/L data can also be used as a stratigraphic tool by assigning samples to aminozones (Groot et al., 1990; Wehmiller et al., 1988). Aminozones are defined by a range or cluster of D/L values. When the D/L ratio of a sample lies within one of these ranges, the sample is assigned the same relative age as that of the aminozone. This approach minimizes small variations in D/L values at specific sites, as well as small age differences among sites within a given region. When correlating D/L ratios from different regions, temperature gradients from any given time in the Pleistocene would be assumed to follow similar latitudinal trends of present day temperature gradients. Thus a sample located in the southern latitudes will contain a higher D/L ratio when compared to a sample of similar age located farther north. This relative dating by amino acid diagenesis has been termed aminostratigraphy by Miller and Hare (1980). The assumption of similar paleoclimatic histories across a region effectively eliminates the temperature dependence, and allows the method to be independent of the kinetics and mechanisms of racemization.

Absolute ages of material can be obtained through amino acid diagenesis only by calibrating D/L values to independent chronologic data, or by applying models of racemization kinetics which integrate the thermal history of the material. Miller and Hare (1980) suggested that an approximate absolute time scale for a locality can be obtained by comparing the D/L values from radiometrically dated samples. However extreme caution should be exercised when absolute ages, based on radiocarbon dating, are extrapolated to older material because of the nonlinearity of racemization kinetics.

In a study of Quaternary sites along the central and southern U.S. Atlantic coastal plain, Wehmiller and Belknap (1982) compared amino acid data (D/L ratios) with uranium-series dates of solitary corals and biostratigraphic data. Within local regions, they found an agreement among the relative dates of material using each of the methods. In some cases, more depositional events were actually identified by the aminostratigraphy. However, several problems with the aminostratigraphy were noted when regional correlations of D/L ratios were made, and when comparing ages from kinetic models with those from U-series dates. Absolute age estimates of D/L values were given by local U-series calibration, and were regionally correlated. These correlations, if true, required latitudinal trends of similar aged D/L values to be highly variable. This variability is in direct conflict with the basic assumptions of aminostratigraphy, which call for the latitudinal trends of isochronous D/L values to approximate those of the present temperature gradients. Furthermore, absolute ages of D/L values given by kinetic models of amino acid racemization do not agree with those given by U-series calibration in two localities: South Carolina and central Chesapeake Bay.

These differences are explained by Wehmiller and Belknap (1982) as either indicating problems in the basic temperature assumptions of aminostratigraphy, or implying that the conflicting U-series dates represent minimum ages for their respective locations. They state that the sample reliability of each of the suspect U-series dates can be questioned because of the abundant ^{232}Th content. A low $^{230}Th/^{232}Th$ ratio normally indicates the sample has been altered diagenetically (Wehmiller and Belknap, 1982).

Radiocarbon Dating

Radiocarbon dating was performed in order to provide independent chronologic data for quality control, and to allow correlations to the amino acid data for absolute age determinations. Radiocarbon methods were chosen over other techniques because the ages were expected to be relatively young.

The fundamental assumption of radiocarbon dating is the existence of an equilibrium between the production and decay of ^{14}C over time (Bowen, 1978). Cosmic ray bombardment of the earth's upper atmosphere initiates ^{14}C production by generating neutrons. When these neutrons collide with ^{14}N atoms, ^{14}C is formed. It is then oxidized to carbon dioxide, and mixed rapidly throughout the atmosphere. Organism uptake of ^{14}C is proportional to stable carbon, and proceeds with normal life processes. However upon death, uptake ceases and radioactive decay begins. Dating of material is applied by measuring the amount of ^{14}C activity in a sample and comparing it to a modern standard. By knowing the rate of decay or half life of ^{14}C, a calculation of the elapsed time since death can be made (Bowen, 1978). However unlike amino acid dating, where the D/L ratios increase with sample age up to an equilibrium level of 1.0, the radioactivity of ^{14}C decreases with sample age, thus making its detection more difficult with older samples. Thurber (1972) gives a limit of 35,000-40,000 years for radiocarbon dating of carbonate material.

Even though radiocarbon dating is generally accepted, there are several problems which require corrections and result in the necessity for careful application of its results: (1) uncertainty in a sample's initial $^{14}C/^{12}C$ ratio, (2) isotopic fractionation of carbon in the sample, and (3) the possibility of sample contamination by extraneous carbon (i.e. the sample has not remained a closed system). For marine samples, a major cause for the uncertainty of the original $^{14}C/^{12}C$ ratio is due to the long residence time of carbon in the ocean. This results in the radiocarbon content of the sample being different from that in the atmosphere, and gives the sample an "initial" age (Thom et al., 1981). This "initial" age can be determined through studies of the local marine environment, and corrected by subtracting from the apparent age (Thurber, 1972).

Other uncertainties in the original radiocarbon content of a sample are due to temporal variations of carbon in the atmosphere. In the recent geologic past, industrialization and nuclear testing have drastically influenced the amount of atmospheric radiocarbon. On a larger time scale, the degree of changes have been less dramatic, and have been the result of variations in climate (which change carbon reservoirs), the cosmic ray flux, and the Earth's magnetic field (Faure, 1977). Corrections for recent fluctuations are made by calibrating the radiocarbon activity of modern standards with dendrochronology and varve chronology. However, the radiocarbon content of the atmosphere prior to 10,000 BP is not well known (Faure, 1977).

A second problem with this method deals with isotopic fractionation. Isotopes of carbon are fractionated by several natural processes, including photosynthesis and isotope exchange among carbon compounds (Faure, 1977). This results in the abundance of stable isotopes (^{13}C and ^{12}C) associated with an organism at death to be different from the amounts in the atmosphere. These differences can be corrected by comparing the $^{13}C/^{12}C$ ratio of the sample to a standard. For each sample, this comparison is usually reported as a ^{13}C value, which averages 0% for marine shells (Bowen, 1978).

Despite the effects discussed above, the major skepticism in the radiocarbon dating of carbonates is due to sample contamination. Contamination of carbonate samples can occur in two ways: by recrystallization and by exchange with the outside environment. In both cases it results in an anomalously young radiocarbon age, and this problem increases with the actual age of the sample. Small amounts of contamination, as little as 1%, can overshadow the initial amounts of radiocarbon, and Thurber (1972) has suggested that all radiocarbon ages of carbonate material over 25,000 years should be considered as minimum ages. Since sample contamination occurs from the shell's surface toward its center, preventative actions prior to sample dating must be carried out. Washing the sample in dilute acid should be performed to remove any surficial contamination. In addition to this, a visual inspection, preferably during sampling, should be done to check for obvious recrystallization or secondary precipitation. If the sample's size permits, scraping away of the surface layers may be done so that only the interior of the shell is dated.

Sampling and Age Determination Procedures

For this study, all twelve samples were analyzed by amino acid racemization, and their results were corraborated with those from radiocarbon dating methods which were performed on portions of two of these samples. The shell material of each sample which underwent both types of analyses was clearly from the same individual. All twelve samples were from the phyllum Mollusca, and ranged from solitary valves to material from discrete shell layers. The primary sampling concern was to use material which had not been reworked, and which was not chemically altered. For this reason, broken and fragmented shells as well as those showing visible signs of secondary mineralization and leaching were discarded. Whenever possible, articulated valves and shells in growth position were used. Also when possible, dates were obtained from material along stratigraphic contacts. Another major concern was to sample material of sufficient size. A minimum size of 0.5 gm is needed for amino acid dating, and 10.0 gm for radiocarbon dating. After sampling, the matrix or sediment was cleaned from the shell material by brush and dental tool.

The amino acid analysis was carried out by Dr. D.L. Belknap at the University of Maine. Complete results, represented by D/L ratios, are given in Appendix A. When the sample size was large enough, the shell's surface layers were scraped away to insure data were obtained from unaltered material. Samples were cleaned in dilute HCL and NH_4OH, then dried and weighed. After cleaning, the samples were dissolved and hydrolyzed in 6N HCL, and the hydrolyzates were desalted on cation exchange resin. This procedure results in a total amino acid mixture. Ester derivatives of this mixture were then prepared and analyzed by capillary column gas chromotography. Peak height ratios were then determined directly from the chromatograms to give D/L values. It should be noted that D/L values from the amino acid leucine have been found by Wehmiller et al. (1988) to offer the best precision and racemization rates for establishing a relative aminostratigraphy.

Radiocarbon age determination was performed by Geochron Laboratories in Cambridge, Massachusetts. Sample preparation consisted of cleaning the shell material in an ultrasonic cleaner, and then removing surficial material by cleaning in dilute HCL. The cleaned shells were then hydrolyzed with HCL under vacuum. This produces CO_2 which was recovered and analyzed by proportional gas counting. By international convention, the dating is based upon a radiocarbon half life of 5570 years, and ages are referenced to 1950 A.D. No significant radiocarbon activity was detected from these samples, which indicates the age limits of this method were being approached. Thus the reported dates are given as minimum ages, and the limit age is based upon a 95% probability. In order to correct for man's influence on the environment, the samples were compared to a modern standard which has 95% of the activity of the National Bureau of Standard's oxalic acid. The reported ages are ^{13}C corrected, but no corrections were made for reservoir effect.

Grain-Size Analysis

Grain-size analysis was performed in order to characterize the sediments making up the shoal. This analysis involved the following procedures: (1) wet sieving to separate the fine fraction (< 0.063 mm or > 4.0 phi), (2) dry sieving the remainder of the sample to separate the sand fraction (between 0.063-2mm or 4- -1 phi) from the gravel fraction (> 2mm or < -1 phi), (3) weighing individual fractions to give the percentage that each contributes to the total sample weight, and finally (4) a sub-sample of the sand fraction was run through a Rapid Sediment Analyzer (RSA).

The RSA is a computerized sedimentation tube which determines a particle's size by measuring its settling velocity. Each size class has a specific settling velocity assuming grain density, shape, concentration, and water temperature are considered. The instrument used for this study consists of a vertical tube filled with de-ionized water, and an electrobalance which is interfaced with a PC. After the sediment is introduced at one end of the tube it settles onto a pan, located at the bottom of the tube, which is suspended from the electrobalance. The distance the sediment falls is known, and the time taken for settling is measured by recording automatically the weight of the material accumulating on the pan. Thus the fractional weight of a sample which settles at a specific rate is determined. The computer, after recording the weights of the different size classes, calculates a series of statistics of the sample.

Petrology

From the models presented, four processes are likely to have dominated the sediments making up the shoal during their last cycle of transportation: (1) aeolian processes in Models A and B, (2) fluvial processes in Models C and D, (3) shoreface erosion in Model E, and (4) onshore transport in Model F. A particle's morphology and texture may or may not indicate characteristics that distinguish these processes. This is because morphologic and textural characteristics of a sediment may be inherited from an earlier deposit of different origin (Folk, 1980). However, petrologic analysis will allow some generalizations to be made about the history of the sediment making up the shoal, and at the very least, may indicate if this material is related to that of the False Cape Ridges.

Three properties of sediment from the Sandbridge Shoal and the False Cape Ridges were evaluated: mineralogy, grain morphology, and grain texture. For each of these properties, a standard binocular microscope with reflected light was used to examine 100 grains per sample. Only the 2-3 phi fraction of each sample was examined in detail in order to eliminate any bias due to varying grain sizes.

The mineral assemblage of a sediment often is used to evaluate a sediment's maturity, or to compare it to sediment from another location. An estimate of the maturity of the sediments was made by trying to determine the ratio of quartz grains (very stable) to feldspar grains (less stable) in each sample, and also by comparing heavy mineral data for each sample which is given by Berquist and Hobbs (1988).

The morphology of grains in each sample was described by evaluating particle roundness and sphericity. These characteristics are a function of a grain's internal properties and its history of transport. Aeolian processes are the most effective in rounding sand grains, while beach sands are more rounded than fluvial sands (Pettijohn, 1975). Little or no rounding of sand grains is thought to occur during fluvial processes because of the large amount of time (thus distance) and energy needed (Folk, 1980). However, once rounding occurs it is not easily lost, and any rounding may be inherited from earlier events of transport. For this reason, grain morphology was used only in comparison of sediments and to substantiate evidence of transport processes found from grain texture.

The roundness of a particle depends on the sharpness or jaggedness of its edges, and the sphericity is a function of a particle's shape. Sample roundness was determined by using the technique described by Powers (1953). He proposed six classes of roundness, which may exhibit a high or low sphericity. Each class was characterized by a numerical interval which has a mean value:

CLASS	MEAN VALUE OF CLASS INTERVAL
Very Angular	0.14
Angular	0.21
Subangular	0.30
Subrounded	0.41
Rounded	0.59
Well Rounded	0.84

Individual particles were assigned to a class by comparing them to a characteristic shape (Fig. 8). An average roundness for the sample was determined by multiplying the number of particles in each class by the mean value of that class. Then the sum of these products was divided by 100 (total number of grains counted). The resultant is the geometric mean of the sample, and thus the sample was assigned to a particular class of roundness.

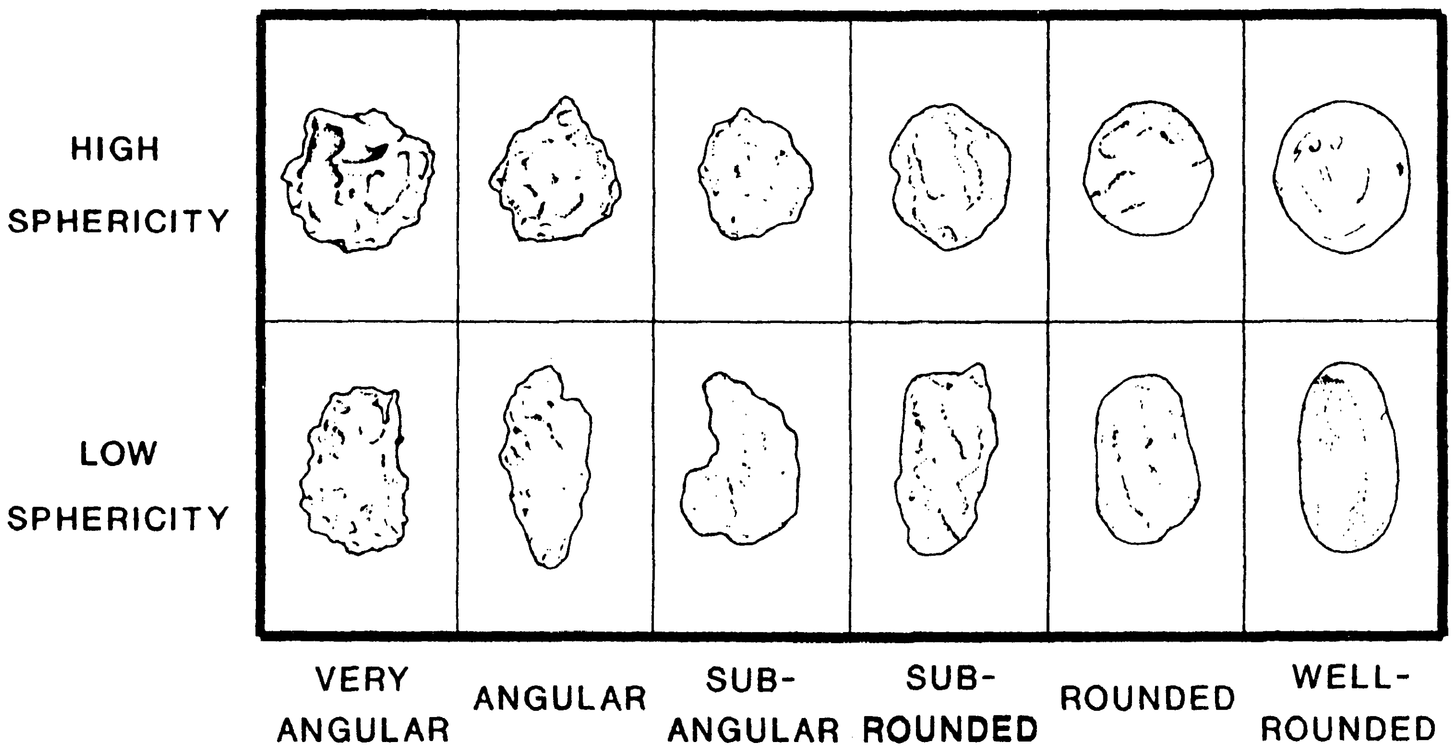
Surface textures of a grain may be described as frosted, polished, or dull. Sediment texture is similar to grain morphology in that it is a function of the inherent properties of a particle as well as the amount of abrasion to which a grain has been subjected. However, less abrasion and transport are required to create or modify these features than are needed for the morphologic features. Therefore, surface textures are more likely to record the latest event of transportation (Pettijohn, 1975).

Frosting occurs on rounded grains and are thought to be a product of aeolian processes or chemical etching. It is indicated by a lusterless, very finely pitted surface. On the other hand, polished

FIGURE 8

Categories of grain shape
used in the petrologic analyses.
(after Powers, 1953)

CATEGORIES OF GRAIN ROUNDNESS



surfaces are created by a smoothing of small irregularities, and occur with a glossy, highly reflective luster. They are believed to be associated with beach environments (Folk, 1980). A surface which is neither polished nor frosted has a dull or flat appearance, and indicates a lack of abrasive action. Percentages of grains exhibiting each of these types of textures were determined for each sample.

Faunal Analysis

The environment of deposition of a particular stratigraphic unit may be indicated by the suite of organism remains that exist in the sediment. For example, shoreface sediments may contain traces of organisms commonly associated with high energy marine conditions, while lagoonal sediments can be expected to contain the remnants of organisms which thrive in low energy brackish waters. However, care must be taken with these interpretations because of the possible transport of shells and organism tests from adjacent environments.

With this in mind, a general assessment of the fauna within the shoal and its surrounding stratigraphy was performed in order to better understand their depositional environments. Large shell material, where present, was sampled from the sedimentary cores. Also, samples taken for grain size analysis were examined with a standard binocular microscope for micro-fauna content. In order to avoid the classification of allochthonous material, only those shells and tests which showed little or no evidence of transport were analyzed. Transport of the larger material may be indicated by the shells appearing out of growth position in the sedimentary cores. It can also be evidenced by rounded and worn fractures and breaks occurring on the shell edges.

Initial analysis involved "lumping" and "splitting" material into common groups based on morphology. Then classification, in most instances down to genus, was performed by referring to accepted texts and field guides such as Moore and Treichert (1969), Gosner (1978), and Rehder (1981).

RESULTS

Shoal Morphology

Correlation of seismic data with vibracores and surface grab samples indicate the areal extent of the Sandbridge Shoal to be roughly 6x8 km. In general, the shoal is a wedge of sand with the thickest amounts of material located in its southwest quadrant (Fig. 9 and 10). The sand body becomes thinner and has less relief toward the north and east. Moreover, the shoal's extreme northern and eastern margins are less well defined because they grade into the adjacent topography. In plan view, the shoal's outline forms a horseshoe shape with the convex side oriented southward (Fig. 11).

The southwest quadrant (or western limb of the horseshoe) is characterized by a series of ridges and troughs oriented approximately N 35 E. These ridges reach 3-4 m above the adjacent shelf surface and

FIGURE 9

Three dimensional view of shelf surface
in the study area. View is towards the southeast.

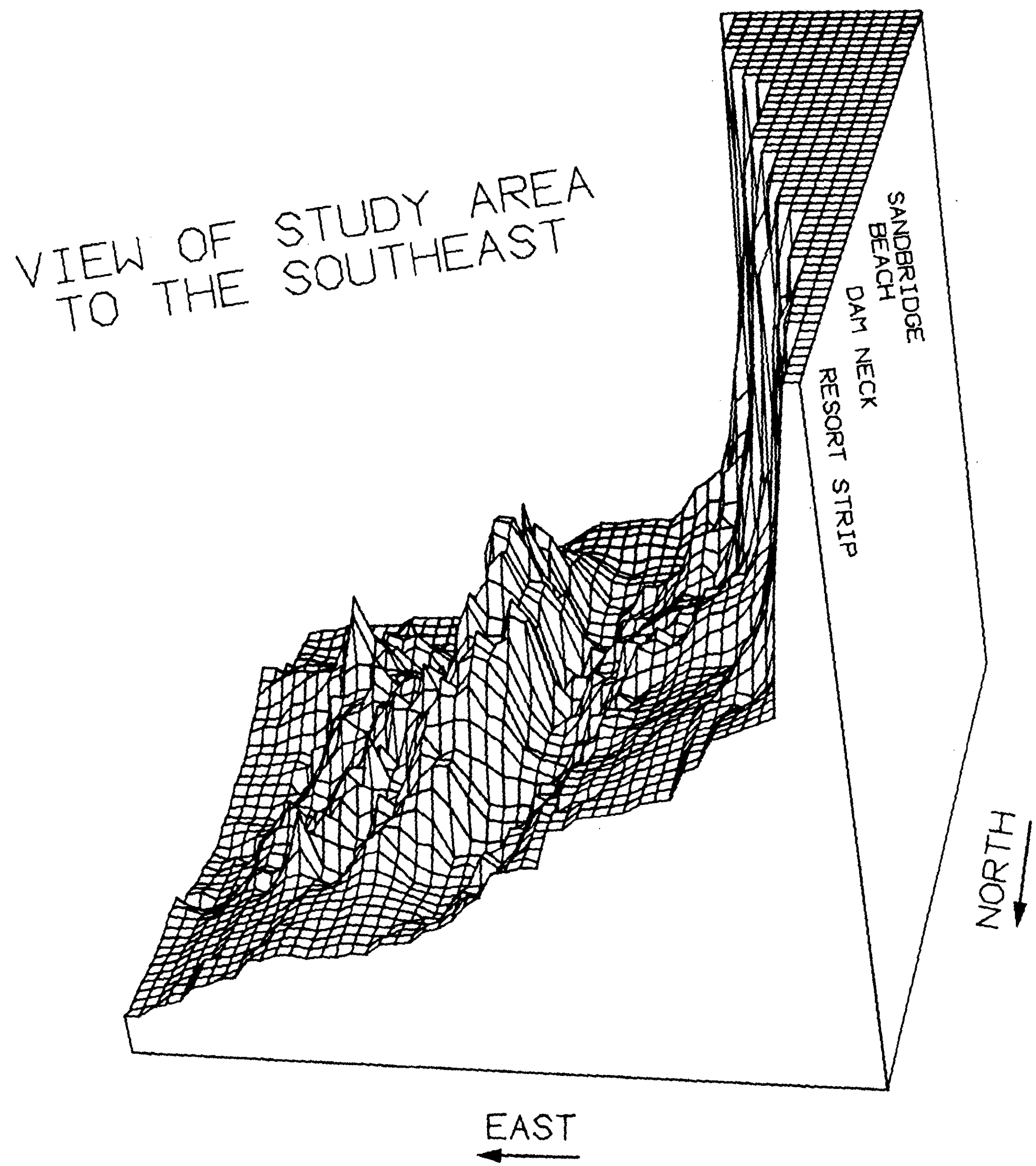

VIEW OF STUDY AREA
TO THE SOUTHEAST
SANDBRIDGE
BEACH
DAM NECK
RESORT STRIP
NORTH
EAST

FIGURE 10

Three dimensional view of shelf surface
in the study area. View is towards the southwest.

VIEW OF
STUDY AREA TO
THE SOUTHWEST

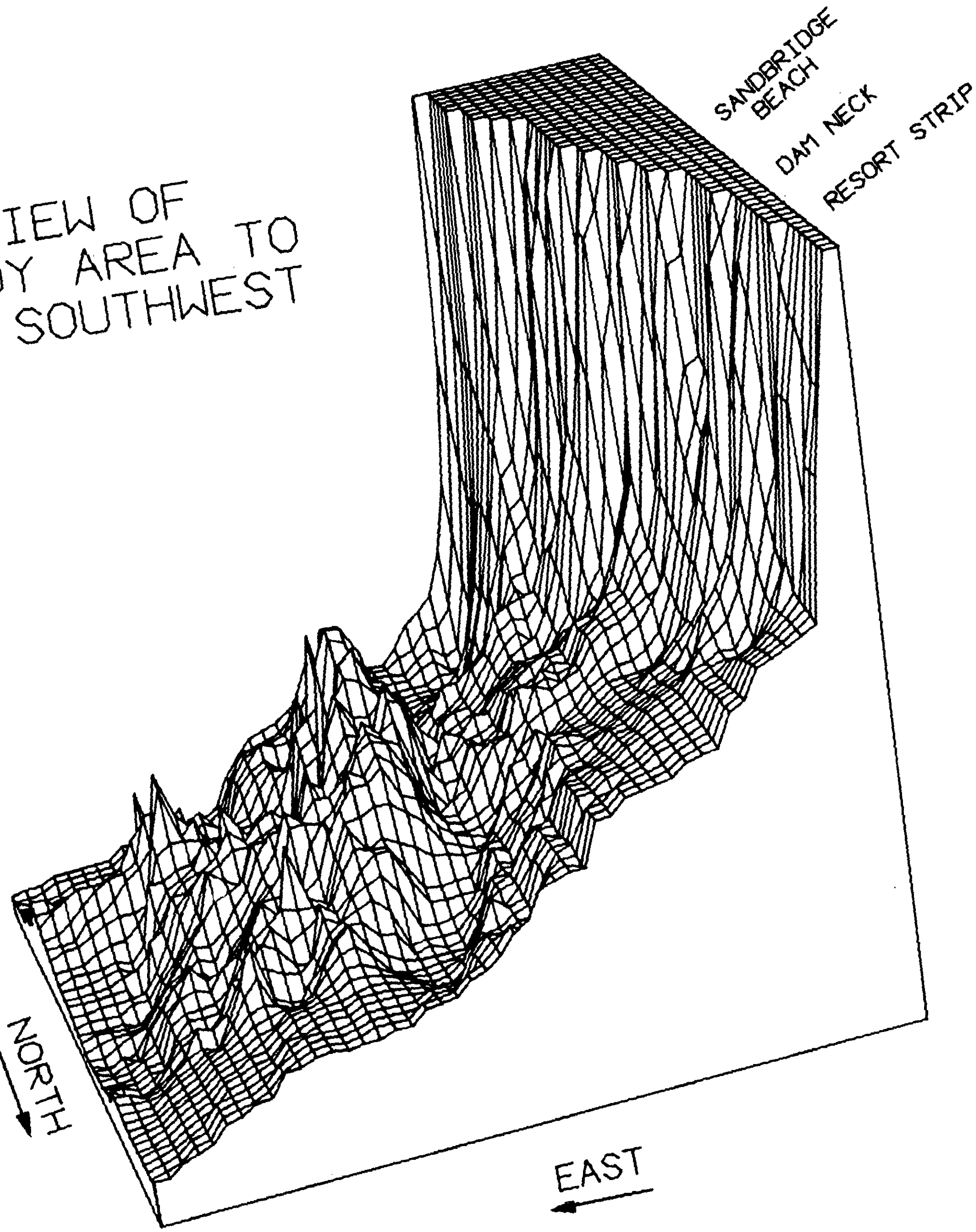


FIGURE 11

Detailed bathymetry of study area
showing outline of Sandbridge Shoal.

BATHYMETRIC MAP OF STUDY AREA

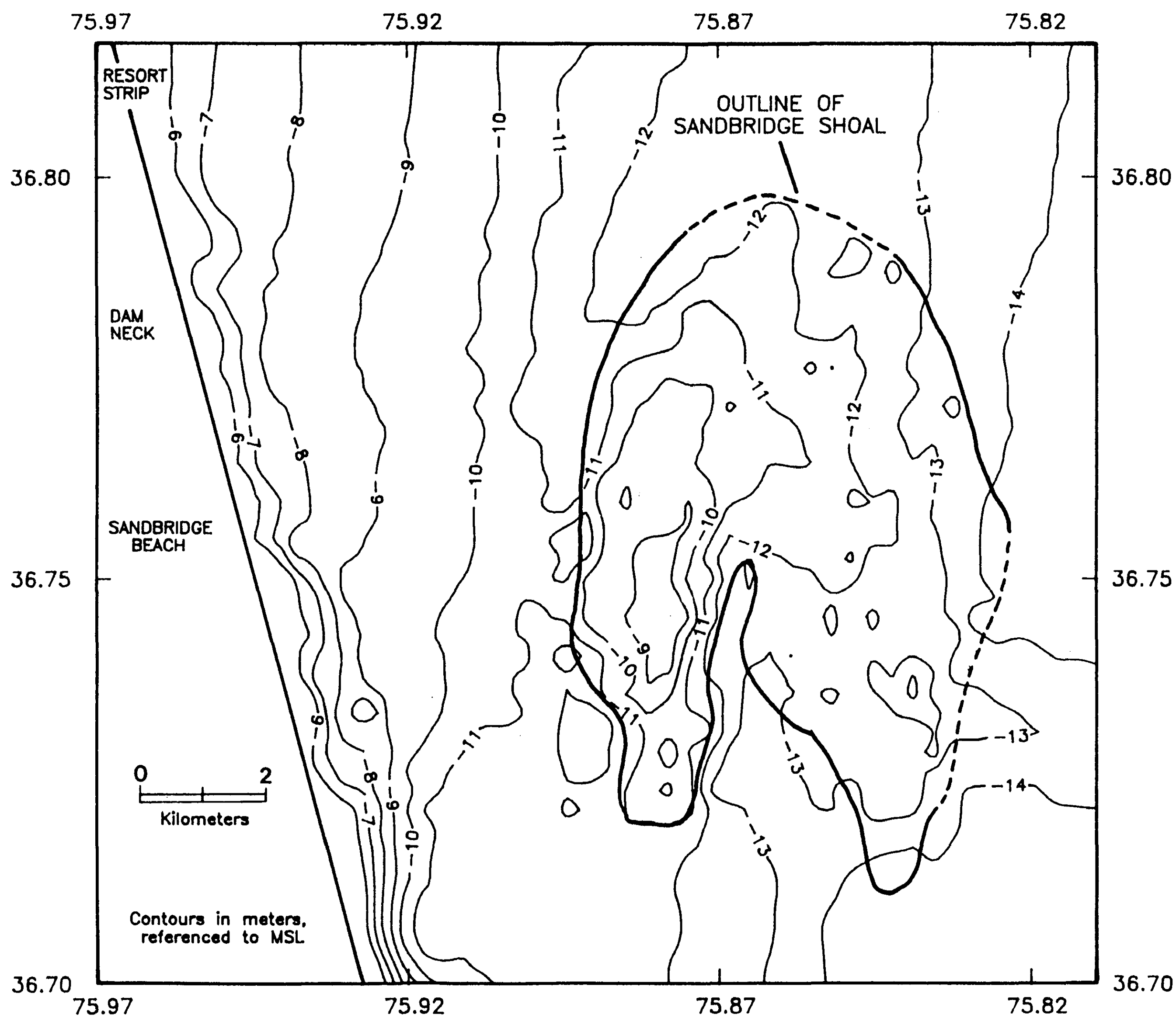
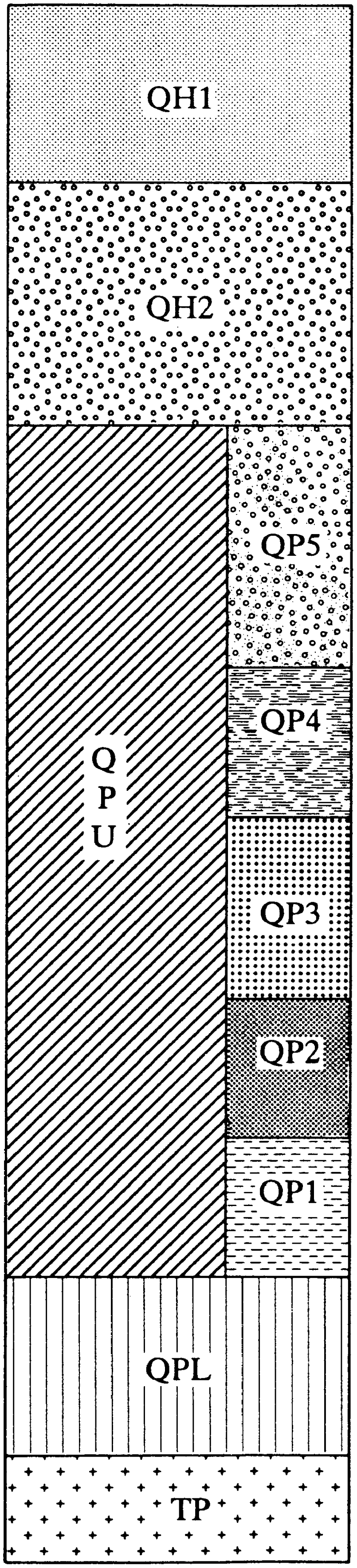


exhibit the shoal's highest relief. The southern and western margins in this quadrant form a terrace 2-3 m above a depression in the bordering sediments (Plates 1B and 2B). This terrace tapers and becomes more obscure to the north. The eastern limb or southeastern quadrant has a more subdued undulating topography that extends 1-3 m above the surrounding shelf surface (Plate 1B). The boundaries of these two limbs are separated by a swale, and the sediments of the shoal slope gradually into this depression.

Shoal Stratigraphy

A generalized stratigraphic section of the study area is given in Table 1. Unit names were assigned on the basis of stratigraphic relationships and geochronology data, which are described in the next section. Stratigraphically, the shoal can be divided into two units. The upper unit, QH2, is characterized by four vibracores (7, 9, 48, 49) (Appendix A). These indicate this unit is composed of clean, well sorted, medium to coarse sand. The sand is typically olive gray in color, and becomes darker with depth. It has a mean grain size of approximately 1.5 phi (0.35 mm), and in all but three samples contains less than 3% fines (silt and clay) (Table 2). In general the sediments become finer with depth, but relatively coarser layers exist throughout the cores indicating storm sequences are superimposed on a general coarsening upward trend. On the surface, the sediments of the shoal become coarser toward the north and east as evidenced by surface grab samples. Furthermore, with the

TABLE 1 GENERALIZED STRATIGRAPHIC SECTION OF STUDY AREA



QH1 - Holocene sand sheet. Dark gray fine to very fine micaceous sand. Some coarser layers indicating storm sequences. Characterized by s-1 in core 47. Also appears in core 46.

QH2 - Upper unit of Sandbridge Shoal. Olive gray, clean, well sorted, medium to coarse sand. In general coarsens upward. Found in upper portions of cores 7, 9, 48, & 49. Separated from lower unit by by weak reflector, R4, which is seen as a thin silt layer in cores 48 & 49, and gravelly shell layer in core 7.

QPU - Upper Pleistocene valley-fill sequence.

QP5 - Lower unit of Sandbridge Shoal. Slightly darker and finer than QH2. Exhibits some crossbedding in core 7. Bottom boundary is strong reflector, R3, which is documented in cores 7 and 48 as a shell layer.

QP4 - Clay and silt interpreted as estuarine. Found in cores 6, 7, 46, 47, and 50.

QP3 - Gray, clean, well sorted, medium to coarse sand. Silty layers and gravelly towards upper contact. Found in s-4 & s-5 of core 47. N-S seismic lines suggest it is a tidal channel.

QP2 - Dark gray fine sand. Found in bottom of core 48. Interpreted as bay-mouth or tidal shoal due to its relationship with QP3.

Qp1 - Clay and silty clay. Interpreted as estuarine from seismic line 25/87. Found in core 49.

QPL - Lower Pleistocene valley-fill sequence. Separated from QPU by strong reflector, R2. Cutting relationships of QPU & QPL seen in seismic lines 7/88 & 8/88.

TP - Interpreted as Pliocene. Defined by deep channel boundaries. Separated from upper units by intermittent reflector, R1. See seismic line 12/88.

TABLE 2 RESULTS OF SEDIMENT ANALYSIS

SAMPLE	DEPTH (m)	UNIT	% GRAVEL < -1 PHI (> 2mm)	% SAND > -1 PHI & < 4 PHI (>1/16 & <2mm)	% OF DOMINANT SAND SIZES PER SAMPLE	% SILT & CLAY > 4 PHI (< 1/16mm)	MEAN/ ST.DEV. (PHI)
CORE 7							
s-2	0 - 0.5	QH2	15.9	83.6	42.7 M 28.3 C 11.2 VC	0.5	0.9/0.7
s-3	0.5 - 1.25	QH2	0.7	98.1	69.2 M 19.8 C 5.2 VC	1.1	1.3/0.6
s-4	1.25 - 1.60	QH2	2.4	96.7	61.5 M 23.4 C 6.3 VC	0.9	1.2/0.6
s-5	1.60 - 1.80	QP5	0.5	96.3	68.0 M 19.9 F 6.0 C	3.2	1.7/0.4
s-6	1.80 - 1.90	QP5	0	77.1	31.3 F 26.3 M 17.2 VF	22.9	2.4/0.7
s-7	2.52 - 2.66	QPU	1.4	88.9	42.6 C 37.9 M 5.8 VC	9.6	0.9/0.5
s-8	2.68 - 2.74	QPU	3.6	89.9	82.6 M 4.6 C 1.2 F	6.5	1.3/0.2
CORE 9							
s-1	0 - 1.55	QH2	0.3	98.6	66.3 M 16.1 C 12.0 F	1.1	1.5/0.5
s-2	1.55 - 2.05	QH2	0.7	90.1	50.7 M 22.6 F 11.7 C	9.2	1.7/0.7
s-3	2.20 - 3.05	QPU	0.3	91.9	45.8 M 40.8 F 3.7 VF	7.8	2.0/0.4
s-4	3.05 - 4.25	QPU	0	97.2	48.5 M 45.2 F 2.2 VF	2.8	2.0/0.3
s-5	3.65 - 4.59	QPU	0	95.8	51.4 F 40.5 M 3.0 VF	4.2	2.1/0.4

TABLE 2 RESULTS OF SEDIMENT ANALYSIS (cont'd)

SAMPLE	DEPTH (m)	UNIT	% GRAVEL < -1 PHI (> 2mm)	% SAND > -1 PHI & < 4 PHI (>1/16 & <2mm)	% OF DOMINANT SAND SIZES PER SAMPLE	% SILT & CLAY > 4 PHI (< 1/16mm)	MEAN/ ST.DEV. (PHI)
CORE 47							
s-1	0 - 0.6	QH1	1.0	85.2	63.3 VF 15.5 F 3.6 C	13.8	3.2/0.6
s-4	2.40 - 2.85	QP3	14.9	59.7	25.1 C 17.6 M 12.3 VC	25.4	0.7/0.8
s-5	2.85 - 3.55	QP3	1.5	96.6	49.5 VC 21.1 C 14.9 F	1.9	1.4/0.8
CORE 48							
R1 s-1	0 - 0.82	QH2	1.3	97.4	74.2 M 13.1 C 7.8 F	1.3	1.5/0.5
R1 s-2	0.82 - 2.10	QH2	0.4	97.4	70.5 M 14.4 F 11.1 C	2.2	1.6/0.5
R2 s-1	2 - ?	QH2	0.3	97.8	69.1 M 17.4 F 9.6 C	1.9	1.6/0.5
R2 s-2	? - 4.39	QH2	1.4	96.1	61.5 M 15.5 F 14.8 C	2.5	1.5/0.6
R3 s-1	4.21 - 5.10	QP5	2.5	95.3	52.2 M 26.1 F 11.4 C	2.2	1.7/0.6
R3 s-2	5.10 - 5.79	QP2	1.0	95.7	60.4 F 24.0 M 5.7 VF	3.3	2.1/0.5

TABLE 2 RESULTS OF SEDIMENT ANALYSIS (cont'd)

SAMPLE	DEPTH (m)	UNIT	% GRAVEL < -1 PHI (> 2mm)	% SAND > -1 PHI & < 4 PHI (>1/16 & <2mm)	% OF DOMINANT SAND SIZES PER SAMPLE	% SILT & CLAY > 4 PHI (< 1/16mm)	MEAN/ ST.DEV. (PHI)
CORE 49							
s-1	0 - 1.61	QH2	0	98.8	71.0 M 15.3 C 10.1 F	1.2	1.5/0.5
s-2	1.61 - 3.14	QH2	3.2	92.3	65.2 M 14.4 F 10.9 C	4.5	1.6/0.5
s-3	3.15 - 4.14	QP5	0.2	95.1	46.7 F 38.9 M 5.0 C	4.7	1.9/0.5
s-6	5.13 - 5.74	QPU	0.1	87.3	60.4 F 22.1 VF 3.5 M	12.6	2.7/0.5

NOTE:		
VC - Very Coarse	0.0 to -1.0 PHI	1.00 to 2.00 mm
C - Coarse	1.0 to 0.0 PHI	0.50 to 1.00 mm
M - Medium	2.0 to 1.0 PHI	0.25 to 0.50 mm
F - Fine	3.0 to 2.0 PHI	0.125 to 0.25 mm
VF - Very Fine	4.0 to 3.0 PHI	0.0625 to 0.125 mm

PHI = -log base 2 of grain diam. in mm

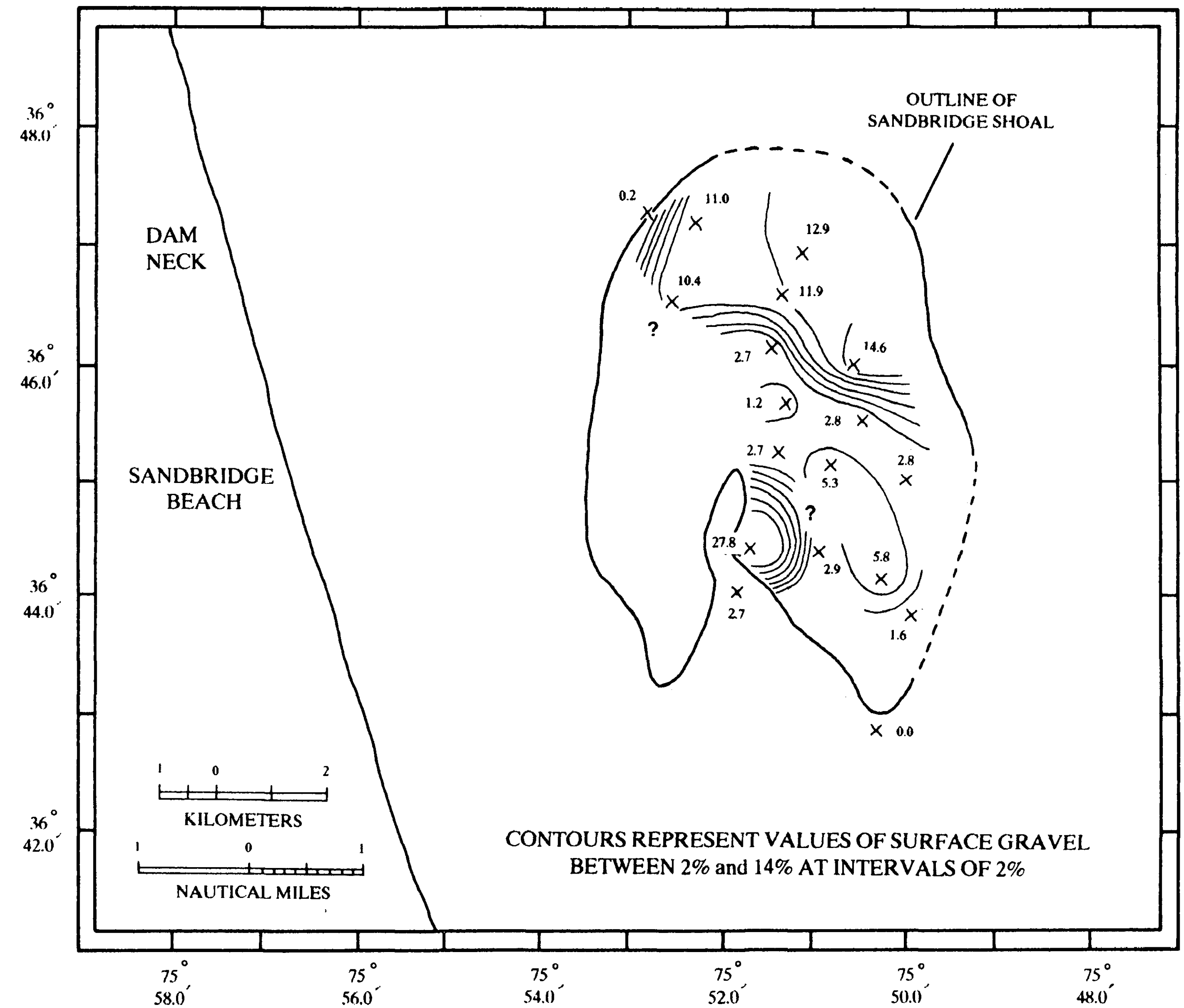
exception of grab number 13, gravel percentages are highest in the northeast section of the shoal (Fig. 12). Several subbottom reflectors, as well as the character of surficial features, indicate movement of the material has occurred towards the south and west (Plates 1B through 4B).

The lower unit, QP5, is present throughout most of the western half of the shoal, and generally pinches out beneath the upper unit before outcropping at the surface. QP5 is present in cores 7, 48 and 49 (Appendix A), and differs from the upper unit by having a slightly finer grain size (mean = 1.8 phi or 0.28 mm) (Table 2). In cores 7 and 49 it becomes finer with depth, and grades into silty fine sand toward the bottom. However, QP5 coarsens downward in core 48. Crossbedding is present, but not well developed, in core 7. QP5 is generally thinner than unit QH2, having an average thickness of 1.5 m and a maximum of 2 m. Conversely, QH2 averages 2.5 - 3 m and has a maximum thickness of 6 m. A conservative estimate of the combined volume of both units is 80 million m^3, with the lower unit making up approximately 20 million m^3.

These two units are separated by a relatively weak and intermittent reflector, labelled R4 on the seismic data. This reflector is evidenced by a 5 cm thick layer of sandy silt and clayey silt in cores 48 and 49 respectively, and by a gravelly, shelly sand layer in core 7. The silt layer is approximately 13 m below MSL, while the coarse sand layer is located 14.4 m below MSL. This difference indicates an absence of the silt layer in core 7 that may

FIGURE 12

Contour map of percent gravel found in surface grab samples.


OUTLINE OF
SANDBRIDGE SHOAL
DAM
NECK
SANDBRIDGE
BEACH
0.2
11.0
12.9
10.4
11.9
?
2.7
14.6
1.2
2.8
2.7
2.8
5.3
?
27.8
2.9
5.8
2.7
1.6
0.0
1
0
2
KILOMETERS
1
0
1
NAUTICAL MILES
CONTOURS REPRESENT VALUES OF SURFACE GRAVEL
BETWEEN 2% and 14% AT INTERVALS OF 2%
36° 48.0´
36° 46.0´
36° 44.0´
36° 42.0´
75° 58.0´
75° 56.0´
75° 54.0´
75° 52.0´
75° 50.0´
75° 48.0´

be due to erosion. The R4 reflector has an undulatory nature in the southern region where most of the shoal's relief is located, and in general slopes downward to the east and north (Plates 1B through 5B).

Underlying and Surrounding Stratigraphy

Throughout most of its area, the two units making up the Sandbridge Shoal have a strong contact with the underlying material. This contact is labelled R3 on the seismic data, and shows up as a sharp, relatively continuous, horizontal reflector (Plates 1B through 5B). This reflector is represented by a 10 cm layer of shell fragments and shell hash in core 7, and a 25 cm layer of shell fragments in core 48.

In the shoal's southwest quadrant, the sediments directly below the R3 reflector can be divided into three separate units. One, unit QP3, underlies a small portion of the shoal's western boundary (Plate 1B). This unit is characterized by samples s-4 and s-5 of core 47, which indicate it is composed of a gray, medium to coarse sand with relatively higher concentrations of silt and gravel towards its upper surface. Unit QP3 has an average thickness of 1.5 m. Channel-shaped reflectors in north-south trending seismic lines, as well as the surrounding stratigraphy, suggest this unit represents a relict tidal channel (Appendix B and Plate 3B).

Another sand layer, unit QP2, underlies the Sandbridge Shoal to the east of QP3. The stratigraphic relationships between these two units suggests that QP2 represents a relict bay-mouth or tidal shoal

(Plate 1B). Seismic data indicate the thickness of unit QP2 averages 1.5 - 2 m. It is represented by sample R3 s-2 of core 48, which is a fine, dark gray sand with a mean grain size of 2.1 phi (0.23 mm).

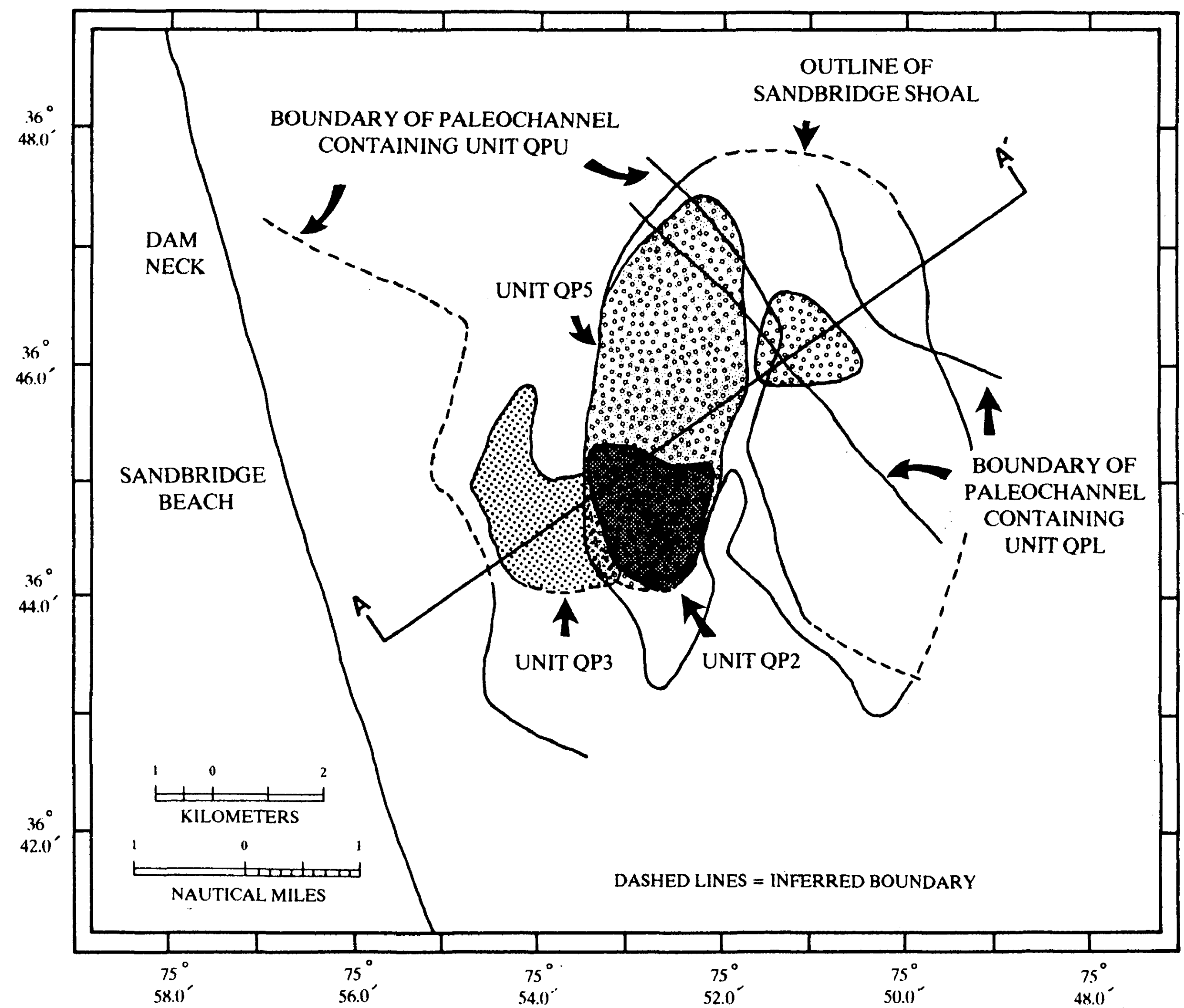
Located below QP2 is a layer of dark gray silty clay which also has an average thickness of 1.5 - 2 m. It is labelled unit QP1, and lies directly beneath the Sandbridge Shoal beyond the northern and southern limits of QP2. This silty clay is found in core 49, and outcrops at the surface in core 50. In both cores the clay contains pods and stringers of sand. Reflectors on seismic line 25\87 indicate unit QP1 represents a period of channel infilling, and thus may be an estuarine clay (Appendix B). Its relationship with the other units is also shown in line 11/88 (Plate 2B).

North of core 49 unit QP1 thins out, and the material underlying the Sandbridge Shoal cannot be correlated to known sediments because of the steep apparent dip of beds to the southwest. Seismic records reveal the shoal partially overlies a large buried paleochannel system (Plates 1B through 5B); the steeply dipping beds indicate channel migration (Plate 3B and line 25/87 in Appendix B). The fluvial system consists of two major southeast trending channels (Fig. 13 and 14). Cutting relationships of these two channels are very obvious along seismic lines 7/88 and 8/88, and indicate that the southernmost channel is younger (Plate 3B).

Sediments associated with channel filling in the younger paleochannel are labelled QPU. Units QP5 through QP1, previously described, are an upper part of this sedimentary package. The channel

FIGURE 13

Areal relationships of major stratigraphic units.
Note that not all stratigraphic units are portrayed here.
See Figure 14 and Table 1.

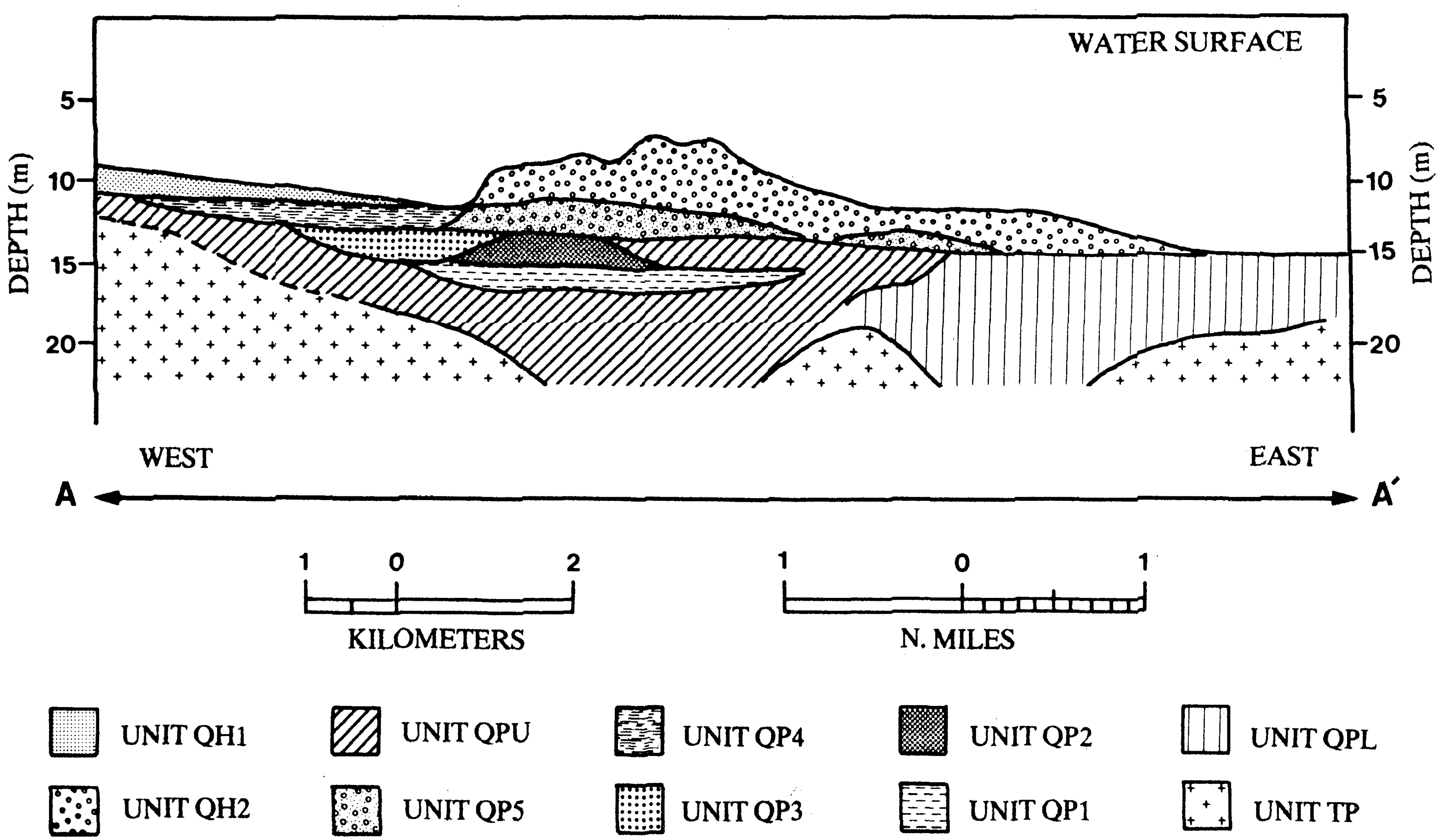


OUTLINE OF SANDBRIDGE SHOAL
BOUNDARY OF PALEOCHANNEL CONTAINING UNIT QPU
DAM NECK
SANDBRIDGE BEACH
UNIT QP5
UNIT QP3
UNIT QP2
BOUNDARY OF PALEOCHANNEL CONTAINING UNIT QPL
A
A'
DASHED LINES = INFERRED BOUNDARY
KILOMETERS
NAUTICAL MILES
36° 48.0'
36° 46.0'
36° 44.0'
36° 42.0'
75° 58.0'
75° 56.0'
75° 54.0'
75° 52.0'
75° 50.0'
75° 48.0'

FIGURE 14

Schematic interpretation of a cross-section along segment A-A′ on Figure 13. See Table 1 for description of stratigraphic units.

SCHEMATIC INTERPRETATION OF CROSS-SECTION A-A



filling sequence in the older paleochannel is termed unit QPL, and these two channel filling events are separated by a strong reflector labelled R2 (Plates 3B and 5B). Beneath the southeast quadrant of the shoal, a broad interfluve separates the two paleochannels (Plate 2B).

The thalweg depths of both of these paleochannels are below the limit of acoustic penetration. However based on the angle of dipping strata and considering the seismic tracklines likely run oblique to the trend of the channels, the thalweg depths are believed to be approximately 40 m below present mean sea level. This depth is estimated by projecting the channel margins downward. Channel boundaries must also be inferred, and the minimum channel widths are estimated to be 2 km for the older paleochannel and 4.5 km for the younger. Seismic lines 4/88 and 12/88 indicate the younger fluvial system consists of a steep-sided relatively deep channel (1.5- 3 km wide) which is flanked by more gently sloping areas (Plate 1B). This further indicates material within the paleochannel represents infilling of an estuarine system. The deepest channel boundaries are believed to be made up of Tertiary sediments, and are labelled TP. They are separated from younger, valley-fill strata by reflector R1 (Plates 1B, 2B, 4B, and 5B).

Unit QPL, representing sediments of the older paleochannel, outcrops at the surface along seismic line 5/88 (Plate 4B). Sediments from the infilling of the younger paleochannel outcrop at two locations in the study area. One location is in a swale abutting the western boundary of the shoal where Unit QP4, a silty clay, outcrops

(Plate 1B). This clay overlies unit QP3, and where not exposed is overlain by a dark gray fine to very fine sand (unit QH1). The second location is in a depression between the two limbs of the shoal, as evidenced by seismic lines 4/88, 7/88, 12/88, and 13/88 (Plates 1B and 3B). Grab sample number 18 represents the sediment of this depression, and is composed of dark gray silty sand.

Geochronology

Results from the amino acid racemization analysis are given in Table 3 and Appendix A. When comparing the raw data (D/L ratios), it should be noted that Mercenaria, Pitar, Astarte, and Rangia have similar amino acid racemization kinetics when found coexisting (Belknap, 1990). They demonstrate a moderate rate of racemization, and are considered a single group in this study. Mulinia and Spisula cannot be compared directly to this group. These two genera demonstrate slower rates of racemization with D/L values approximately 5 to 20 % lower.

The study area lies within Aminostratigraphic Region II of Wehmiller et al. (1988), which includes southern New Jersey, Delaware, Maryland, Virginia, and northeastern North Carolina (Fig. 15). Based on Mercenaria samples, they recognize five aminozones in this region (IIa through IIe). Based on data from their study, these aminozones have the following ranges of D/L leucine values:

IIa: 0.18 - 0.29

IIb: 0.31 - 0.33

IIc: 0.36 - 0.44

IId: 0.51 - 0.59

IIe: 0.81 - 0.89

When comparing the results of the Sandbridge Shoal study area with the values for these aminozones, it is obvious that all but four samples are associated with aminozones IIa and IIb. Samples 7 and 12 (D/L leucine values of 0.376 + .011 and 0.350 + .010 respectively) indicate a slightly higher degree of racemization, and may represent the upper part of aminozone IIc. Sample 6 exhibits the highest stage of racemization in this study with a D/L leucine ratio of 0.80 + .04. This sample was chalky in appearance, and was the only one that showed visible signs of leaching and alteration. However, poor shell preservation is believed to cause anomalously low D/L values, and thus this sample can be assigned to aminozone IIe. In contrast, the juvenile Spisula of sample 11 has a D/L leucine ratio of 0.003 which indicates very little racemization has occurred. Thus, sample 11 cannot be associated with aminozone IIa, and must be much younger than the other samples in this study.

Region II aminozones have been proposed to have the following age estimates (Wehmiller et al., 1988; Groot et al., 1990):

IIa-IIb: 75,000-130,000 yrs BP; Isotopic Stage 5a to 5e

IIc: 200,000-250,000 yrs BP; Isotopic Stage 7

IId: 400,000-600,000 yrs BP; Isotopic Stage 11, 13 or 15

IIe: No attempt is made to assign dates due to the degree of racemization. However, samples probably represent the Yorktown Formation or its equivalents, and have an early Pleistocene to Pliocene age.

Two of these aminozones, which are probably represented by samples from this study, have been thoroughly calibrated by other dating techniques. Solitary corals from aminozone IIa in the Gomez and New Light Pits of Norfolk, Virginia and the Stetson Pit of North Carolina have given multiple U-Th dates clustering around 75,000 years (Szabo, 1985; Wehmiller et al., 1988). Also a coral from an aminozone IIc site in Ponzer, North Carolina has been dated by U-Th and U-trend dating, and an age between 200,000 to 220,000 years was given (Szabo, 1985; Wehmiller et al., 1988). Furthermore, verification of these calibrations has been given by electron spin resonance dates from the Gomez Pit site (Mirecki et al., 1989; Groot et al., 1990).

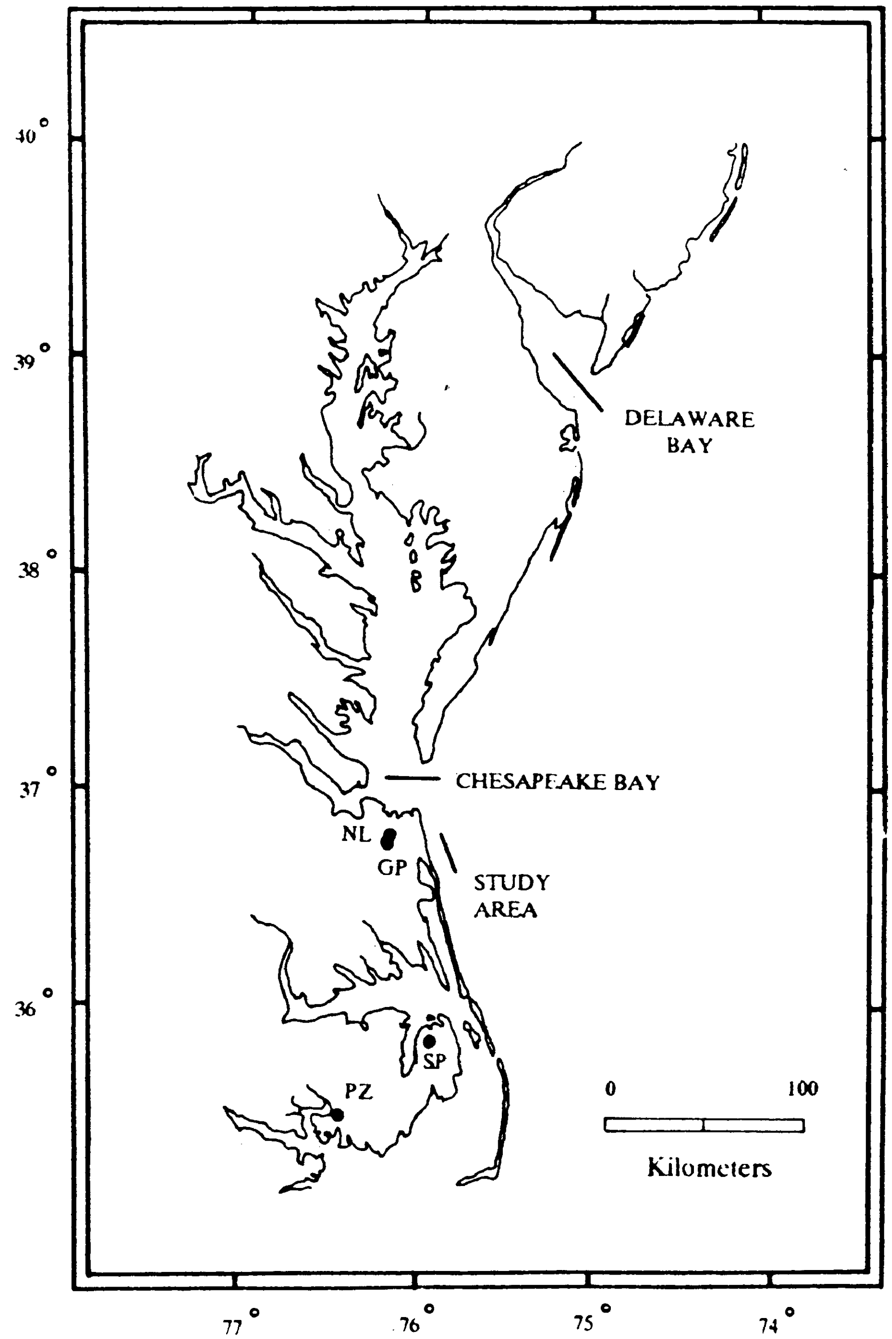
As presented above, these ages indicate that aminozone IIa-IIb represents isotopic Stage 5, and aminozone IIc isotopic Stage 7. It has been proposed that aminozone IIa is equivalent to late Stage 5 (substage 5a), and aminozone IIb represents early Stage 5 (substage 5e) (Belknap and Wehmiller, 1980). However, at this time there is not enough data to make this distinction (Wehmiller et al., 1988). Thus aminozones IIa and IIb are combined.

TABLE 3 RESULTS OF AMINO ACID RACEMIZATION ANALYSIS

SAMPLE	LOCATION	DEPTH MSL	Genus, species	D/L LEU	REMARKS
1	Core 46 -4.7 m	-15.7 m	*Mercenaria campechiensis*	0.240 +.010	Lustrous, well preserved, single broken hinge frag.
2	Core 47 -1.6 m	-13.6 m	*Mercenaria campechiensis*	0.304 + -	Lustrous, well preserved, single broken hinge frag.
3	Core 47 -2.8 m	-14.8 m	*Astarte castanea*	0.248 +.006	Slightly abraded, well preserved, single valve
4	Core 48 -5.0 m	-13.8 m	*Mulinia lateralis*	0.176 +.001	Moderately well preserved, single valve
5	Core 49 -4.2 m	-14.2 m	*Mulinia lateralis*	0.232 +.003	Lustrous, well preserved, single valve
6	Core 50 -5.3 m	-17.2 m	*Rangia cuneata*	0.80 +.04	Chalky, leached, moderately preserved single valve
7	Core 06 -2.9 m	-16.0 m	*Mercenaria campechiensis (?)*	0.376 +.011	Lustrous interior, bored, mod. well pres., umbonal frag.
8	Core 07 -1.6 m	-14.4 m	*Mulinia lateralis*	0.258 +.002	Lustrous to dull, well preserved, single valve
9	Core 07 -1.9 m	-14.7 m	*Mulinia lateralis*	0.231 +.001	Lustrous to dull, well preserved, single valve
10	Core 07 -3.6 m	-16.4 m	*Pitar morrhuana*	0.314 +.005	Lustrous, well preserved, single valve frag.
11	Core 09 -1.9 m	-15.2 m	*Spisula sp.* (juvenile)	0.003 +.000	Lustrous, extr. well preserved, single valve
12	Core 09 -2.1 m	-15.4 m	*Mercenaria campechiensis*	0.350 +.010	Lustrous, well preserved, single valve hinge frag.

FIGURE 15

Map of Aminostratigraphic Region II showing the spatial relationship between the study area and the location of reference sections used in calibrating the aminostratigraphy.
GP - Gomez Pit, Va.
NL - New Light Pit, Va.
PZ - Ponzer, N.C.
SP - Stetson Pit, N.C.
(after Wehmiller et al., 1988)



40°
39°
38°
37°
36°
DELAWARE BAY
CHESAPEAKE BAY
NL
GP
STUDY AREA
SP
PZ
0
100
Kilometers
77°
76°
75°
74°

These age calibrations are helpful in forming a kinetic model used to produce numerical age estimates. Age estimation is an iterative process which not only requires age calibration, but also temperature control (Belknap, 1990). The Effective Quaternary Temperature or EQT is used to describe the integrated thermal history of a region. For the Norfolk area, the EQT is believed to be 6.5 ^{o}C for late Stage 5, 8.5 ^{o}C for middle Stage 5, and 11.0 ^{o}C for early Stage 5 (Figure 22 in Wehmiller et al., 1990; Belknap, 1990). The sites in this study may be slightly cooler, especially for early Stage 5, because the samples are from offshore vibracores (Belknap, 1990). For this study, the kinetic model assumed that Mercenaria D/L leucine ratios of 0.24 correspond to 75 ka, 0.36 to 120 ka, and 0.42 to 250 ka.

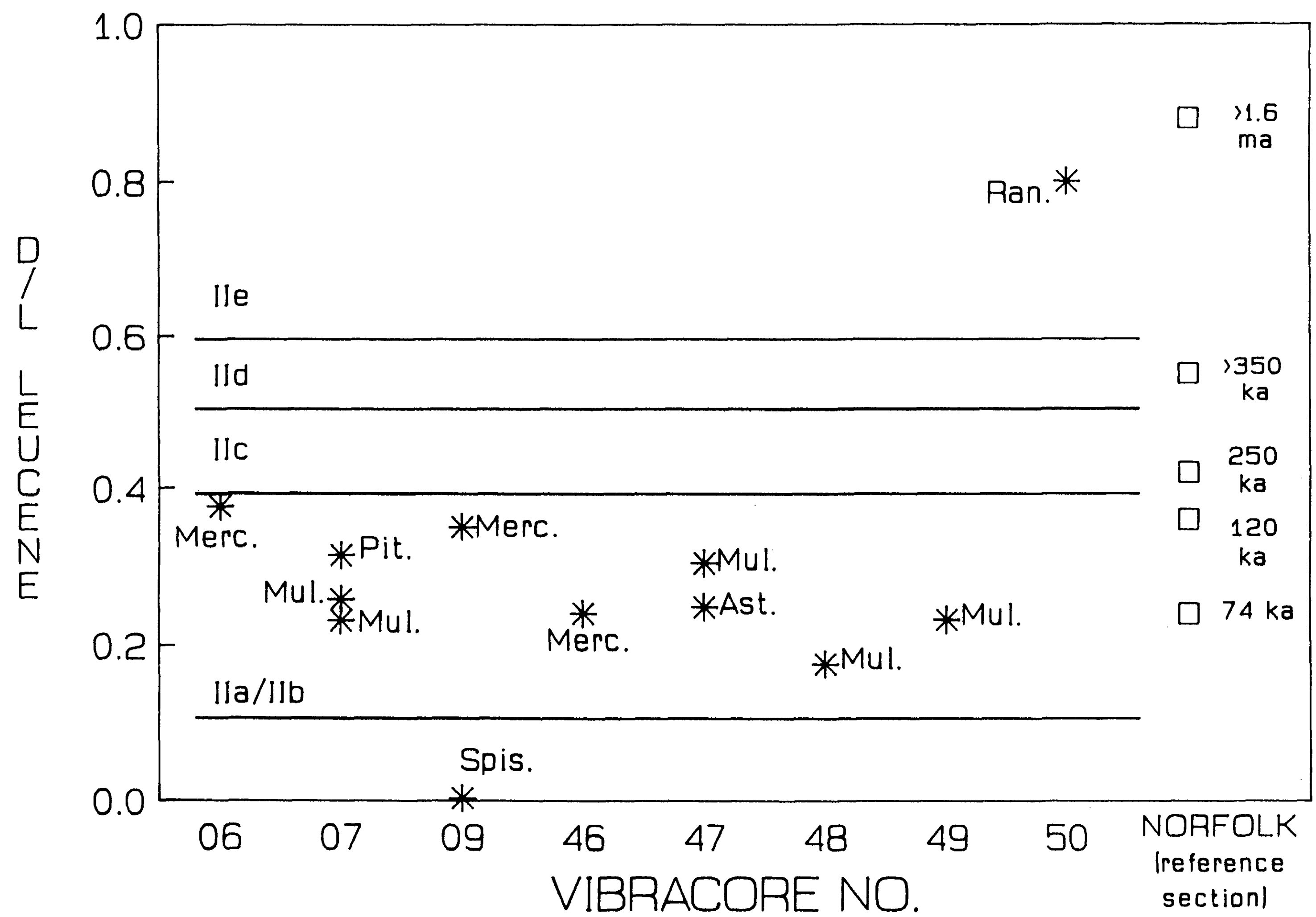
The results of the model age estimates are given in Table 4 and Figure 16. All of the samples, with the exception of 6 and 11, are estimated to be between early to late Stage 5, which correlate to aminozones IIa and IIb. Sample 6 is believed to be greater than 1.2 million years, and sample 11 is considered to be modern, probably less than 2 ka. Samples 7 and 12 are estimated to be 112 +22 -18 ka, and 91 +18 -15 ka respectively. These early Stage 5 dates are much younger than the late Stage 7 (upper aminozone IIc) age which was inferred above by comparing the samples to a range of D/L leucine values from accepted Region II aminozones. This difference is probably due to the age controls used in the kinetic model.

TABLE 4
KINETIC MODEL AGE ASSIGNMENTS

SAMPLE	LOCATION	STRATIGRAPHIC UNIT	KINETIC MODEL AGE	ISOTOPIC STAGE
11	Core 09 -1.9 m	QH2 - Upper unit of Sandbridge Shoal	< 2 ka	Stage 1 (modern)
4	Core 48 -5.0 m	QP5 - Lower unit of Sandbridge Shoal	60 - 80 ka	
5	Core 49 -4.2 m	QP1 - estuarine clay and silt	60 - 80 ka	EQT 6.5 C
8	Core 07 -1.6 m	QH2 - Upper unit of Sandbridge Shoal	60 - 80 ka	
9	Core 07 -1.9 m	QP5 - Lower unit of Sandbridge Shoal	60 - 80 ka	middle to
1	Core 46 -4.7 m	QP4 - estuarine clay and silt	64 ka +13 -11	late Stage 5
3	Core 47 -2.8 m	QP3 tidal channel	70 ka +14 -11	
2	Core 47 -1.6 m	QP4 - estuarine clay and silt	81 ka +16 -11	EQT 8.5 C
10	Core 07 -3.6 m	QP4 - estuarine clay and silt	88 ka +17 -14	
12	Core 09 -2.1 m	QPU - Upper Pleistocene undivided	91 ka +18 -15	early Stage 5
7	Core 06 -2.9 m	QPU - Upper Pleistocene undivided	112 ka +22 -18	EQT 10 C
6	Core 50 -5.3 m	QPU - Upper Pleistocene undivided	> 1.2 ma	

FIGURE 16

Plot of D/L leucine values from vibracores in the study area showing relationship to aminozones and independent age data from the reference section in Norfolk, Virginia. The age data from Norfolk were used for the kinetic model age assignments. Note: abbreviations give genus type of the samples, see Table 3.


D/L LEUCENE
1.0
0.8
0.6
0.4
0.2
0.0
IIe
IId
IIc
IIa/IIb
Merc.
Pit.
Mul.
Mul.
Merc.
Spis.
Merc.
Mul.
Ast.
Mul.
Mul.
Ran.
>1.6 ma
>350 ka
250 ka
120 ka
74 ka
06
07
09
46
47
48
49
50
NORFOLK (reference section)
VIBRACORE NO.

A portion of the same shell used in the amino acid dating of samples 2 and 12 also underwent radiocarbon analysis. The results of the radiocarbon dating agree with the dates assigned by amino acid racemization analysis:

Sample 2: Radiocarbon Age > 42,700 yrs BP

Sample 12: Radiocarbon Age > 38,500 yrs BP

The consistency of these data indicates that all of the samples are Pleistocene in age except for sample 11 which is Holocene; thus, the designation of stratigraphic units as lower Pleistocene (QPL), upper Pleistocene (QPU), and Holocene (QH). Furthermore, the amino acid analysis points to an Isotopic Stage 5 age for most samples.

It is possible that some of the shells are reworked. If this is the case, then the condition of the shells indicates they have not been transported a great distance. Most samples were single valves with a lustrous appearance, and the fragmented shells were angular in shape. None of the shells showed signs of abrasion except for sample 3 which was only slightly abraded. Therefore with only two exceptions, these shells likely represent the sedimentary units in which they were found. Sample 6 is believed to be reworked because it is estimated to be much older than the other samples. Sample 8 is estimated to be Pleistocene in age, but is assigned to a Holocene stratigraphic unit. This assignment is based on the sample being located just above reflector R4, which separates units QH2 and QP5. Thus sample 8 probably represents mixing or reworking of older material at the base of unit QH2.

When the kinetic model results are considered, the age estimates (within reported errors) agree with the stratigraphic relationships, and indicate that sample 6 has been reworked from a much older deposit. However, because amino acid dating methods are presently in an experimental stage, it is best to consider age estimates of aminozones rather than specific samples (Groot et al., 1990). With the exception of sample 11 (considered to be modern) samples from this study represent aminozones IIa-IIb, possibly IIc, and IIe. Also, with the exception of sample 11, all of the samples were located in strata identified as unit QPU or one of its constituents (ie. QP5 thru QP1). Wehmiller et al. (1988) reported that aminozone IIa and IIc (as well as IIa and IId) have been found superposed in several outcrops of the Sedgefield member of the Tabb Formation in the Gomez and New Light pits. Peebles (1984) characterized the Sedgefield member as consisting of valley-fill deposits which accumulated during a late Pleistocene marine transgression. Therefore, stratigraphic unit QPU (which includes QP5 thru QP1) is considered to represent the Sedgefield member of the Tabb Formation, and sample 6 (which represents aminozone IIe) is probably reworked from the Yorktown or Chowan Formation. Units QH1 and QH2 are considered Holocene in age.

Petrology

Samples from the Sandbridge Shoal and a shoal in the False Cape Ridge system were analyzed for sediment maturity. Feldspar staining techniques were attempted in order to determine quartz:feldspar ratios. However, very few stained grains were produced from samples in either location revealing the high maturity and quartzitic nature of these sands. As indicated by Berquist and Hobbs (1988), the heavy mineral assemblage of sands from both localities is very similar, and total heavy mineral content is typically less than 1 percent by weight (ranging from 0.62 to 0.91). However their core sample 48-4, which corresponds to samples R3 s-1 and R3 s-2 in this study, contains a slightly higher total heavy mineral content (1.79% by weight). This sample consists mostly of sediments from the lower unit of the Sandbridge Shoal, but also has material from unit QP2 which is interpreted as a bay mouth or tidal shoal.

Results from grain shape and textural analysis are given in Table 5. These indicate that shoal sediments from both the False Cape area and the Sandbridge Shoal can be described as subangular with a low sphericity. Furthermore, there is no indication of a difference in grain shape within the Sandbridge Shoal. Textural analysis indicated a slightly higher percentage of frosted grains (indicating aeolian action) in the False Cape samples. When comparing sediments within the Sandbridge Shoal, sediments from the lower unit also showed a slight increase in frosting.

TABLE 5 RESULTS FROM ANALYSIS OF GRAIN SHAPE AND GRAIN TEXTURE

SANDBRIDGE SHOAL (CORE 48)

	GRAIN SHAPE			GRAIN TEXTURE		
SAMPLE LOCATION	SAMPLE MEAN	ROUNDNESS CLASS	SPHERICITY	PERCENT FROSTED	PERCENT DULL	PERCENT POLISHED
0 - 2.10 m UNIT QH2	0.343	subangular	low	15	56	29
1.92 m - ? UNIT QH2	0.310	subangular	low	16	51	33
? - 4.21 m UNIT QH2 & QP5	0.344	subangular	low	17	53	30
4.21 - 5.79 m UNITS QP5 & QP2	0.343	subangular	low	22	49	29

FALSE CAPE RIDGES

0 - 1.16 m	0.319	subangular	low	30	36	34
1.13 - 2.41 m	0.312	subangular	low	26	40	34
2.35 - 3.08 m	0.333	subangular	low	25	48	27
2.99 - 3.96 m	0.312	subangular	low	30	38	32

Faunal Analysis

An analysis of the types of shelled fauna found within the sediments of the Sandbridge Shoal and the surrounding stratigraphy is shown in Table 6. Living environments of the genera identified are in Table 7. Because of the possibility of reworking and transport of these shells, these data cannot stand alone to give independent conclusions. However, they can be used as supporting evidence. The individuals found in units QPU and QP4 are typically found in estuarine environments. Nassarius normally occupies mud flats and shallow mud bottoms, and the woody, fibrous material in unit QPU could indicate former submerged aquatic vegetation or marsh grass. The Rangia, because of its age relationship, and the Nucula, because it is found on the shelf, are probably reworked. The Astarte found in units QP3 and QP5 indicate cooler environmental conditions. However because unit QP3 is interpreted as a former tidal channel, the individual found here was likely transported in from the shelf. The genera found in units QH2 and QP5 are found in relatively high salinity environments.

Most of these shells had a "dull, earthy" appearance. The upper unit of the Sandbridge Shoal is the only unit to have shells with a "young" appearance (signified by a pearly finish); and even here, the majority of shells had a much more earthy look. However one individual in unit QP5, the Donax shell, had a "youthful" look. This shell came from Run 3 of core 48, and could indicate contamination from above when jetting during the coring process.

TABLE 6 RESULTS OF FAUNAL ANALYSIS

FAMILY	GENERA	COMMON NAME	NO.	REMARKS
UNIT QH2 - interpreted as upper unit of Sandbridge Shoal				
MACTRIDAE	*Spisula*	surf clam	52	AA sample 11
	Mulinia	dwarf surf clam	17	AA sample 8
CARDIIDAE	?	cockles	5	
DONACIDAE	*Donax*	coquina shell	4	
CUPULADRIIDAE	*Discoporella*	Bryozoan	3	
SOLENIDAE	*Ensis*	razor clam	3	
NATICIDAE	?	moon shell	1	
UNIT QP5 - interpreted as lower unit of Sandbridge Shoal				
MACTRIDAE	*Mulinia*	dwarf surf clam	12	AA sample 4
	Spisula	surf clam	6	
CARDIIDAE	?	cockles	3	
DONACIDAE	*Donax*	coquina shell	2	
NUCULIDAE	*Nucula*	Atlantic nut clam	2	
ASTARTIDAE	*Astarte*		1	
CUPULADRIIDAE	*Discoporella*	Bryozoan	1	
UNIT QP4 - interpreted as estuarine clay and silt				
VENERIDAE	*Mercenaria*	quahog	3	AA samples 1 & 2
	Pitar	false quahog	2	AA sample 10
MACTRIDAE	*Mulinia*	dwarf surf clam	3	AA sample 9
UNIT QP3 - UNIT QP3 - interpreted as tidal channel				
ASTARTIDAE	*Astarte*		1	AA sample 3
UNIT QPU - interpreted as undivided valley-fill strata of upper Pleistocene				
MACTRIDAE	*Mulinia*	dwarf surf clam	6	
	Rangia		1	AA sample 6
VENERIDAE	*Mercenaria*	quahog	2	AA samples 7 & 12
NUCULIDAE	*Nucula*	Atlantic nut clam	2	
NASSARIIDAE	*Nassarius*	dog welk	1	
?	?	fibrous material		

TABLE 7 LIVING ENVIRONMENTS OF GENERA FOUND IN STUDY AREA

GENERA	RANGE	HABITAT
Astarte	Nova Scotia to New Jersey	Moderately shallow water shelf. Indicator of relatively cool conditions.
Discoporella	New York to North Carolina	Sandy shallow shelf.
Donax	New York to Florida	Intertidal zone on high energy beaches.
Ensis	Nova Scotia to South Carolina	Sands and sandy muds in intertidal to subtidal zones down to 37 m.
Mercenaria	New Jersey to Texas	Shallow water shelf, lagoon, and estuarine in sands or muds. Salinities > 15 ppt.
Mulinia	Maine to Texas	Shallow water, back-barrier lagoon, and estuarine. Can withstand a wide range of salinities.
Nassarius	Cape Cod to Gulf of Mexico	Intertidal to subtidal zones on mud flats and shallow mud bottom.
Nucula	Nova Scotia to Texas	Shallow to deep water shelf in sand and mud.
Pitar	Canada to North Carolina	Shallow water shelf, lagoon, and estuarine in sand or muddy sand. Salinities > 15 ppt.
Rangia	Maryland to Texas	Brackish water. Maximum salinity 15 ppt.
Spisula	Nova Scotia to South Carolina	Moderately shallow shelf.

DISCUSSION

The Models

Several possible interpretations for the origin of the Sandbridge Shoal are discussed in the six models presented earlier. An overview of the comparison of observed and expected results is given in Table 8. When determining which model best fits the observed results, it should be noted that the importance of any given characteristic of the shoal is different for each model. Therefore, an exact interpretation cannot be made from this table alone. However it does allow a closer review of the results, and indicates that most of these models can be easily rejected.

For example consider model A, a relict point bar. In this model, the sand body lies between the channel boundaries and within its sides (Fig. 6). However, seismic data indicates the Sandbridge Shoal is situated above the two paleochannels, and is separated from them by a strong reflector, R3. Furthermore, the sedimentary characteristics of the Sandbridge Shoal are contrary to a facies model of relict point bars. Point bar facies consist of a coarsening upward sequence of crossbedded sands with a base of relatively coarser channel lag material (Walker, 1984). This is not evident in the data. Also, the faunal analysis found genera throughout the Sandbridge Shoal which are normally present in relatively high salinity environments. However, a point bar deposit would likely have existed in the upper sections of an estuary. A transgressing sea may allow this type of

TABLE 8

COMPARISON OF OBSERVED AND EXPECTED RESULTS

+ Indicates observed results match those expected
- Indicates observed results do not match those expected
n/a - not applicable   fd - flood delta   fl,eb - fluvial and ebb deltas

GENERAL CHARACTERISTICS OF THE SANDBRIDGE SHOAL	RELICT Pt. Bar A	RELICT Delta B	RELICT Barrier C	RELICT Spit D	Detached Shf. Ridge E	Offshore Bar F
Composed of clean, well sorted, medium to coarse sand.	+	+	+	+	+	+
Sand body is situated above a paleochannel system, and separated from it by a strong horizontal reflector.			+	+	+	+
Lagoonal and estuarine sediments are located beneath and landward of the sand body.	+	+	+	+	+	+
Sediments fine downward with little or no crossbedding.					n/a	+
Storm sequences are present in sediments.		+	+	+	+	+
Relatively low percentage of grains show evidence of aeolian action.	n/a	n/a			n/a	+
Lack of high concentrations of heavy minerals.	n/a	n/a			+	+
Presence of only high salinity fauna.			+	+	+	+
Made up of two distinguishable units, with the lower unit indicated as being relatively older.						
Sediments of the upper unit appear to have been transported landward.		+ fd - fl,ed	+	+		+
Preservation potential during shoreface erosion with a relative rise in sea level.	+	+ fd - fl,ed			+	+
Composition and texture similar to False Cape Ridges.	n/a	n/a	n/a	n/a	+	n/a

assemblage to occur in a relict point bar deposit, but it would be found only near the top surface.

Model B represents a fluvial or tidal delta interpretation for the shoal's origin. Both fluvial and ebb tidal deltas typically prograde seaward. However, the surface morphology indicates the sediments of the Sandbridge Shoal have been transported from the east and northeast, or landward. Also, surface grab samples indicate a fining of material landward. This is in contrast to general facies models for fluvial deltas (Walker, 1984). Furthermore, the potential for preservation of an ebb tidal delta sequence is low due to wave and current action as the position of the tidal inlet shifts (Blatt et al., 1980).

The shoal's stratigraphic position allows the flood tidal delta interpretation to be rejected. A flood tidal delta is situated within an estuarine system and not above it, as is the case with the Sandbridge Shoal. Also, well developed crossbedding, a prominent feature found in both fluvial and tidal delta facies, is not found in the sediments of the Sandbridge Shoal with the exception of weak cross stratification in unit QP5 of core 7.

The four remaining models agree more closely with the data, and the grounds for their rejection are less obvious. For example consider models C and D, which involve a relict barrier and spit respectively. In each, lagoonal or estuarine sediments should lie directly beneath and shoreward of the sand body. These types of deposits are present in units QP4 through QP1. Furthermore, these deposits would be separated from the sand body by a sharp boundary due to barrier migration or spit progradation. This surface could be represented by reflector R3. Evidence of inlet filling or channel progradation should be present, which is given by steeply dipping beds beneath R3 on north-south seismic lines. Also a typical transgressive sequence should be shown in the strata, and this is present in cores 7 and 49. Furthermore, the sediments should exhibit excellent sorting and evidence of aeolian action.

While the sediments of the Sandbridge Shoal indicate good sorting, the percentage of grains which are pitted or frosted is relatively low. Also, there is an interesting lack of crossbedding which should be present if either model C or D are correct. Furthermore a concentration of heavy minerals is not present, though it may be argued that a source did not exist. However it should be noted that unit QP5, the lower unit of the Sandbridge Shoal, shows an increase in the percentage of both frosted grains and total heavy mineral content when compared to the upper unit. Also, the lower unit contains weak cross stratification in core 7. In any event, it is unlikely that either of the large subaerial features represented by models C and D could survive and remain intact after wave and current action is exerted on them during the process of drowning. Only a few such cases are documented in the literature (Sanders and Kumar, 1975; Penland et al., 1986), and the preservation potential for these positive relief features is low during shoreface erosion. Therefore, it is doubtful that the Sandbridge Shoal represents an intact relict barrier or spit complex.

Next consider model E, a detached shoreface ridge. Most of the characteristics of the Sandbridge Shoal agree with this model. For example, this model requires a strong basal contact between the sand body and the surrounding stratigraphy, which is represented by reflector R3. Shoreface connected ridges contain strata representing storm events, and layers of coarser material found in the cores indicate these types of events are recorded in the sediments of the shoal. Futhermore, this model suggests that the Sandbridge Shoal may be a precursor of the False Cape Ridge System. Thus similarities in composition, texture, and faunal assemblage may exist between the two. In general this was found to be the case by the petrologic and faunal analyses.

However, a major discrepancy exists. The Sandbridge Shoal is a wedge of sand which tapers toward the east and northeast. Also subbottom reflectors, surficial features, and the landward decrease of gravel in surficial samples indicate sediments of the shoal have been transported from the east and northeast. If the Sandbridge Shoal is interpreted as a detached shoreface ridge, modern storm currents would tend to transport sediments such that the shoal would thin and its surface taper toward the south and west. Thus, the wedge of sand would be oriented in the opposite direction. This inferred direction of transport results in model E not being an acceptable interpretation for the origin of the shoal.

Finally consider model F, which represents the modern development of an offshore bar. The observed characteristics of the Sandbridge Shoal match very well with the results expected for this model (Table 8). An apparent shortfall is the similarity in composition and texture of the shoal's sediments and those of the False Cape Ridge System. On the other hand, this likeness does not necessarily discount the offshore bar model. If there were obvious differences, then it could be concluded that the sediments came from two different sources and probably resulted from different processes. However, similarities in sedimentary characteristics is not enough justification that the two areas are related. In other words, a comparison of these sediments can only support model F and not refute it. Sediments from both areas may have similar geologic histories in that they probably were transported by fluvial processes onto the shelf and were subsequently reworked. The processes of reworking (including the most recent stage of transport) could have been very different, and still have produced similar sediment qualities.

One characteristic of the Sandbridge Shoal which has not been considered up until this point is the interpretation of two distinct units within the sand body. This is based on the presence of reflector R4. This reflector is represented as a thin silt layer in cores 48 and 49, and as a coarse shelly layer in core 7. Also, geochronology data based on samples from both its top and bottom boundaries indicate the lower unit may be much older than the upper. Further evidence of a separate unit is given by a slightly finer grain size in all of the cores, and core 7 shows weak crossbedding in the lower unit. By distinguishing this lower unit, none of the individual models can be used alone to explain the shoal's origin. However some combination of these models is possible.

Relationships with Surrounding Stratigraphy

The interpretation of the lower unit of the Sandbridge Shoal, as well as other units defined in the study area, requires a consideration of not only the specific unit characteristics but also their relationship with the surrounding stratigraphy. As shown earlier, the continental shelf has undergone a series of transgressions and regressions related to glacial episodes.

Peebles (1984) presented a model of the types of stratigraphy that can be expected to result from a marine transgression. This model consists of (but is not limited to) a valley-fill sequence made up of coarse fluvial basal sediments grading upward into paludal and then estuarine deposits. The sedimentary package is bounded by unconformities, and may be capped by barrier or subaqueous bar deposits.

The data indicate that such a sedimentary package, represented by unit QPU and probably QPL, exists in the study area. The channel fill sequence is obvious, with only the upper estuarine sediments being penetrated by the cores. The silts and clays in units QP1 and QP4 are likely estuarine in origin, and the fine sands in unit QP2 are believed to represent a bay-mouth or tidal shoal. The medium to coarse sands in unit QP3 have been interpreted as a tidal channel. Following this reasoning, unit QP5 may be the upper part of this valley-fill sequence. The characteristics of this unit, given earlier, indicate this interpretation is possible. In this case, the uppermost deposits of a valley-fill sequence could be a thin, smeared out remnant of a barrier or bar that survived shoreface erosion. Or it could consist of relatively coarse material which represents a lag left behind as the shoreline advanced landward. The sand size found in unit QP5, and its fining downward trends present in cores 7 and 49 indicate the former interpretation to be more plausible.

Shape of the Shoal

The shape and morphology of the Sandbridge Shoal was described earlier, and together with the sedimentary characteristics, gave evidence that the material in the upper unit was transported landward. However, this leaves the question of how the shoal attained its horseshoe or barcan like shape. Two explanations exist. First, sediments in the shoal could have accumulated in two separate events. The first event would have deposited material along its western margin, and sediment from the second event may have been deposited such that they overlapped only in the northern and central sections of the shoal. However, no evidence of such a break in deposition exists in the data.

Secondly, the horseshoe shape could be due to the modern hydraulics. This is evidenced by a u-shaped depression or swale existing between the southwestern and southeastern limbs. Seismic line 7/88 is oriented along the margin of this depression, and shows surface features that indicate movement of material within the swale is towards the north along the axis of the depression.

CONCLUSIONS AND AVENUES FOR FURTHER INVESTIGATION

Located approximately 5.5 kilometers offshore, the Sandbridge Shoal is a deposit of clean, well sorted, medium to coarse sand which tapers and thins to the east and northeast. In plan view it is a horseshoe or barcan shaped feature. The shoal is situated above a large paleochannel system, and lagoonal or estuarine sediments are located beneath and landward of the sand body. Sediments within the shoal fine downward, and those on its surface are coarser in the northeast quadrant. The sediments show little evidence of aeolian processes, and lack a high concentration of heavy minerals. Evidence of only high salinity organisms was found within the shoal.

Most of the models which were presented for shoal origin can be refuted by this description alone. Furthermore, the data indicate that the Sandbridge Shoal consists of two separate units of different ages. As a result of this interpretation, none of the models, alone, are able to explain the shoal's formation. Therefore, the traditional theories of linear shoal origin (i.e. the entire sand body is either a product of modern hydraulic processes or it is a relict feature) do not apply in the case of the Sandbridge Shoal. It can be argued that the shoal should be defined by the upper unit alone, and the feature could then be explained entirely by modern processes. However, sediments from both units are similar in faunal content, grain size, sorting, silt/clay content, etc.

Therefore, the data indicate that the formation of this feature occurred in two stages. The characteristics of the lower unit of the shoal, as well as its relationship with the surrounding stratigraphy, indicate that it likely represents the relatively thin remains of a barrier or submerged bar which was present on the shelf during a late Pleistocene transgression. When determining which late Pleistocene transgression corresponds to the formation of the lower unit, it must be emphasized that the amino acid analyses is best utilized in giving an age range rather than a specific date. In other words, one must consider data within aminozones rather than specific samples. Units QP5 and QPU have been correlated with aminozone IIa, and thus are indicated as having been deposited during isotopic Stage 5. The boundary between Unit QP5 and the underlying strata lies approximately 15 m below present sea level. Therefore, considering the sea level curves of Chappell and Shackleton (1986), Cronin et al. (1981), and Bard et al. (1990), three possible marine transgressions have been documented which could have given rise to the lower unit of the Sandbridge Shoal (Fig. 3). These climaxed between 75-80 ka (-18 to +10 m), between 95-105 ka (-18 to +10 m), and between 115-125 ka (0 to +18 m). Differences in the exact timing and elevation of these sea-level highstands (referenced to present day sea-level) are due to regional tectonics, and crustal adjustments due to glacial activity and sediment loading.

The second stage in the formation of the Sandbridge Shoal appears to have occurred during the Holocene transgression. The data indicate that during this time the upper unit was deposited as an offshore bar. The immediate question which results from this interpretation deals with the ultimate source of material for the upper unit. One possibility involves relict fluvial deposits located to the northeast. The paleochannel represented by unit QPL outcrops at the surface, and is present in this area. However additional vibracores and the extension of seismic data to the north and east is required before any conclusions can be made as to the source of this sediment.

Another interesting question concerns why the upper unit was deposited at this particular position on the shelf. This may be explained by an equilibrium response of the shoreface to a decreased rate of sea level rise. During a rapid rise in sea level, erosion on the upper shoreface is relatively more severe than at other locations. A slowing of sea level rise would produce an approach of the shoreface profile to equilibrium. This would result in relatively more erosion on the middle and lower portions of the shoreface, and would give rise to onshore transport (Van Straaten, 1973).

The rate of sea level rise is believed to have undergone a dramatic decrease three times during the Holocene transgression:

approximately 14 ka, between 11-11.5 ka (Fairbanks, 1989; Bard et al., 1990) and between 4-6 ka (Fairbanks, 1989). The position of the shoreline when these particular events occurred during the Holocene transgression was approximately -70 m (14 ka), between -70 and -40 m (11 to 11.5 ka), and between -8 and -12 m (4 to 6 ka) below present sea level (Fig. 4). Given relative rates of sea level rise between 2.7 and 4.4 mm/yr (Froomer, 1980) and considering a lag period may exist between the slowing of sea level rise and the approach to equilibrium, the position of the upper unit could be related to a decrease in the rate of sea level rise which occurred between 4 and 6 ka. Furthermore seismic data indicate the lower unit of the Sandbridge Shoal likely had up to 1.5 m of relief when it was exposed on the shelf surface. Therefore, it may have acted as a barricade and trapped the sediments of the upper unit as they were transported landward.

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APPENDIX A

LOG OF VIBRACORE

CORE 06 | SEPT. 29, 1989 | DEPTH: 13.1 m

LORAN: 27130.0, 41165.0 | LAT/LON: 36 45.25 N, 75 53.54 W

Composite of two runs (R1,R2) with total PENETRATION = 6.10 m

DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00			Micaceous, very fine, sandy silt with widely scattered shell fragments. Top 15 cm is fluid.	UNIT QP4 Upper Pleistocene estuarine clay and silt
0.50			Becomes clayey silt with some fine sand.	
1.00			high concentration of clam shells, up to 4 cm Becomes silty clay with scattered shell fragments.	
1.50			Muddy fine to medium sand with fragments up to 4 cm.	
			Silty clay with pods and stringers of fine to very fine, silty sand.	R1: pen. 3.35 m rec. 3.88 m
2.00				
2.50			sandy silt lense with several subangular, white, quartzitic, coarse gravel	
3.00		#7 AA	Silty coarse sand with some subrounded gravel and pods of fine sandy silt.	UNIT QPU Upper Pleistocene undivided
			becomes medium to fine sand	
3.50		s-1	becomes coarser, mostly medium sand	#7 MSL -16.0 m *Mercenaria:* AA = 112 ka +22 -11
			begin to have scattered shell fragments with some fibrous "woody" material	
4.00			Silty clay with occasional stringers and pods of silty medium to fine sand. Stringers up to 1 cm thick. Infrequent layers (5 - 10 cm thick) of widely scattered, very fine, shell fragments. Dark Greenish Gray 5GY 4/1	
4.50				
5.00			stringers more infrequent and contain mostly silt	R2: jet to 3.35 m vib. to 6.10 m rec. 3.70 m
5.50				
6.00				BOTTOM @ 6.10 m

LOG OF VIBRACORE

CORE 07 SEPT. 29, 1989 DEPTH: 12.8 m

LORAN: 27128.5, 41167.5 LAT/LON: 36 45.44 N, 75 53.21 W

Composite of two runs (R1,R2) with total PENETRATION = 6.10 m

DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00		s-2	Coarse sand with some medium sand and gravel. Loosely packed with abundant shell fragments. Yellowish Gray 5Y 7/2	UNIT QH2 Upper unit of Sandbridge Shoal
0.50		s-3	Medium sand with some coarse sand and very widely scattered shell fragments. More tightly packed. Alternating layers of Light Olive Gray, 5Y 6/2, and Olive Gray 5Y 5/2.	R1: pen. 4.88 m rec. 3.78 m
1.00			layer of coarse sand and shell fragments, 5 cm thick	
			layering of color diminishes, becomes Light Olive Gray	#8 MSL -14.4 m
		s-4	becomes coarser	*Mulinia:* AA = 60 - 80 ka
1.50		#8 AA	shelly, gravelly layer	
		s-5	Medium to fine sand, siltier with depth. Dark Gray 5Y 4/1 Some cross-bedding, but not well developed.	UNIT QP5 Lower unit Sandbridge Shoal
		s-6 / #9 AA	Silty fine to very fine sand. Olive Black 5Y 2/1 Shell layer & shell hash at base in clayey, sandy, silt matrix.	
2.00			Silty clay with pods and lenses of silty sand. Clay is Dark Gray, 5Y 4/1, and sand is Light Gray, N7.	UNIT QP4 Upper Pleistocene estuarine clay and silt
			clay becomes Grayish Olive 10Y 4/2	#9 MSL -14.7 m
2.50		S-7	Med-cse sand, yellow gray to orange brown, inclined 50 .	*Mulinia:*
			Silty clay layer, inclined approximately 30 .	AA = 60 - 80 ka
		S-8	Medium sand, yellow gray to orange brown, inclined 20 .	
3.00			Silty clay with pods and lenses of silty sand. Above 3.0 m lenses are inclined. Clay is Dark Gray, sand is Light Gray	
3.50				#10 MSL -16.4 m *Pitar:*
		#10 AA	Abundant clam shells in very silty, medium to coarse sand matrix.	AA = 88 ka +17 -14
4.00			Muddy, medium to coarse sand interbedded with silty clay. Sandy layers contain shell material (mostly clam shells), and the clay layers have lenses and pods of silty fine sand. Dark Gray 5Y 4/1	UNIT QPU Upper Pleistocene undivided
4.50				
5.00				R2: jet to 3.68 m vib. 6.10 m rec. 3.0 m
5.50			Silty fine to very fine sand with silt lenses, very compact. Upper contact, 10 cm layer of medium to fine sand, inclined approximately 30 . Dark Gray 5Y 4/1	
6.00				BOTTOM @ 6.10 m

LOG OF VIBRACORE

CORE 09 | SEPT. 29, 1989 | DEPTH: 13.3 m

LORAN: 27122.5, 41167.5 | LAT/LON: 36 45.22 N, 75 51.83 W

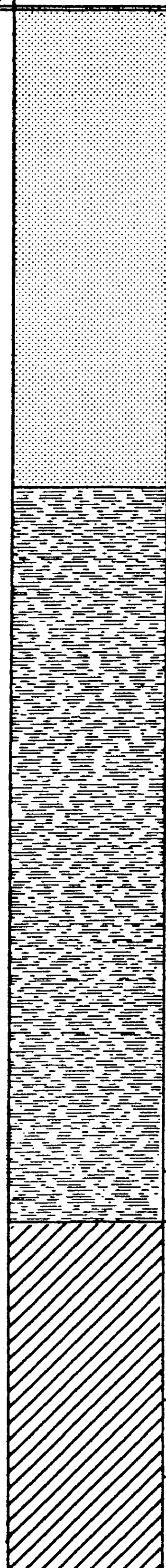
Composite of two runs (R1,R2) with total PENETRATION = 5.33 m

DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00			Medium to fine sand. Pale Yellowish Brown 10YR 6/2 coarser layer 5cm thick	UNIT QH2 Upper unit of Sandbridge Shoal
0.50		s-1		R1: pen. 5.33 m rec. 4.25 m
1.00			becomes Olive Black 5Y 2/1 in pods and layers	
1.50		s-2 #11 AA	becomes finer and more homogeneous in color, Dark Gray 5Y 4/1	#11 MSL -15.2 m *Spisula:* AA < 2 ka
2.00		#12 AA/RC	Silty to sandy clay with gravel and shells at base.	
			Medium to fine sand with pods and laminations of very silty fine sand and silty clay. Coarser sand is Light Gray, N7, and fine sand and clay is Olive Black, 5Y 2/1.	UNIT QPU Upper Pleistocene undivided
2.50		s-3		#12 MSL -15.4 m *Mercenaria:* AA = 91 ka +18 -15 RC > 38.5 ka
3.00				
3.50		s-4		R2: jet to 3.68 m vib. to 4.59 m rec. 0.91 m
4.00		s-5	concentration of clam shell fragments with occasional gravel	
4.50			very fine sandy silt layer	BOTTOM @ 4.59 m
5.00				
5.50				
6.00				

CORE 46
LORAN: 27135.1, 41159.9
PENETRATION: 5.82 m

LOG OF VIBRACORE
AUGUST 02, 1987
LAT/LON: 36 45.02 N, 75 55.00 W
RECOVERY: 6.10 m

DEPTH: 11.0 m



DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00		s-1	Fine micaceous sand with scattered shell fragments. Dark Gray 5Y 4/1	UNIT QH1 Holocene sand sheet
0.50				
		s-2	Coarse shelly sand with silty clay.	
1.00		s-3	Silty clay and silty sand laminations.	
		s-4	Medium sand with scattered shell fragments. Dark Gray 5Y 4/1	
1.50		s-5	shell hash 6 cm thick, becomes Gray 5Y 5/1	
2.00		s-6	Silty clay with 2 to 10 cm thick laminations of fine sand. Gray 5Y 5/1	UNIT QP4 Upper Pleistocene estuarine clay & silt
			shell hash with fine sand 5 cm thick	
2.50				
3.00				
3.50		s-7	coarse sand 5 cm thick	
4.00				
4.50		s-8 #1 AA		#1 MSL -15.7 m *Mercenaria:* AA = 64 ka +13 -11
5.00		s-9	Coarse sand layer (5 cm thick) over medium sand with scattered shell fragments. Dark Gray 5Y 4/1	UNIT QPU Upper Pleisotcene undivided
			Medium to fine sand with silty clay laminations up to 2 cm thick.	
5.50		s-10	Coarse sand with abundant shell fragments. silty clay layer 2 cm thick	
6.00		s-11	Medium to fine sand with scattered shell fragments.	BOTTOM @ 6.10 m

CORE 47
LORAN: 27130.0, 41159.9
PENETRATION: 4.15 m

LOG OF VIBRACORE
AUGUST 02, 1987
LAT/LON: 36 44.81 N, 75 53.82 W
RECOVERY: 3.55 m

DEPTH: 12.0 m

DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00		s-1	Fine to very fine micaceous sand. Very Dark Gray 5Y 3/1	UNIT QH1 Holocene sand sheet
0.50				
			Slightly silty clay with coarse to fine sand laminations 1 to 5 cm thick. Dark Gray 5Y 4/1	UNIT QP4 Upper Pleistocene estuarine clay and silt
1.00		s-2		
1.50		#2 AA/RC		#2 MSL -13.6 m *Mercenaria:* AA = 81 ka +16 -11 RC > 42.7 ka
2.00		s-3		
2.50			Coarse shelly sand with shell fragments up to 5 cm.	UNIT QP3 Upper Pleistocene tidal channel sands
		s-4 #3 AA	silty clay layer 5 cm thick	
3.00		s-5	Medium to coarse sand with scattered shell and trace of subangular gravel. Gray 5Y 5/1	#3 MSL -14.8 m *Astarte:* AA = 70 ka +14 -11
3.50				BOTTOM @ 3.55 m
4.00				
4.50				
5.00				
5.50				
6.00				

LOG OF VIBRACORE

CORE 48 | AUGUST 02, 1987 | DEPTH: 8.8 m

LORAN: 27135.1, 41160.0 | LAT/LON: 36 44.61 N, 75 52.66 W

Composite of three runs (R1,R2,R3) with total PENETRATION = 5.79 m

DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00		R1 s-1	Medium to coarse sand with scattered shell fragments. Light Olive Brown 2.5Y 4/4	UNIT QH2 Upper unit of Sandbridge Shoal
0.50				R1: pen. 2.22 m rec. 2.10 m
1.00		R1 s-2	becomes fine to coarse sand with fewer shell fragments Olive Gray 5Y 4/2	
1.50				
2.00				R2: jet to 1.92 m vib. to 4.39 m rec. 3.99 m
2.50		R2 s-1 (?)	becomes coarse to medium sand, Dark Gray 5Y 4/1	
3.00			begin medium to fine sand layers	
3.50		R2 s-2 (?)	becomes finer	
			Very fine sandy silt layer 5 cm thick.	
4.00			Medium to fine sand with widely scattered shell fragments. Coarsens downward and lightens in color. Olive Gray 5Y 4/2	UNIT QP5 Lower unit of Sandbridge Shoal
4.50		R3 s-1		R3: jet to 4.21 m vib. to 5.79 m rec. 1.22 m
			becomes coarse to medium very shelly sand Grayish Brown 2.5Y 5/2	#4 MSL -13.8 m
5.00		#4 AA		*Mulinia:* AA = 60 - 80 ka
		R3 s-2	Medium to fine sand. Dark Gray 5Y 4/1	UNIT QP2 Upper Pleistocene bay-mouth or tidal shoal
5.50				BOTTOM @ 5.79 m
6.00				

CORE 49
LORAN: 27125.1, 41170.0
PENETRATION: 6.03 m

LOG OF VIBRACORE
AUGUST 02, 1987
LAT/LON: 36 45.43 N, 75 52.34 W
RECOVERY: 5.74 m

DEPTH: 10.0 m

DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00			Medium to coarse sand with widely scattered shell fragments. Light Olive Gray 5Y 6.2	UNIT QH2 Upper unit of Sandbridge Shoal
0.50			becomes Olive Gray 5Y 5/2	
		s-1		
1.00				
			becomes coarser	
1.50				
2.00			becomes Dark Gray 5Y 4/1	
		s-2		
2.50				
3.00			Very clayey silt layer, 5 cm thick.	
			Fine to medium sand with scattered shell fragments. Olive Gray 5Y 5/2 Coarsens down to 3.35 m, then becomes finer with depth.	UNIT QP5 Lower unit of Sandbridge Shoal
3.50		s-3		
4.00			becomes silty fine sand, Dark Gray 5Y 4/1	
		#5 AA	Silty clay with pods of medium to coarse shelly sand and medium to fine sand, some gravel in sand pods. Gray 5Y 5/2	#5 MSL -14.2 m *Mulinia:* AA = 60 - 80 ka
		s-4		
4.50				UNIT QP1 Upper Pleistocene estuarine clay and silt
		s-5		
5.00				
			Silty fine to very fine sand with widely scattered shell fragments.	UNIT QPU Upper Pleistocene undivided
		s-6		
5.50				
				BOTTOM @ 5.74 m
6.00				

LOG OF VIBRACORE

CORE 50
AUGUST 02, 1987
DEPTH: 11.9 m
LORAN: 27125.0, 41150.0
LAT/LON: 36 43.79 N, 75 53.01 W
PENETRATION: 5.82 m
RECOVERY: 6.10 m

DEPTH (m)	LEGEND	SAMPLE	DESCRIPTION	REMARKS
0.00		s-1	Micaceous silt with very fine sand and clay. Dark Gray 5Y 4/1	UNIT QP4 Upper Pleistocene estuarine clay and silt
0.50			becomes micaceous silty clay	
		s-2	Mottled micaceous fine sand and clay. Sand increases downward. Very Dark Gray 5Y 3/1	
1.00				
		s-3	Clay. Gray 5Y 5/1	UNIT QPU Upper Pleistocene undivided
1.50				
		s-4	becomes well compacted silty clay Dark Gray 2.5 Y 4/1	
2.00				
2.50				
3.00				
3.50		s-5		
4.00				
4.50				
5.00				
			concentration of shell fragments	
		#6 AA	concentration of shell fragments	#6 MSL -17.2 m *Rangia:* AA > 1.2 mya
5.50		s-6		
			layer of fine sand and silty clay, 5 cm thick Very Dark Gray 5Y 3/1	
			becomes Dark Gray 5Y 4/1 shell hash in clay matrix	
6.00				Bottom @ 6.10 m

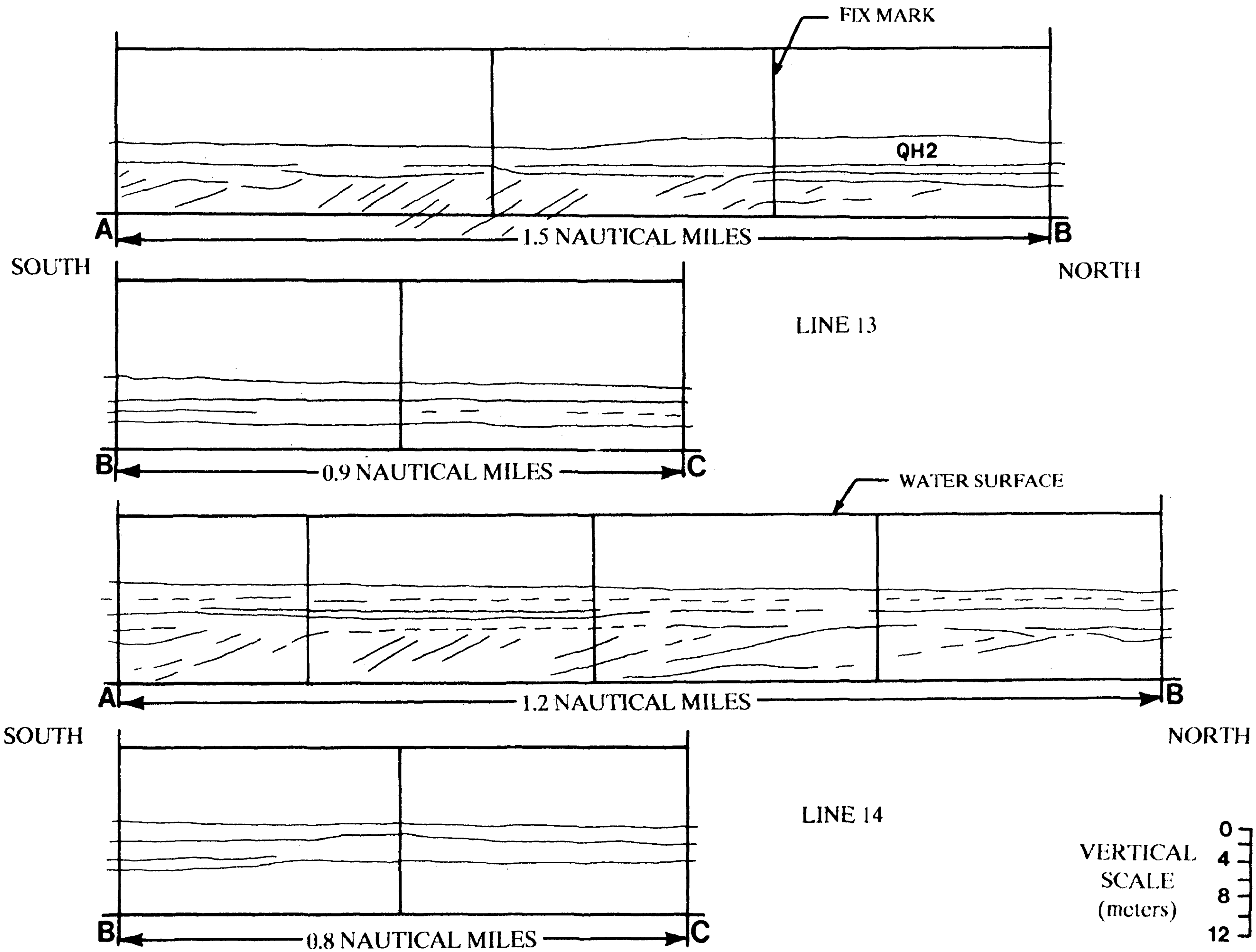
RESULTS OF AMINO ACID RACEMIZATION ANALYSIS, D/L RATIOS

analysis performed by Dr. D.F. Belknap - Univ. of Maine at Orono

SAMPLE	D/L ALA	D/L VAL	D/L LEU	D/L ASP	D/L PHE	D/L GLU	ASP/ LEU	ALEU/ ISO	n
1 *Mercenaria campechiensis*	.42	.16	.240 +.010	(.52)	.26	.18	2.5	(.24)	2
2 *Mercenaria campechiensis*	.44	.19	.304 + -	.54	.29	.19	6.3	(.40)	2
3 *Astarte castanea*	.30	.15	.248 +.006	.54	.20	.16	(10)	.28	2
4 *Mulinia lateralis*	.26	.10	.176 +.001	.37	.11	.12	15.5	(.22)	2
5 *Mulinia lateralis*	.32	.12	.232 +.003	.40	.23	.16	(22)	.25	2
6 *Rangia cuneata*	.82	.48	.80 +.04	.76	.50	.42	(6)	1.14	2
7 *Mercenaria campechiensis (?)*	.47	.22	.376 +.011	.53	.35	.24	(10)	(.40)	2
8 *Mulinia lateralis*	.36	.12	.258 +.002	.42	.21	.16	(14)	.32	2
9 *Mulinia lateralis*	.36	.10	.231 +.001	.41	.20	.16	(17)	.26	2
10 *Pitar morrhuana*	.42	.16	.314 +.005	.42	.32	.20	(23)	.32	2
11 *Spisula sp.*	.02	(.01)	.003 +.000	.09	.02		7.0	0.1	2
12 *Mercenaria campechiensis*	.43	.19	.35 +.010	.53	.34	.20	8.5	(.36)	2

APPENDIX B

Reproductions of subbottom acoustic records obtained in 1987, and corresponding interpretations for north-south trending tracklines. Descriptions of stratigraphic units are given in Table 1.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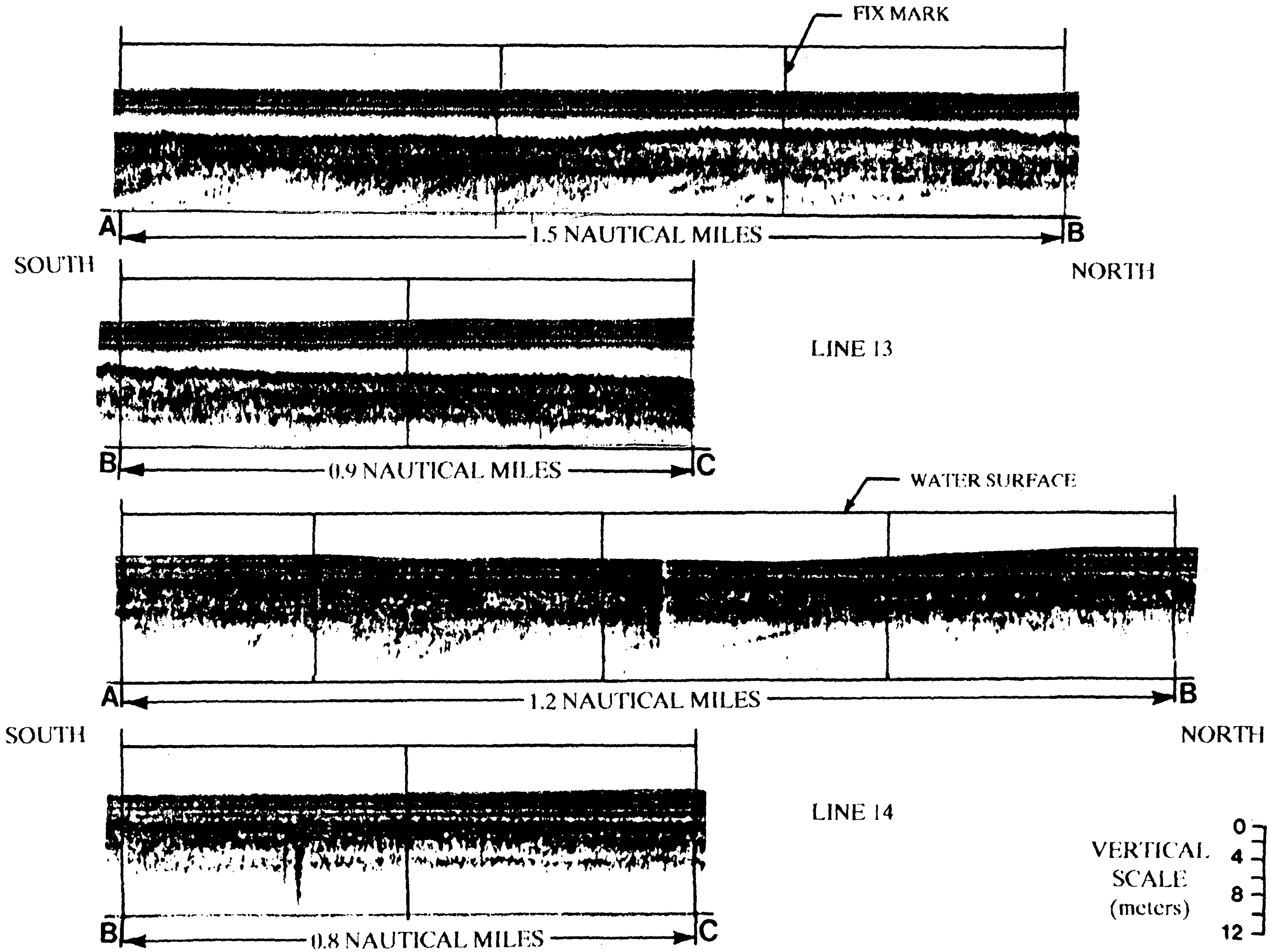
B
SOUTH
NORTH
LINE 13
B
0.9 NAUTICAL MILES
C
WATER SURFACE
A
1.2 NAUTICAL MILES
B
SOUTH
NORTH
LINE 14
B
0.8 NAUTICAL MILES
C
VERTICAL
SCALE
(meters)
0
4
8
12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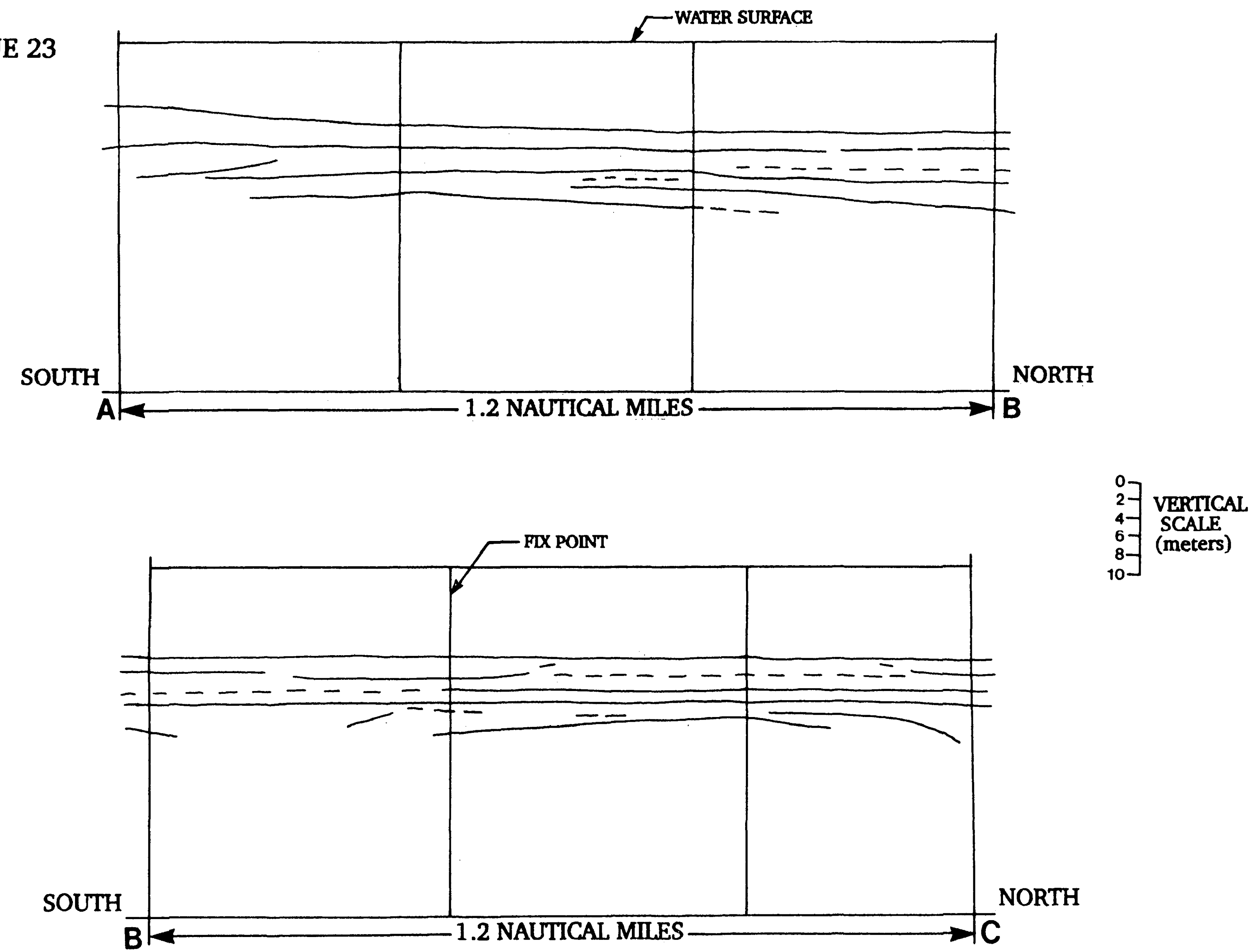
NORTH
LINE 13
B
0.9 NAUTICAL MILES
C
WATER SURFACE
A
1.2 NAUTICAL MILES
B
SOUTH
NORTH
LINE 14
B
0.8 NAUTICAL MILES
C
VERTICAL
SCALE
(meters)
0
4
8
12

LINE 23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NORTH
A
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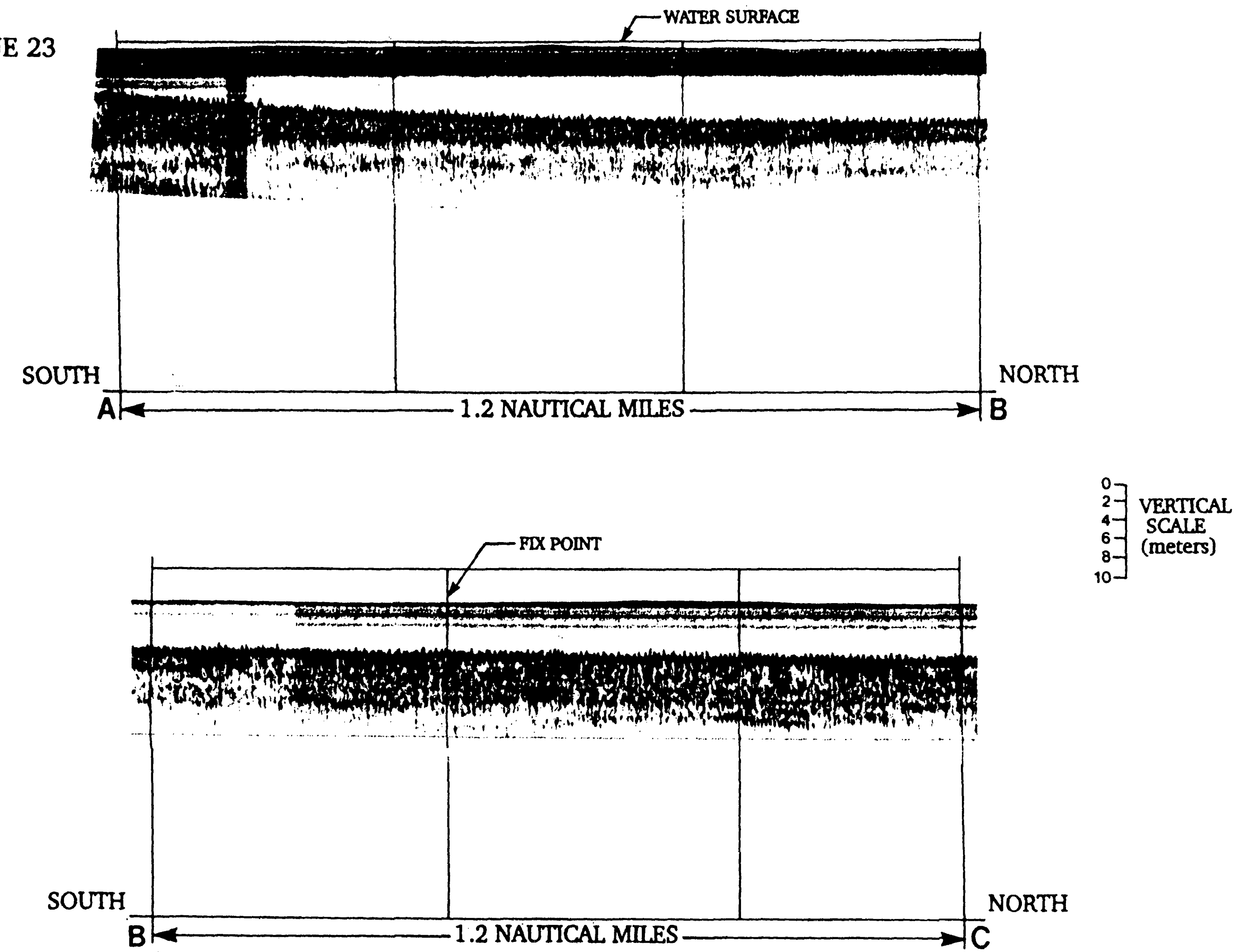
B
FIX POINT
SOUTH
NORTH
B
1.2 NAUTICAL MILES
C
0
2
4
6
8
10
VERTICAL
SCALE
(meters)

LINE 23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NORTH
A
1.2 NAUTICAL MILES
B
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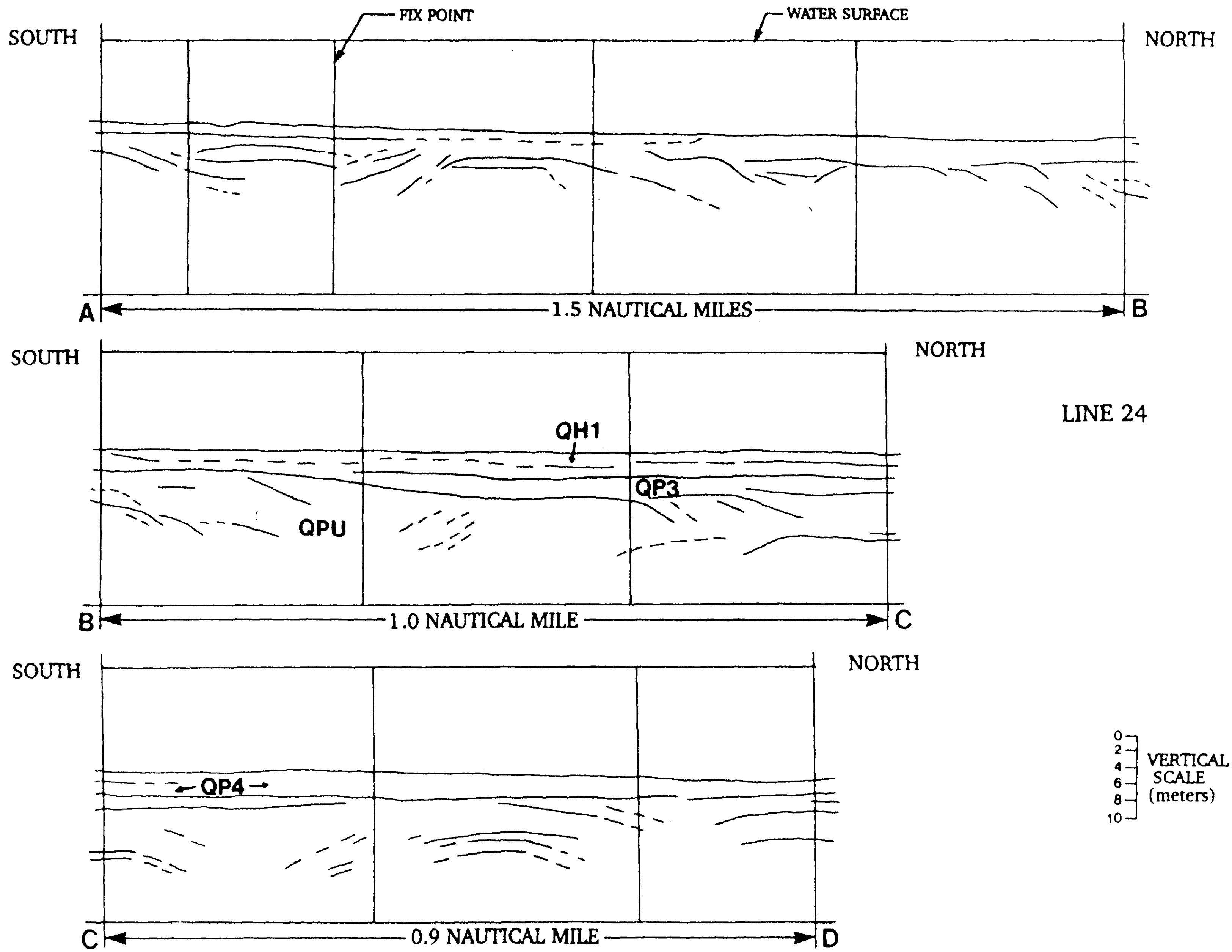
SOUTH
NORTH
B
1.2 NAUTICAL MILES
C
0
2
4
6
8
10
VERTICAL
SCALE
(meters)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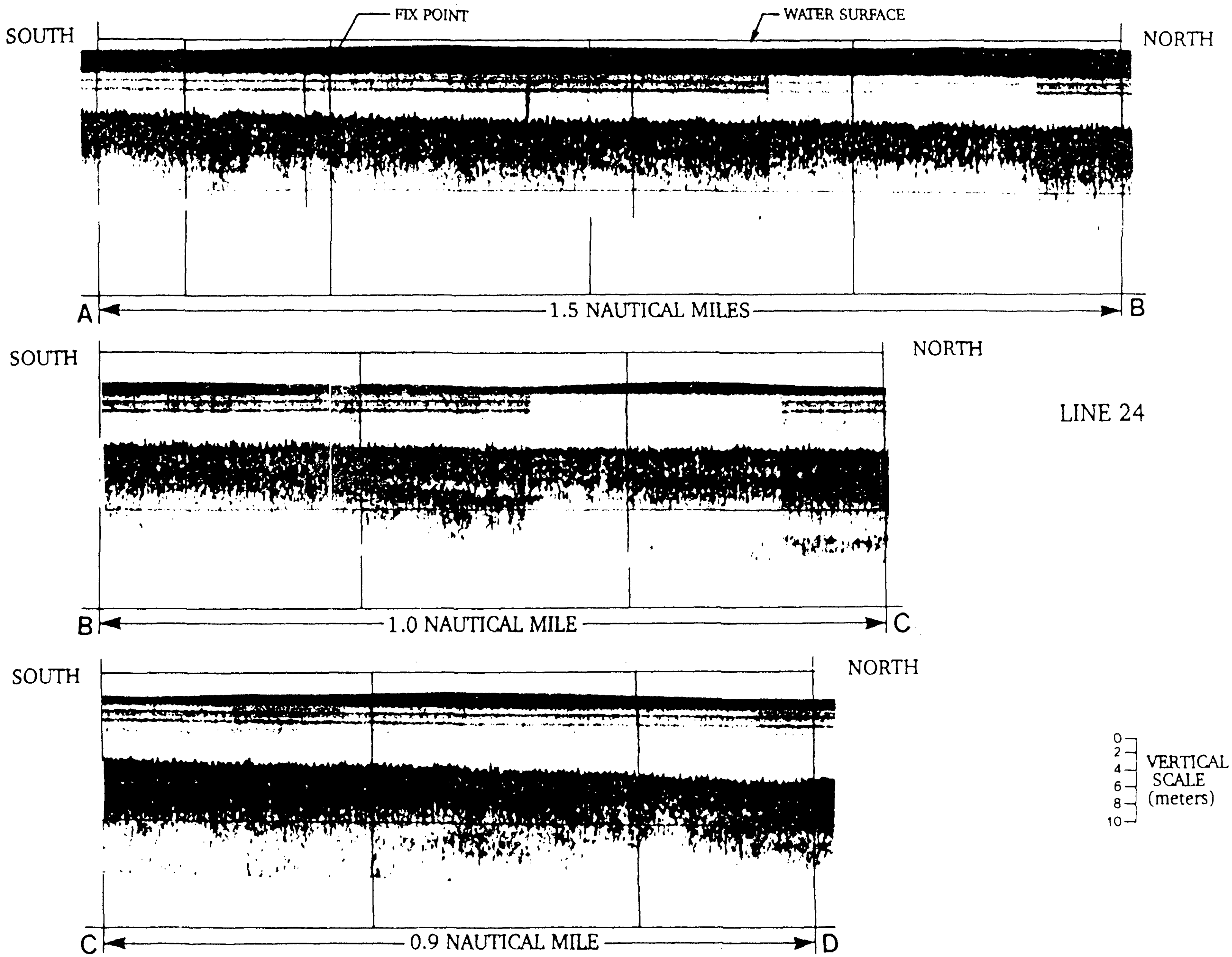
WATER SURFACE
NORTH
A
1.5 NAUTICAL MILES
B
SOUTH
NORTH
LINE 24
QH1
QP3
QPU
B
1.0 NAUTICAL MILE
C
SOUTH
NORTH
QP4
0
2
4
6
8
10
VERTICAL
SCALE
(meters)
C
0.9 NAUTICAL MILE
D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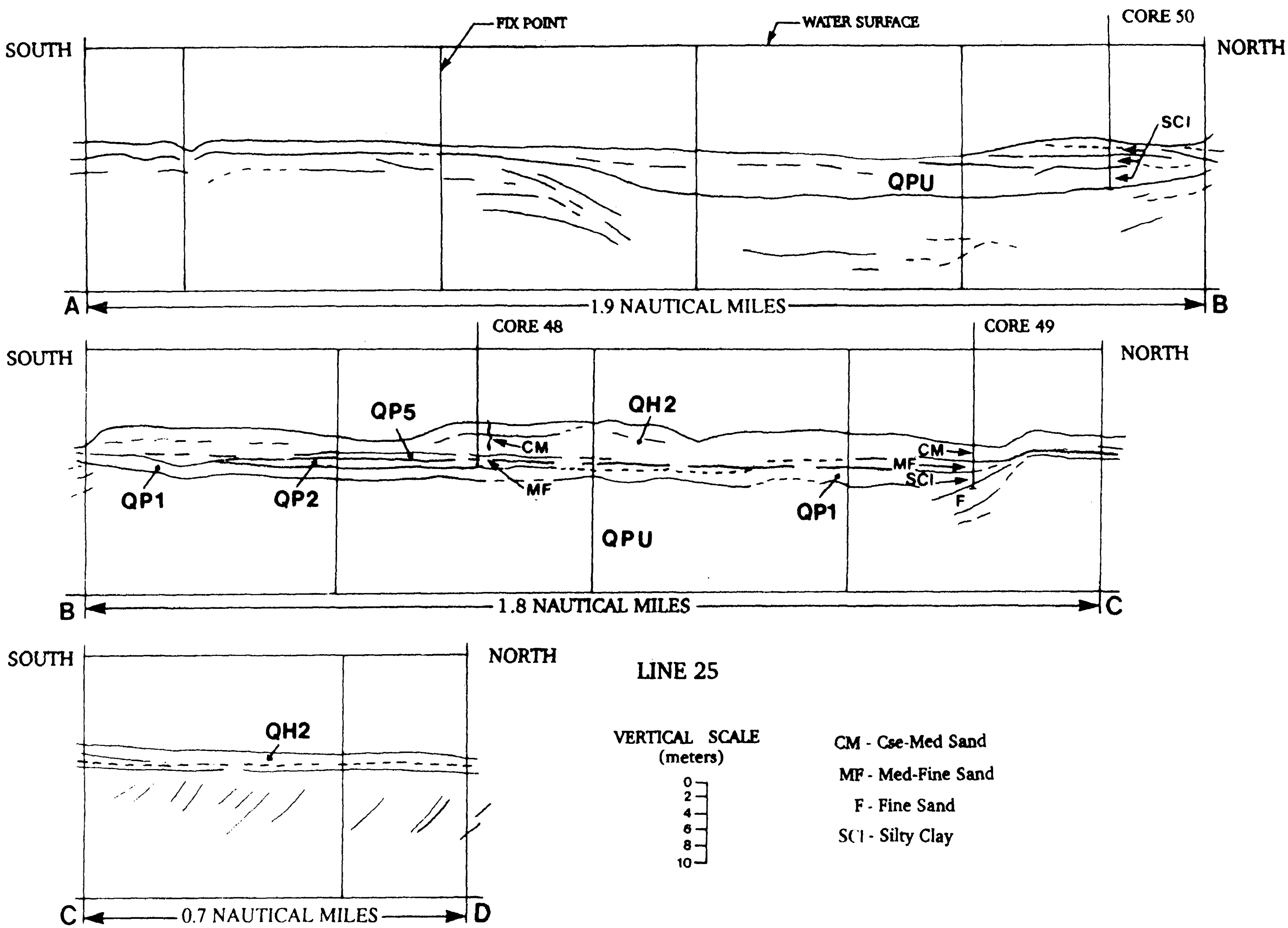
NORTH
A
1.5 NAUTICAL MILES
B
SOUTH
NORTH
LINE 24
B
1.0 NAUTICAL MILE
C
SOUTH
NORTH
C
0.9 NAUTICAL MILE
D
0
2
4
6
8
10
VERTICAL
SCALE
(meters)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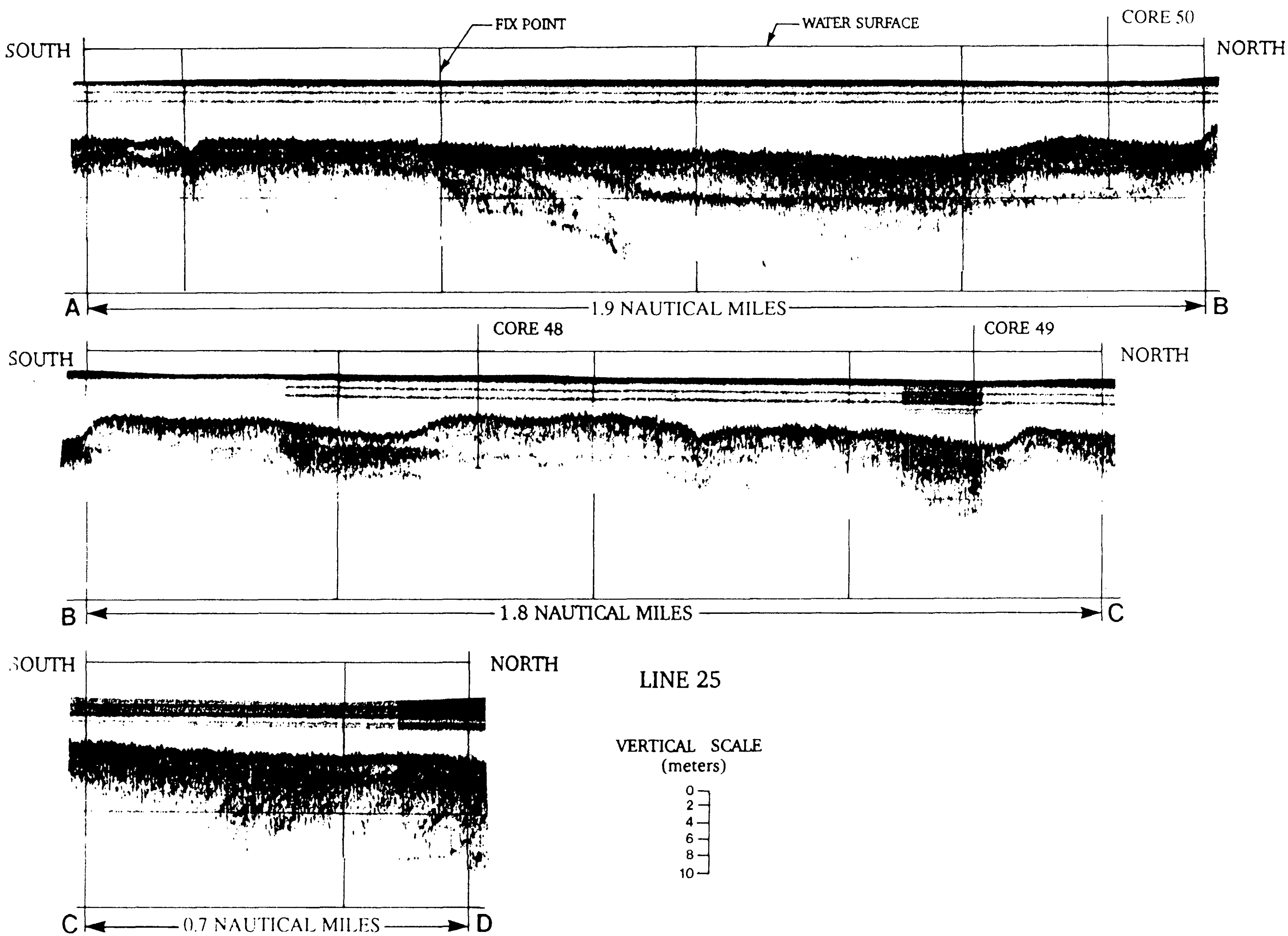
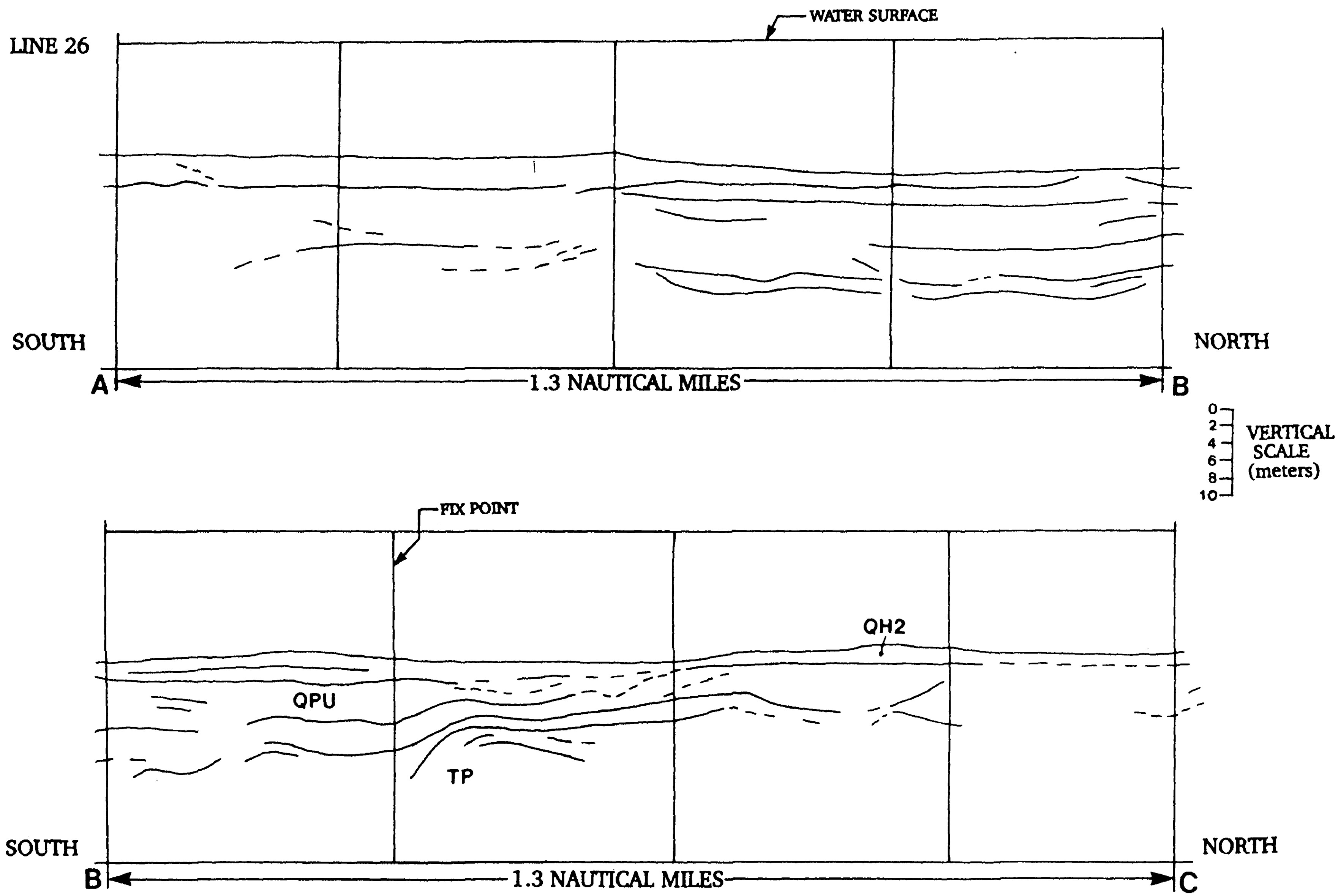
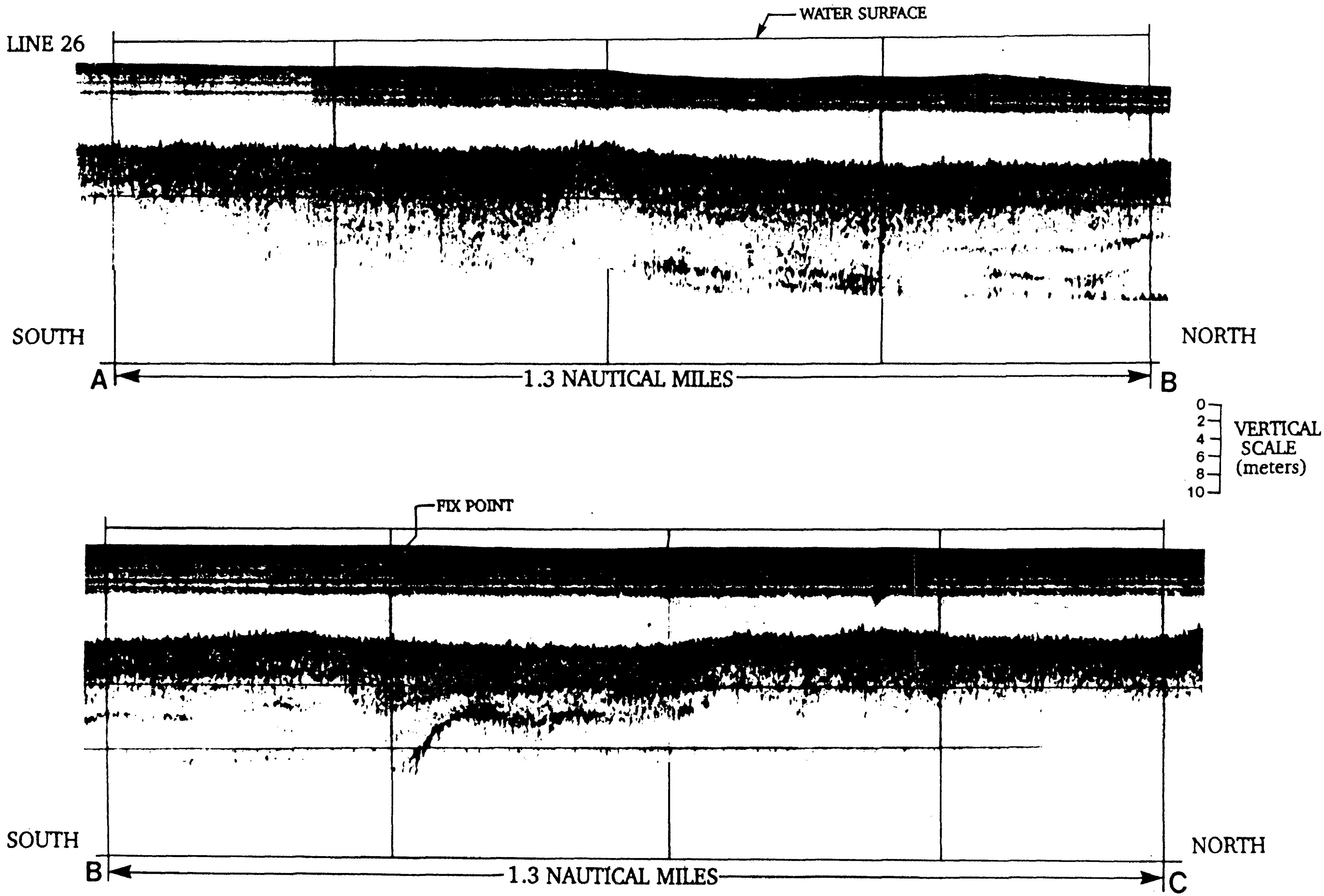
WATER SURFACE
CORE 50
SOUTH
NORTH
SCl
QPU
A
1.9 NAUTICAL MILES
B
CORE 48
CORE 49
SOUTH
NORTH
QP5
QH2
CM
MF
SCl
F
QP1
QP2
QP1
QPU
B
1.8 NAUTICAL MILES
C
SOUTH
NORTH
QH2
C
0.7 NAUTICAL MILES
D
LINE 25
VERTICAL SCALE
(meters)
0
2
4
6
8
10
CM - Cse-Med Sand
MF - Med-Fine Sand
F - Fine Sand
SCl - Silty Clay

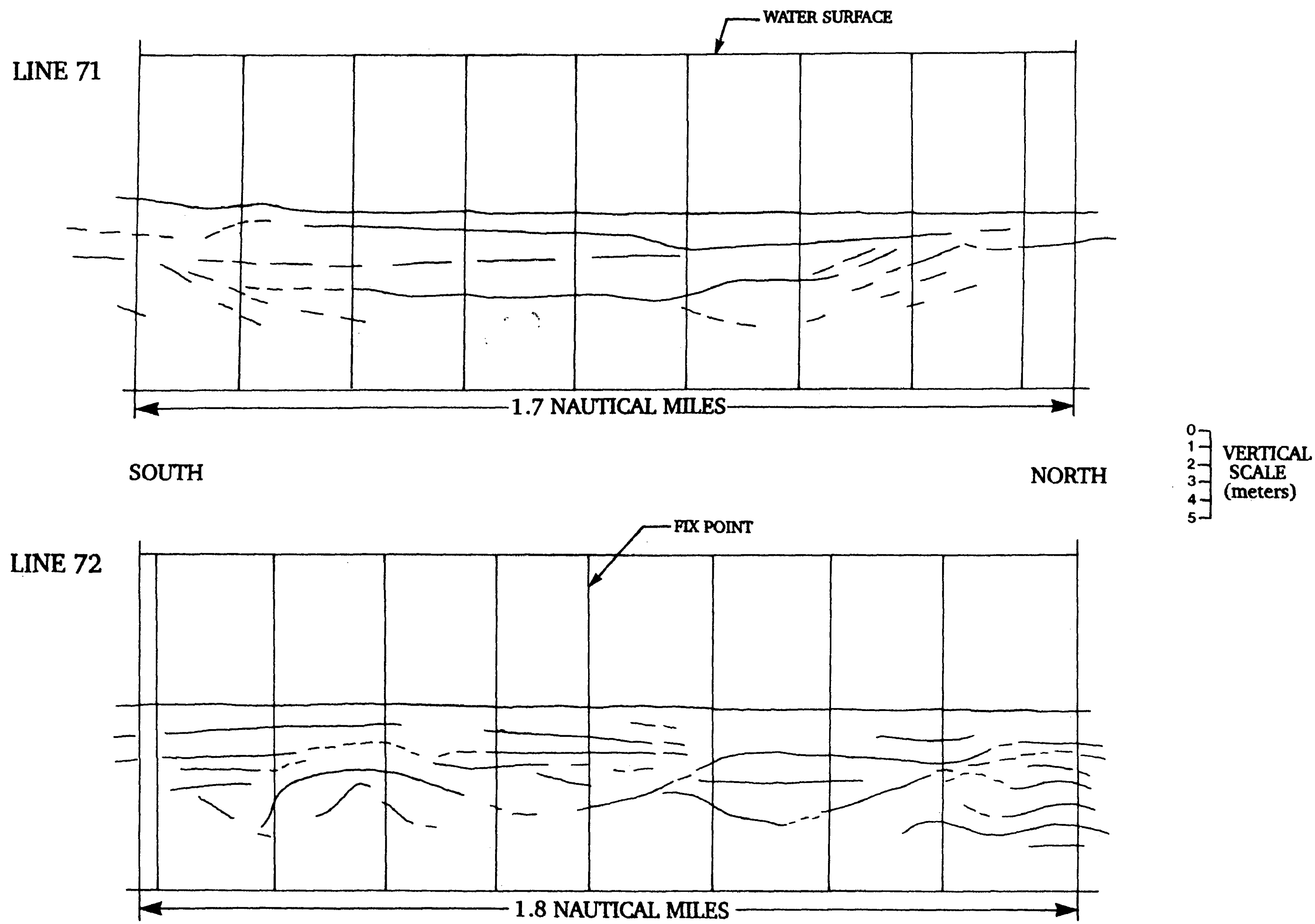


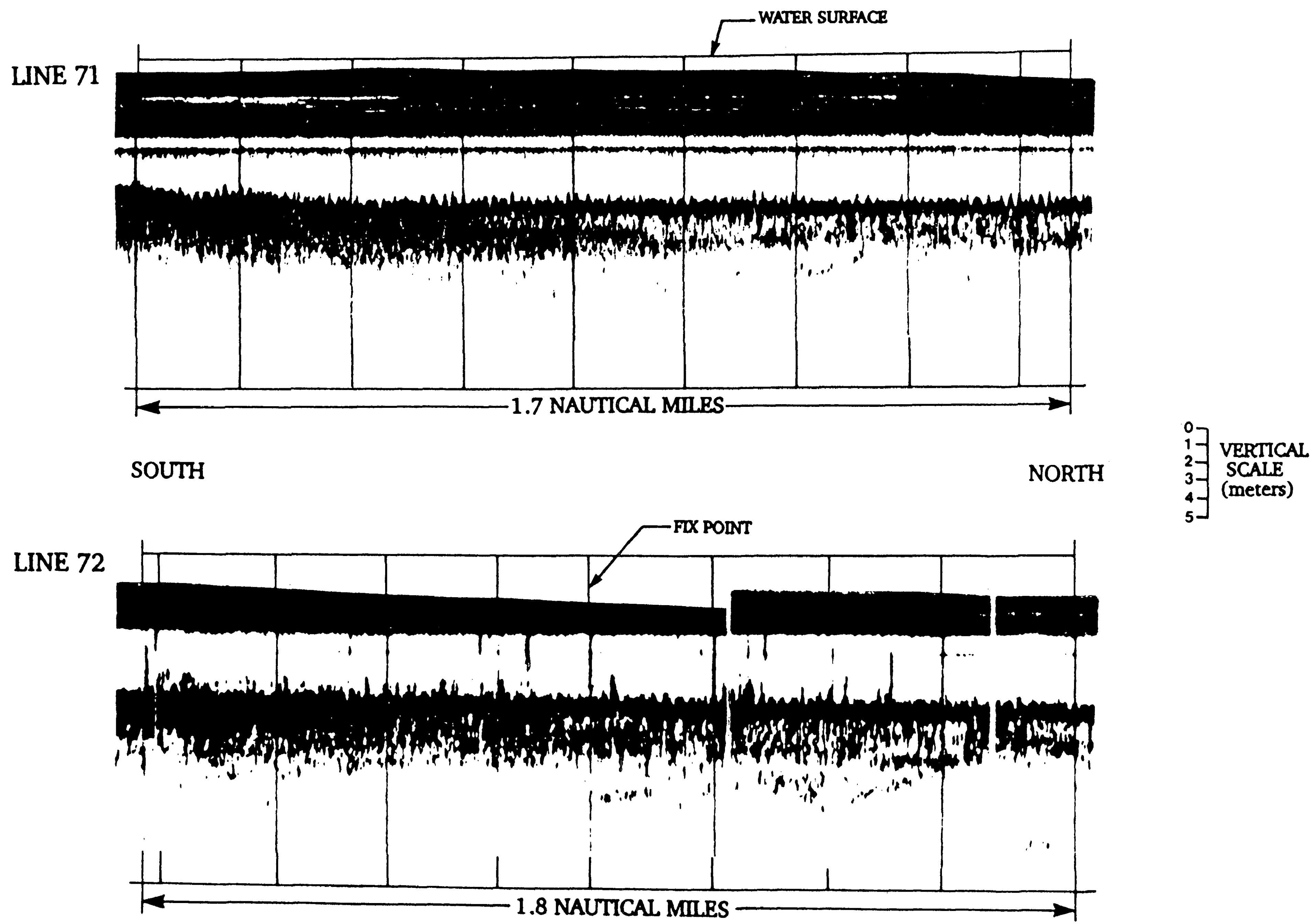
SOUTH
FIX POINT
WATER SURFACE
CORE 50
NORTH
A
1.9 NAUTICAL MILES
B
CORE 48
CORE 49
SOUTH
NORTH
B
1.8 NAUTICAL MILES
C
SOUTH
NORTH
C
0.7 NAUTICAL MILES
D
VERTICAL SCALE
(meters)
0
2
4
6
8
10

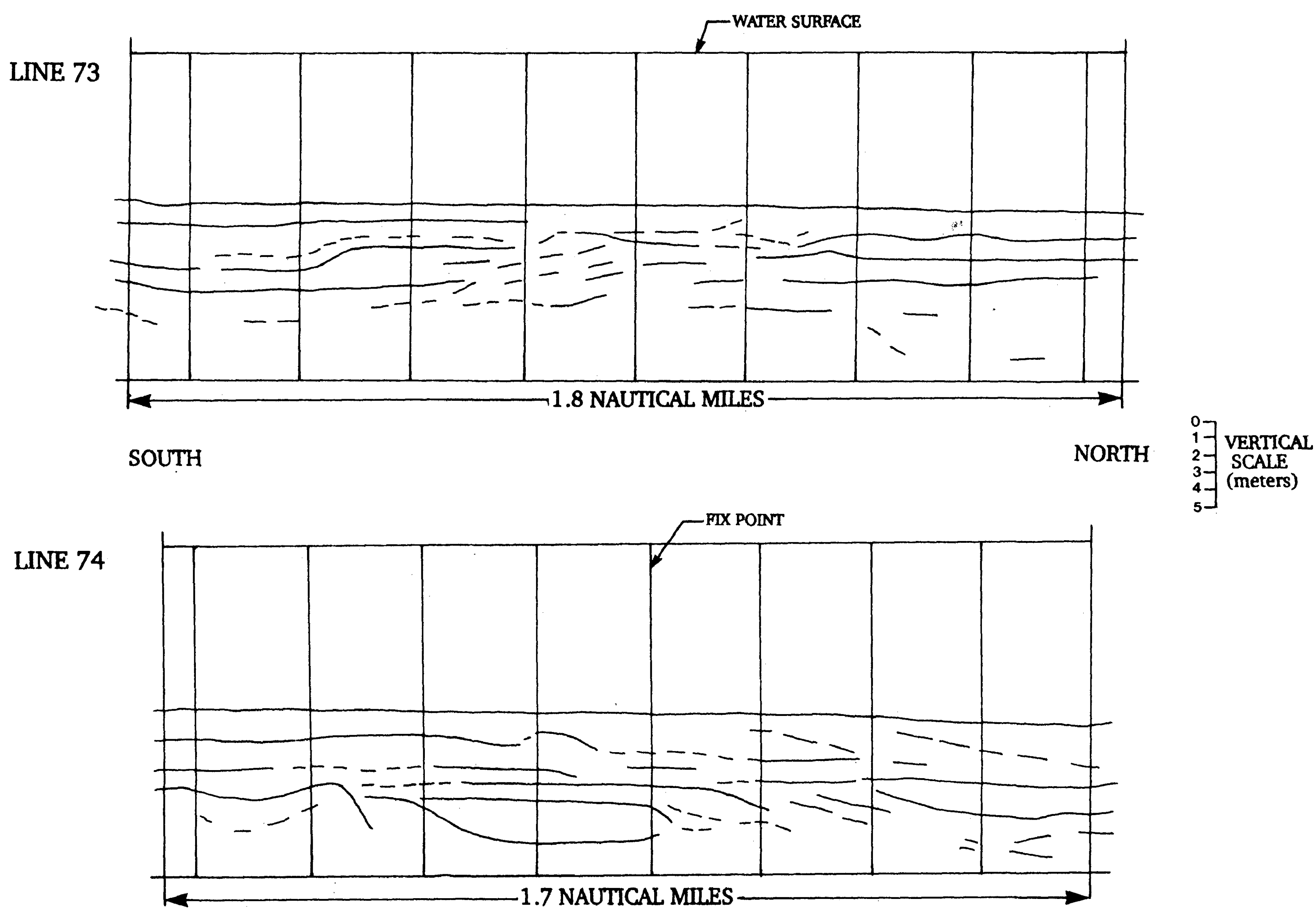
LINE 25

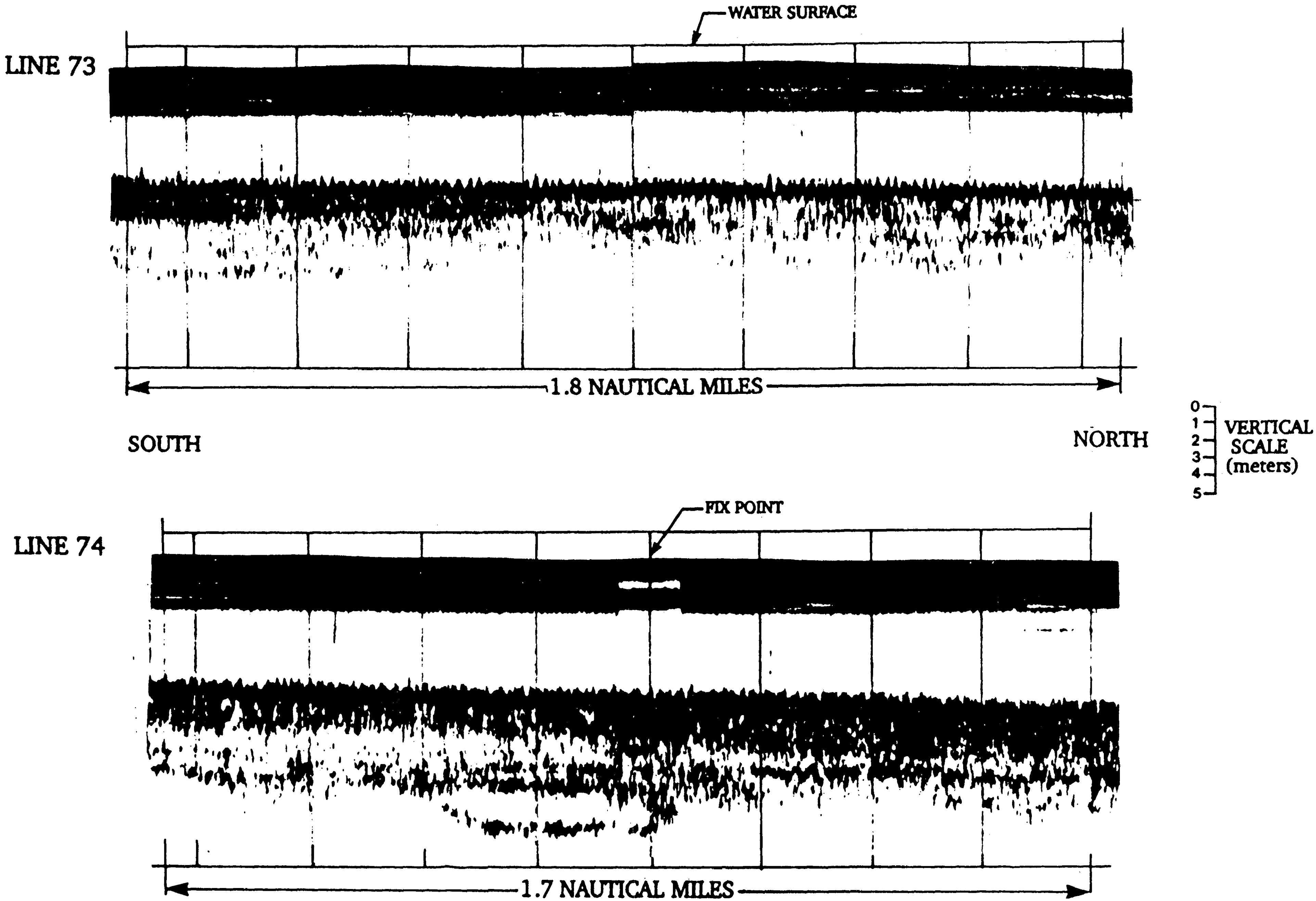

LINE 26
WATER SURFACE
SOUTH
NORTH
A
1.3 NAUTICAL MILES
B
0
2
4
6
8
10
VERTICAL
SCALE
(meters)
FIX POINT
QH2
QPU
TP
SOUTH
NORTH
B
1.3 NAUTICAL MILES
C

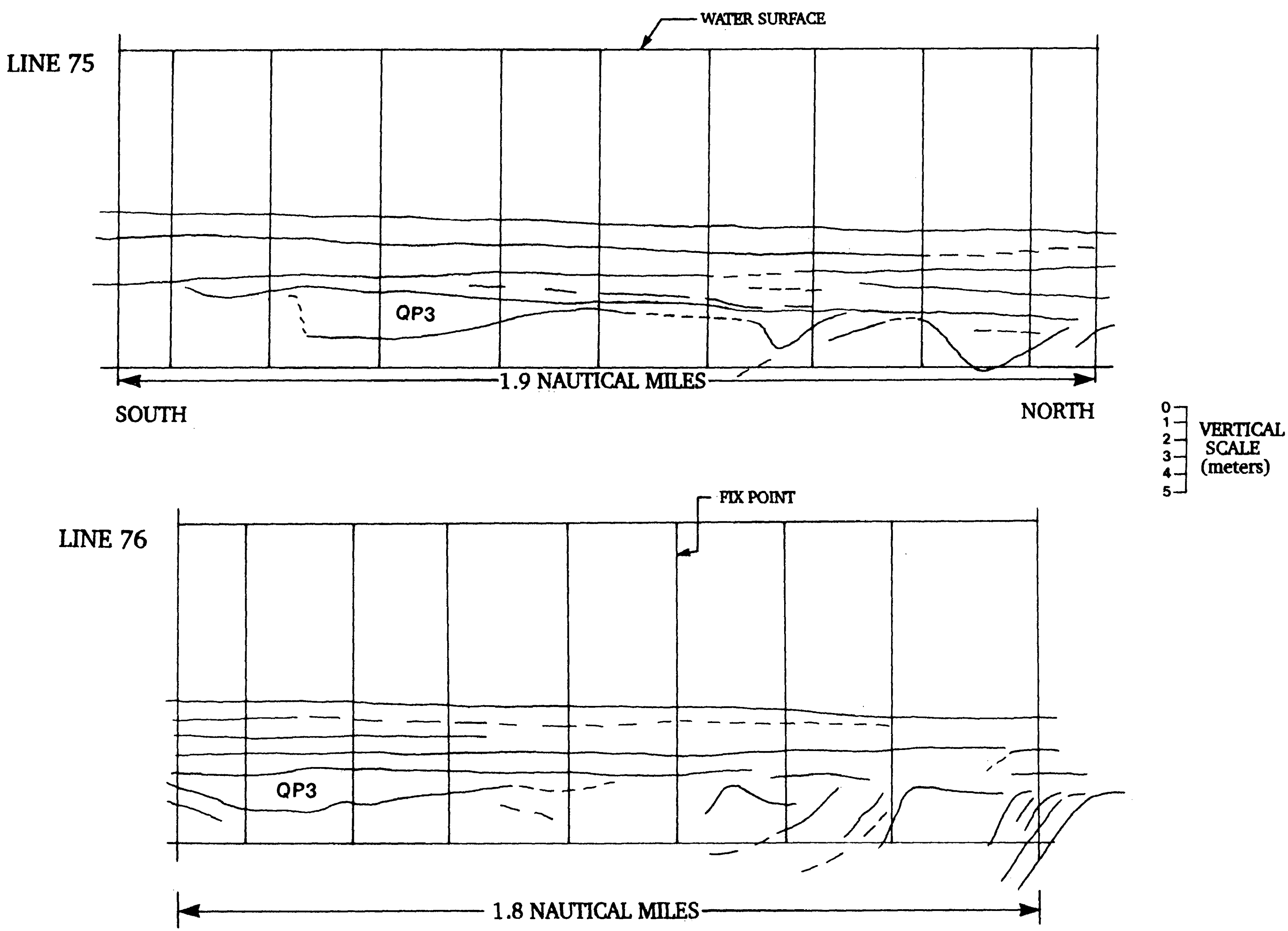

LINE 26
WATER SURFACE
SOUTH
NORTH
A
1.3 NAUTICAL MILES
B
0
2
4
6
8
10
VERTICAL SCALE (meters)
FIX POINT
SOUTH
NORTH
B
1.3 NAUTICAL MILES
C

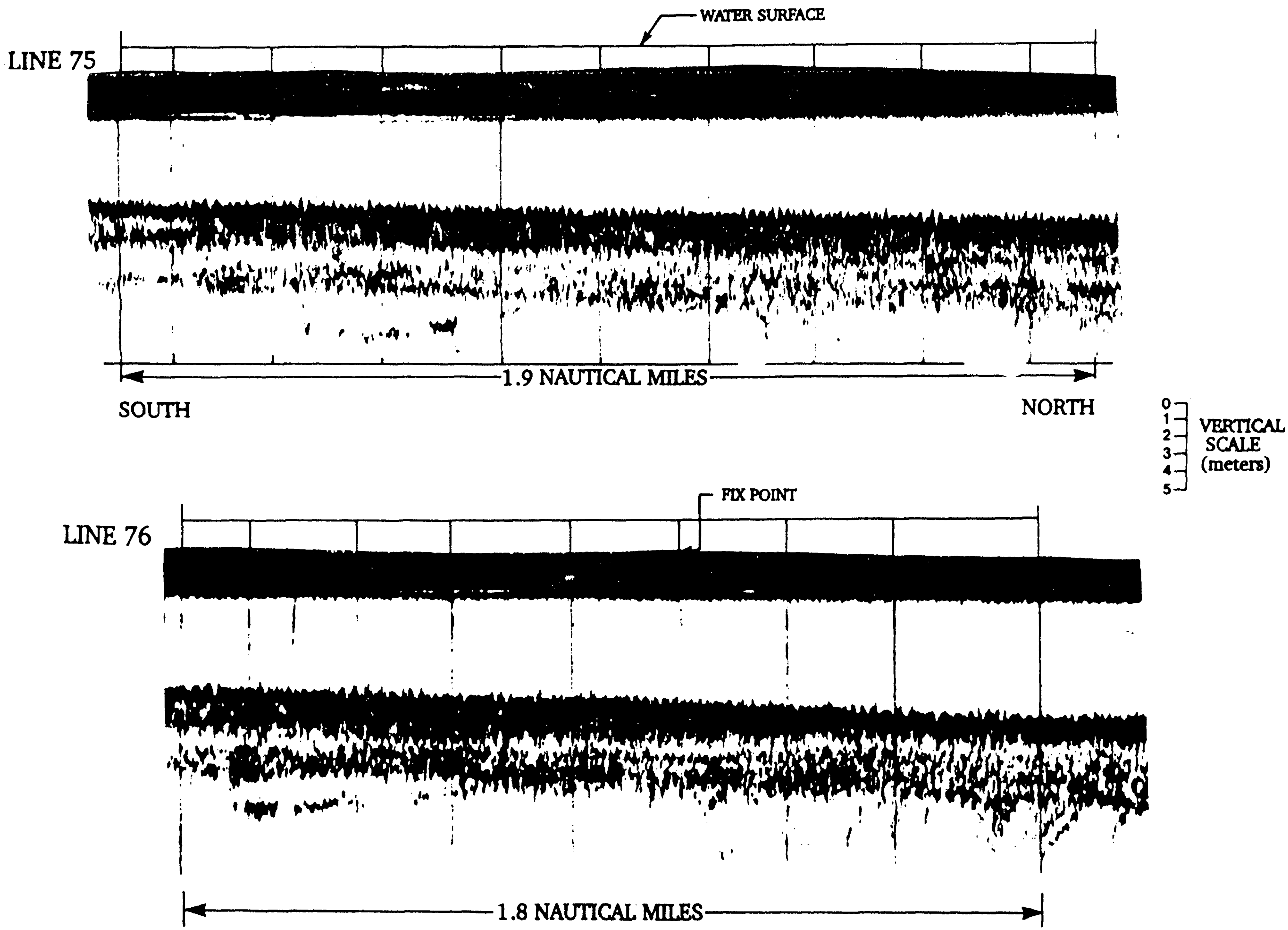

WATER SURFACE
LINE 71
1.7 NAUTICAL MILES
SOUTH
NORTH
0
1
2
3
4
5
VERTICAL SCALE (meters)
FIX POINT
LINE 72
1.8 NAUTICAL MILES

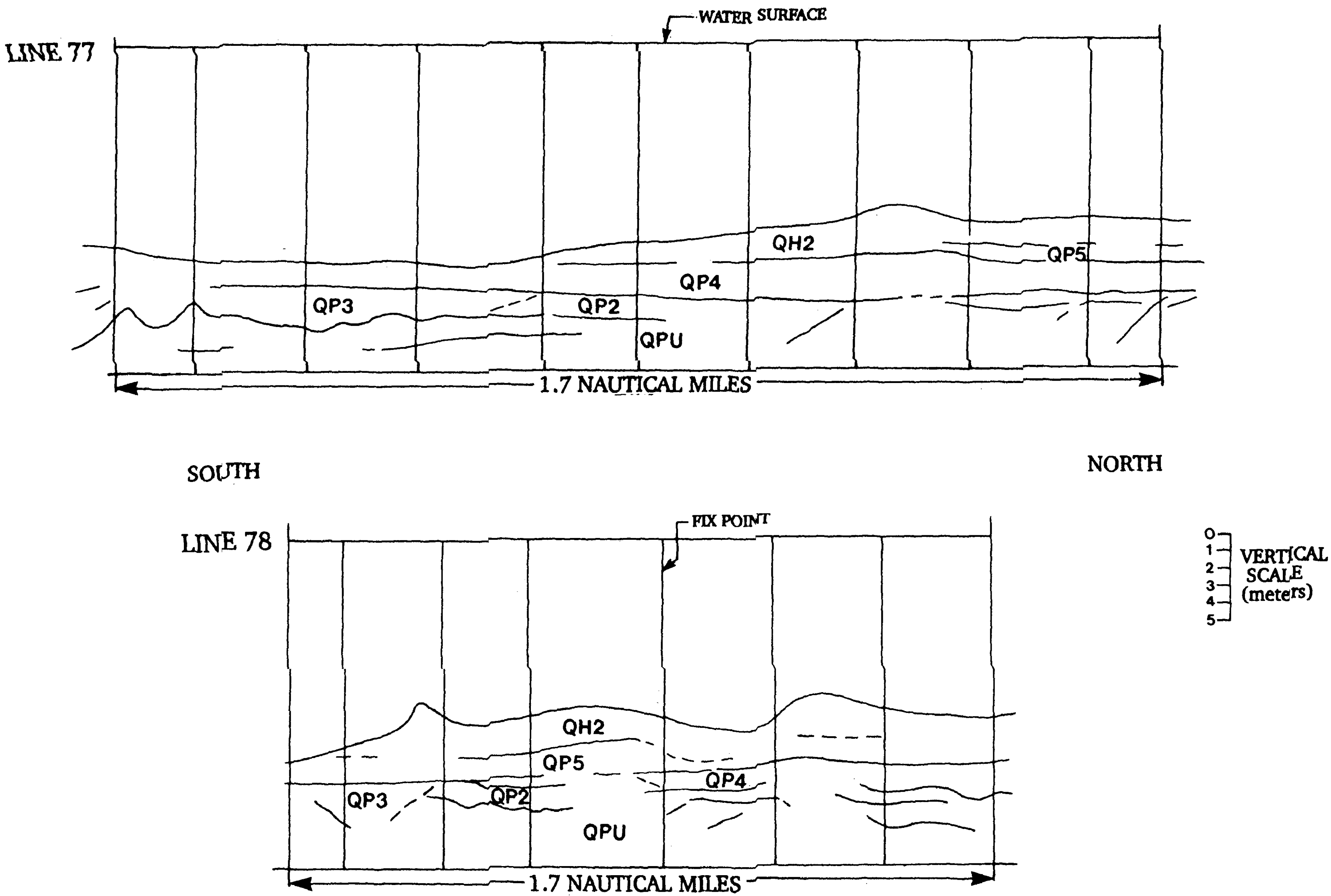

LINE 71
WATER SURFACE
1.7 NAUTICAL MILES
SOUTH
NORTH
LINE 72
FIX POINT
1.8 NAUTICAL MILES
0
1
2
3
4
5
VERTICAL SCALE (meters)

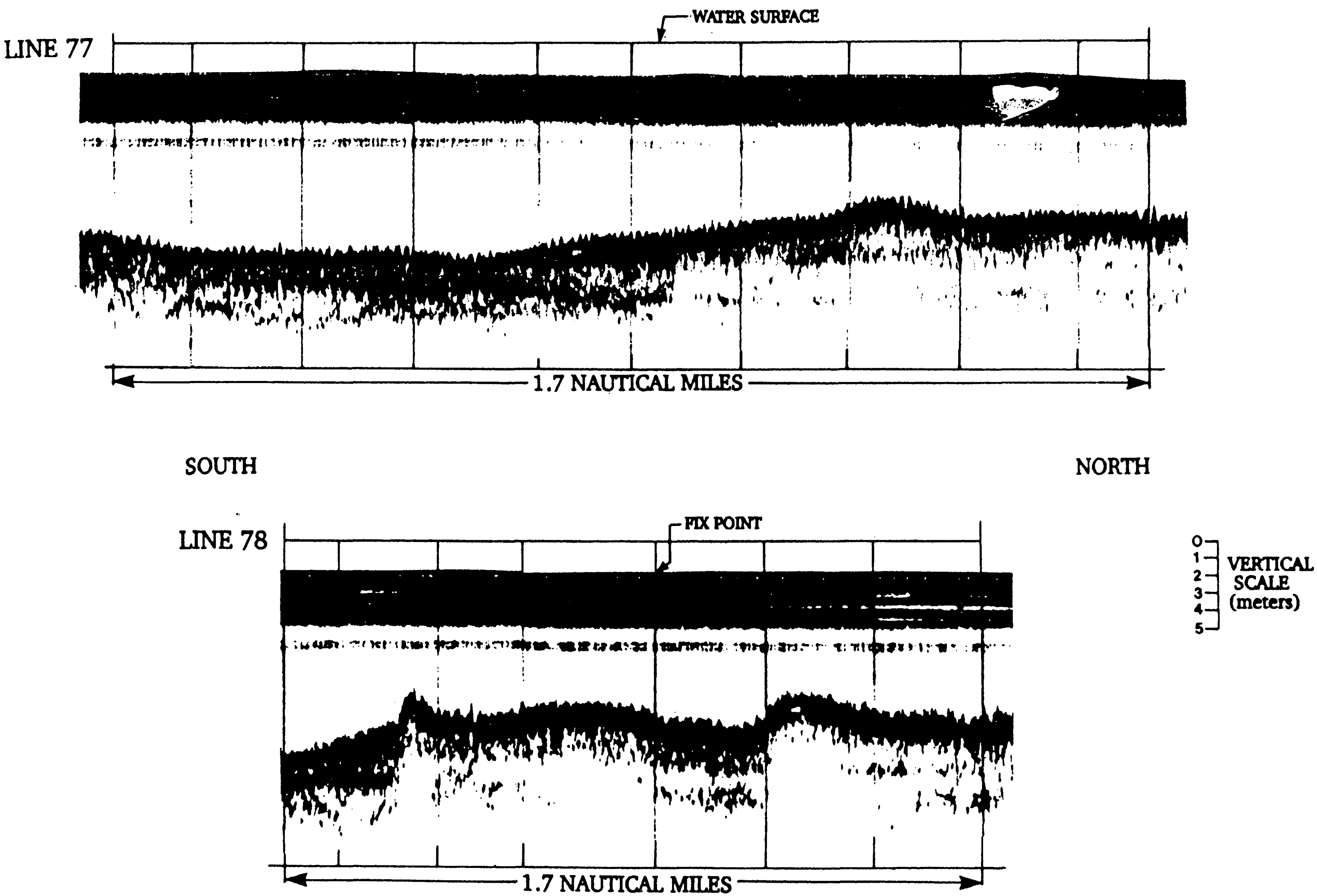

LINE 73
WATER SURFACE
1.8 NAUTICAL MILES
SOUTH
NORTH
0
1
2
3
4
5
VERTICAL SCALE (meters)
LINE 74
FIX POINT
1.7 NAUTICAL MILES

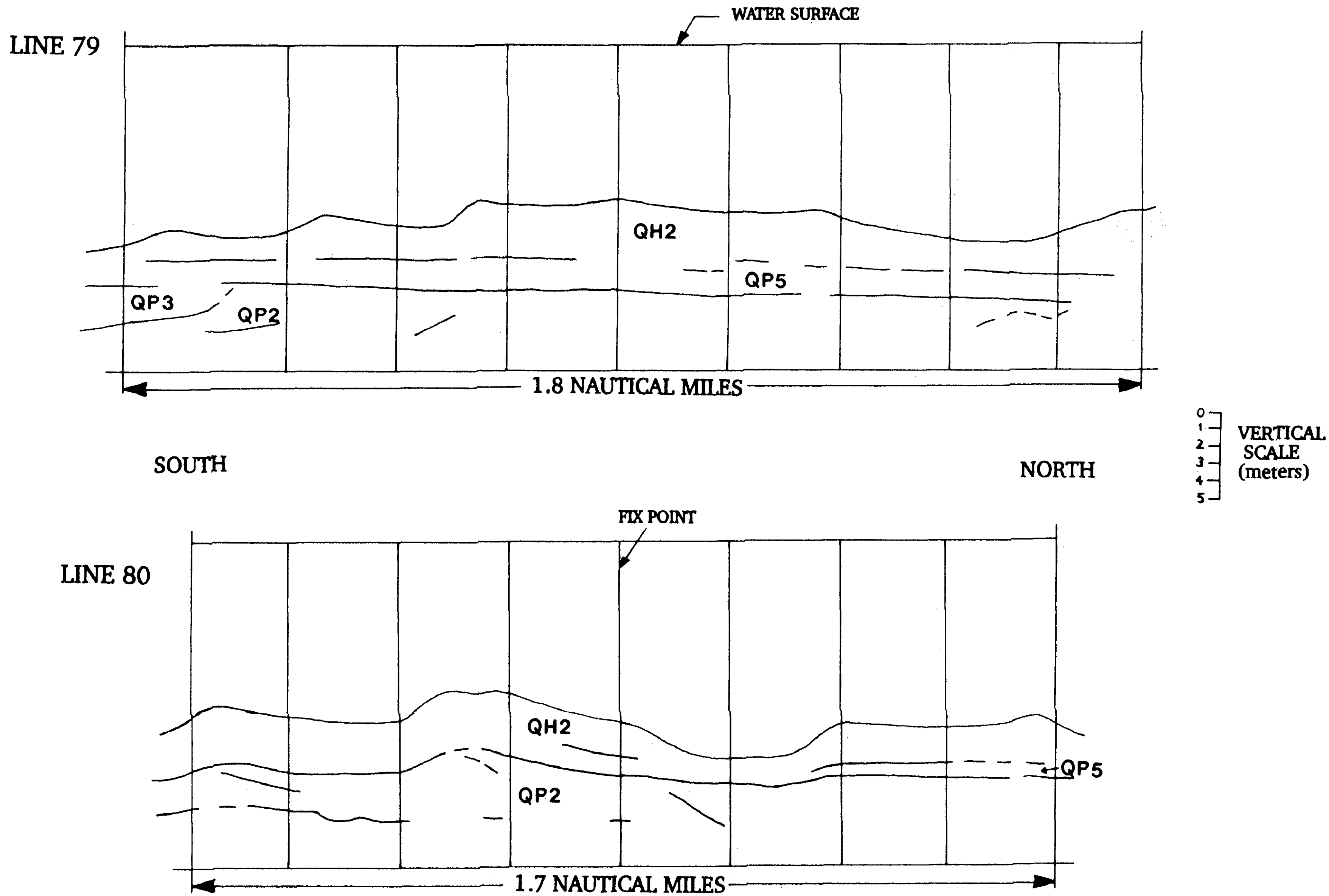

LINE 73
WATER SURFACE
1.8 NAUTICAL MILES
SOUTH
NORTH
0
1
2
3
4
5
VERTICAL
SCALE
(meters)
LINE 74
FIX POINT
1.7 NAUTICAL MILES

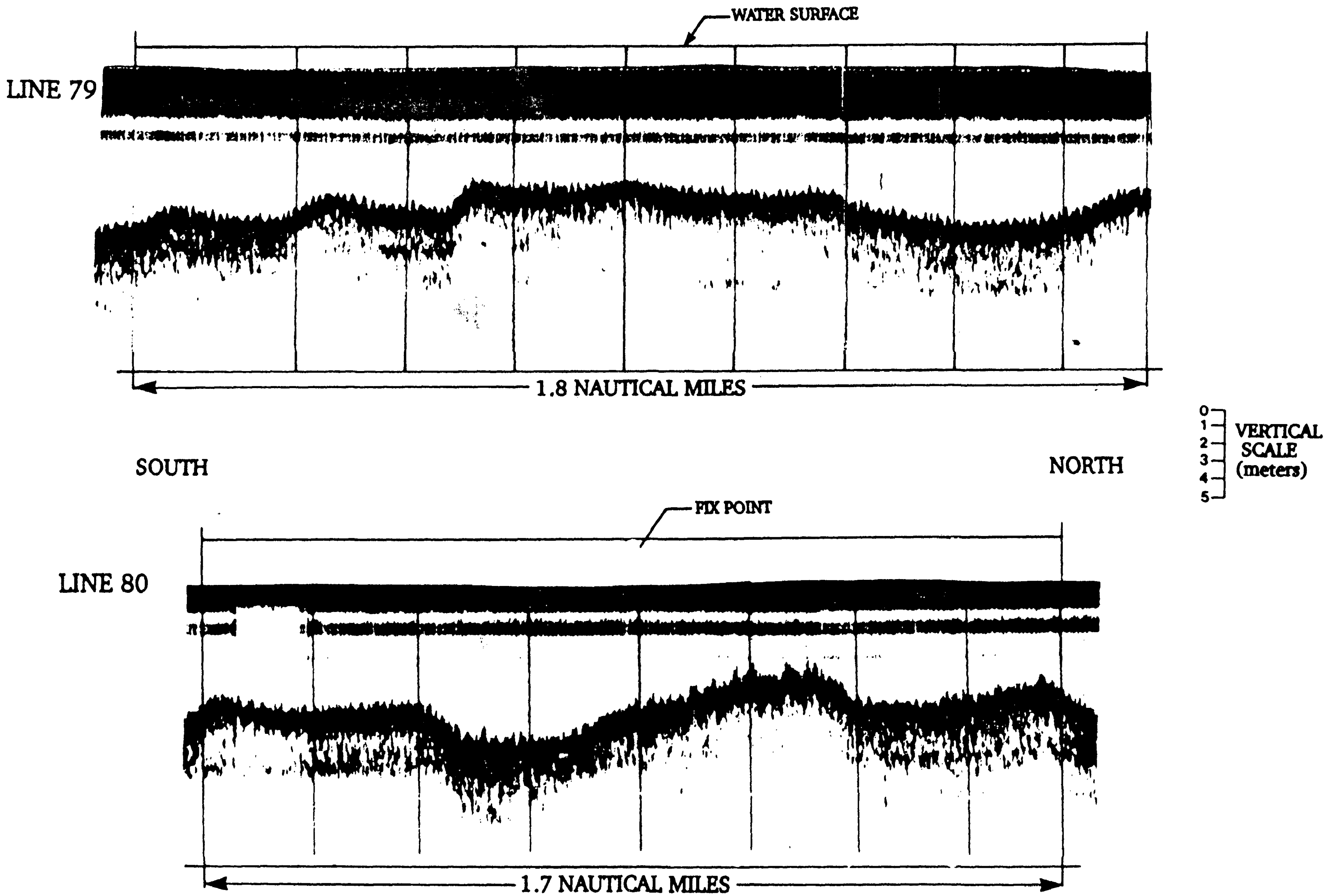

WATER SURFACE
LINE 75
QP3
1.9 NAUTICAL MILES
SOUTH
NORTH
0
1
2
3
4
5
VERTICAL
SCALE
(meters)
FIX POINT
LINE 76
QP3
1.8 NAUTICAL MILES


LINE 75
WATER SURFACE
1.9 NAUTICAL MILES
SOUTH
NORTH
0
1
2
3
4
5
VERTICAL
SCALE
(meters)
LINE 76
FIX POINT
1.8 NAUTICAL MILES

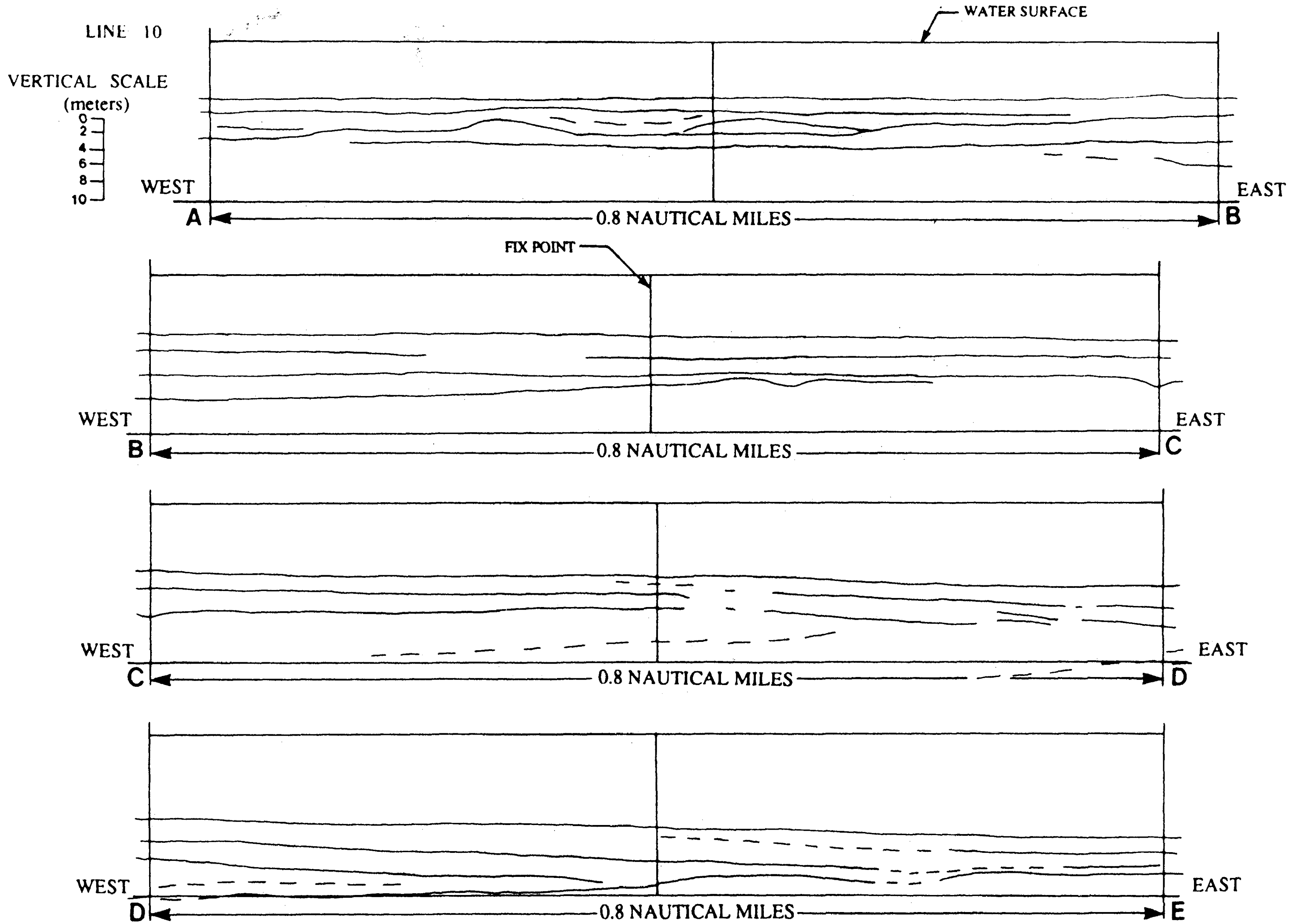

LINE 77
WATER SURFACE
QH2
QP5
QP4
QP3
QP2
QPU
1.7 NAUTICAL MILES
SOUTH
NORTH
LINE 78
FIX POINT
QH2
QP5
QP4
QP3
QP2
QPU
1.7 NAUTICAL MILES
0
1
2
3
4
5
VERTICAL
SCALE
(meters)

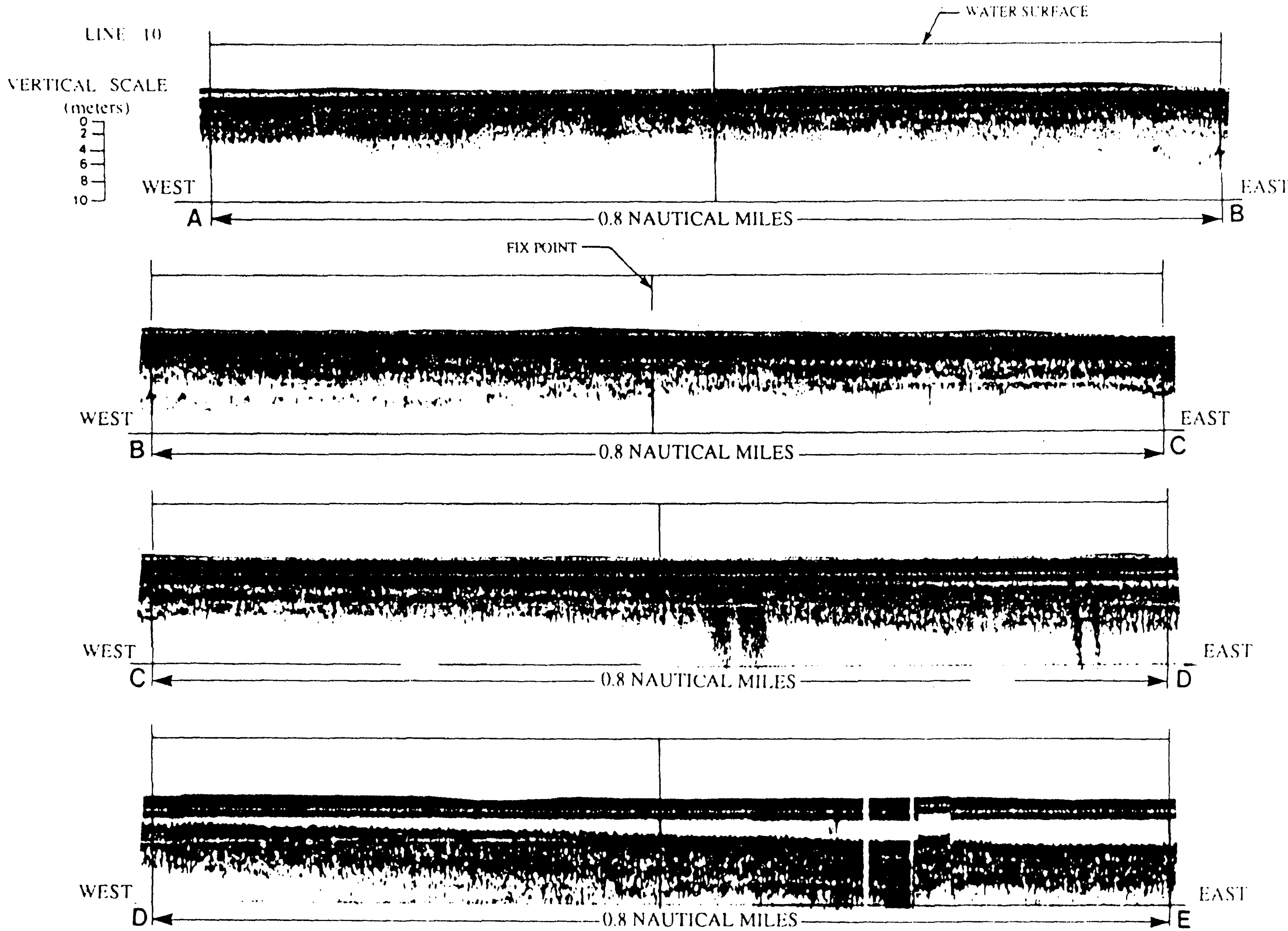

LINE 77
WATER SURFACE
1.7 NAUTICAL MILES
SOUTH
NORTH
LINE 78
FIX POINT
1.7 NAUTICAL MILES
0
1
2
3
4
5
VERTICAL SCALE (meters)

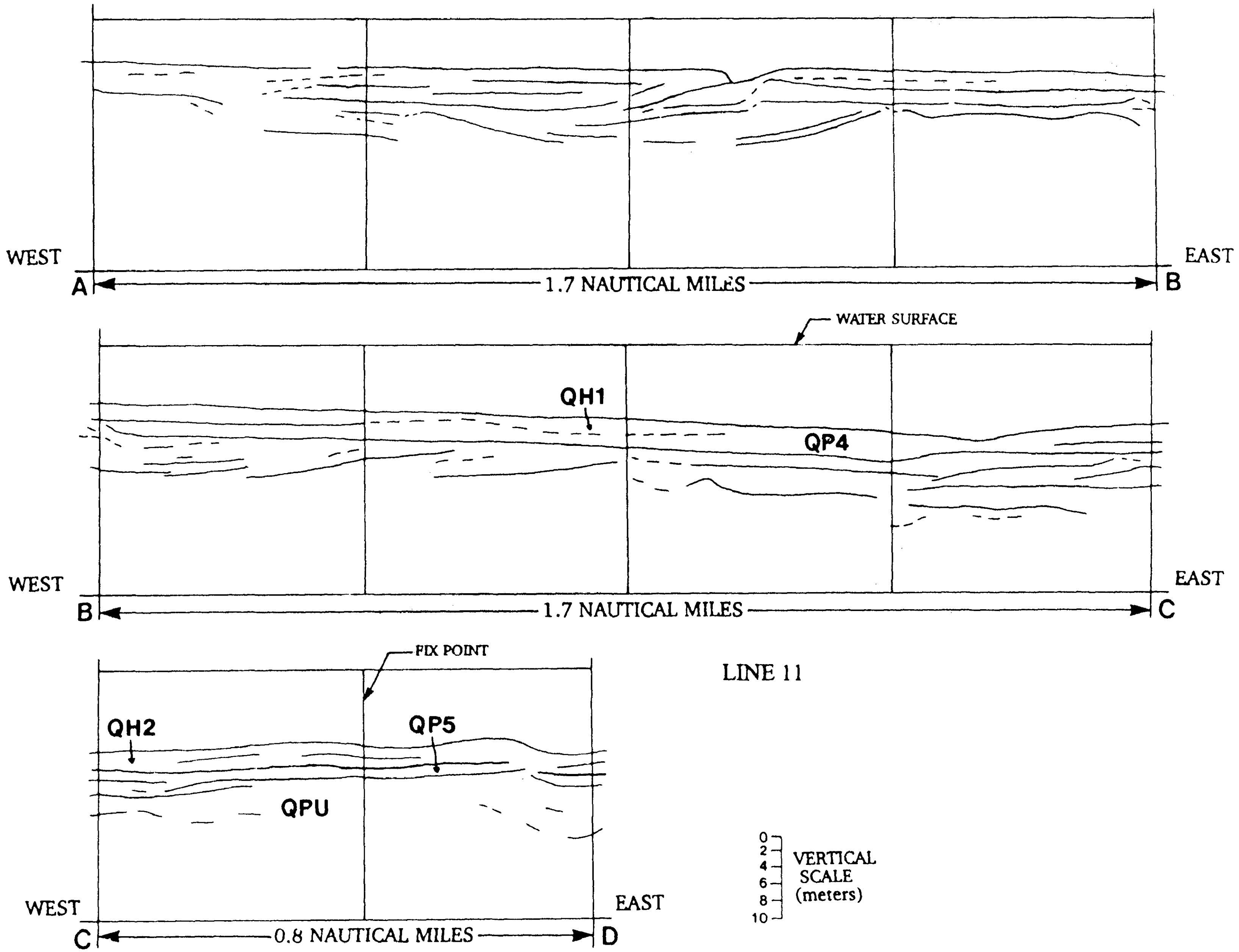

LINE 79
WATER SURFACE
QH2
QP5
QP3
QP2
1.8 NAUTICAL MILES
SOUTH
NORTH
0
1
2
3
4
5
VERTICAL
SCALE
(meters)
FIX POINT
LINE 80
QH2
QP5
QP2
1.7 NAUTICAL MILES

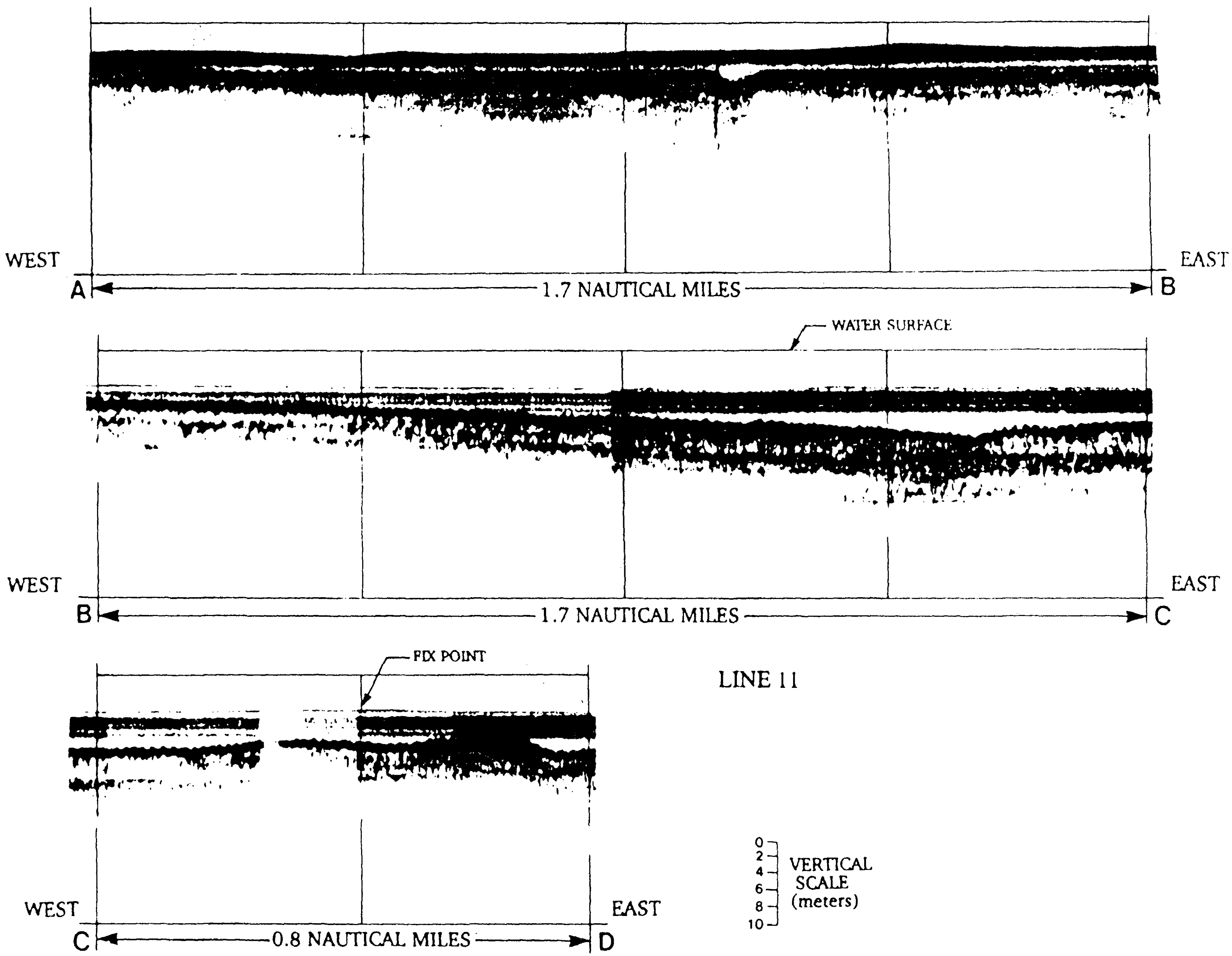

WATER SURFACE
LINE 79
1.8 NAUTICAL MILES
SOUTH
NORTH
0
1
2
3
4
5
VERTICAL
SCALE
(meters)
FIX POINT
LINE 80
1.7 NAUTICAL MILES

Reproductions of subbottom acoustic records obtained in 1987, and corresponding interpretations for east-west trending tracklines. Descriptions of stratigraphic units are given in Table 1.

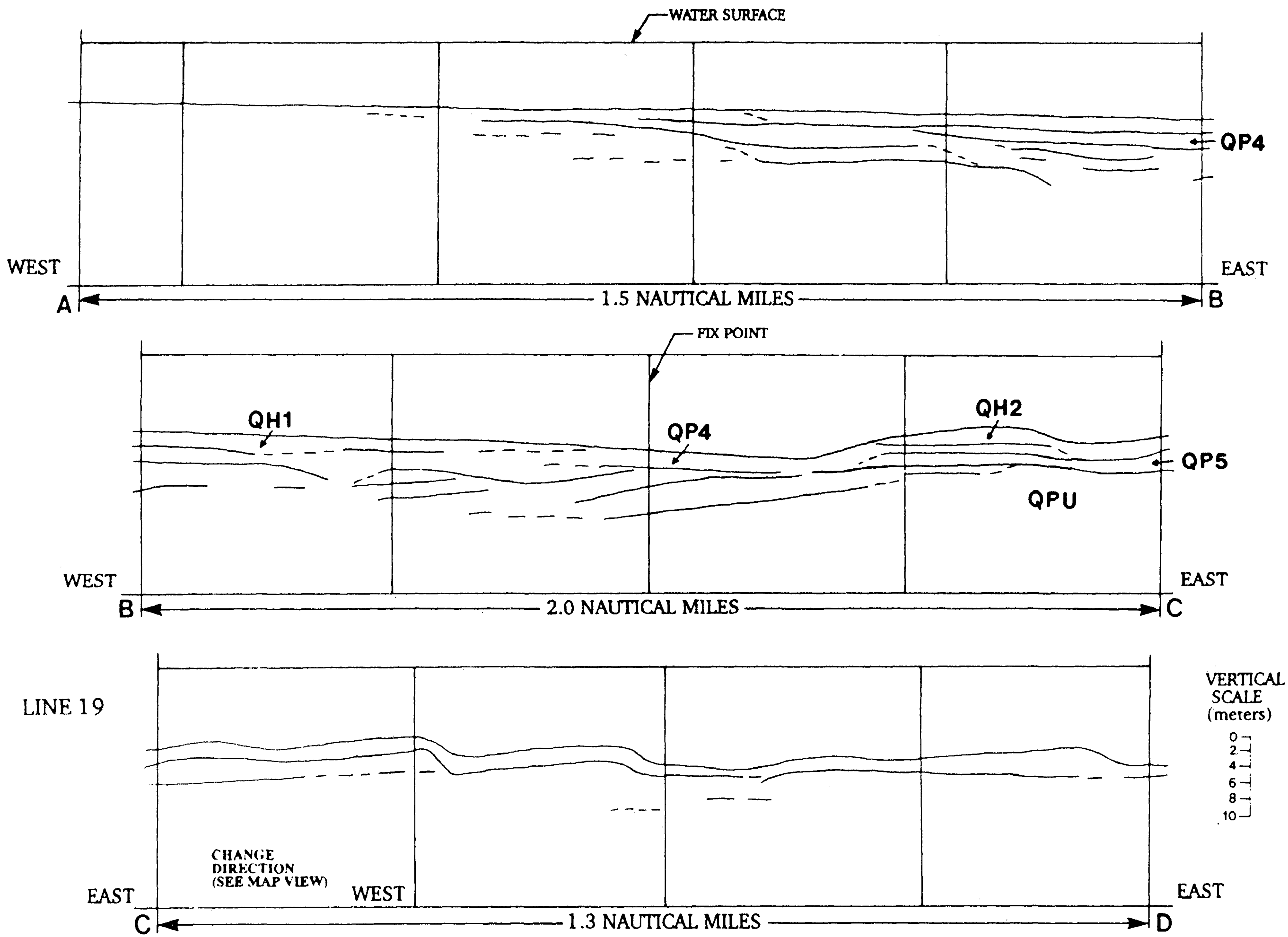

LINE 10
VERTICAL SCALE
(meters)
0
2
4
6
8
10
WATER SURFACE
WEST
EAST
A
B
0.8 NAUTICAL MILES
FIX POINT
WEST
EAST
B
C
0.8 NAUTICAL MILES
WEST
EAST
C
D
0.8 NAUTICAL MILES
WEST
EAST
D
E
0.8 NAUTICAL MILES

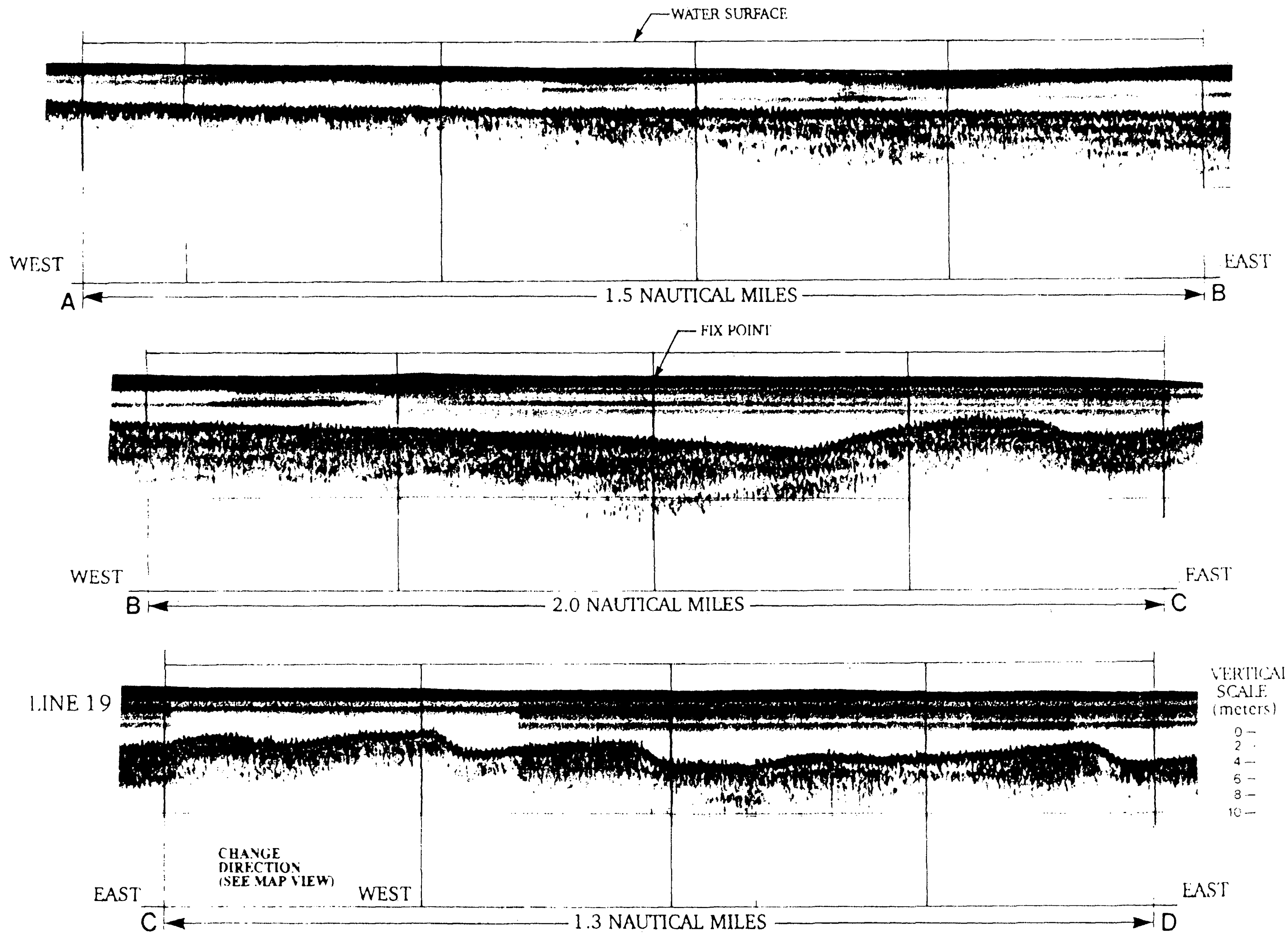

LINE 10
VERTICAL SCALE
(meters)
0
2
4
6
8
10
WATER SURFACE
WEST
EAST
A
B
0.8 NAUTICAL MILES
FIX POINT
WEST
EAST
B
C
0.8 NAUTICAL MILES
WEST
EAST
C
D
0.8 NAUTICAL MILES
WEST
EAST
D
E
0.8 NAUTICAL MILES

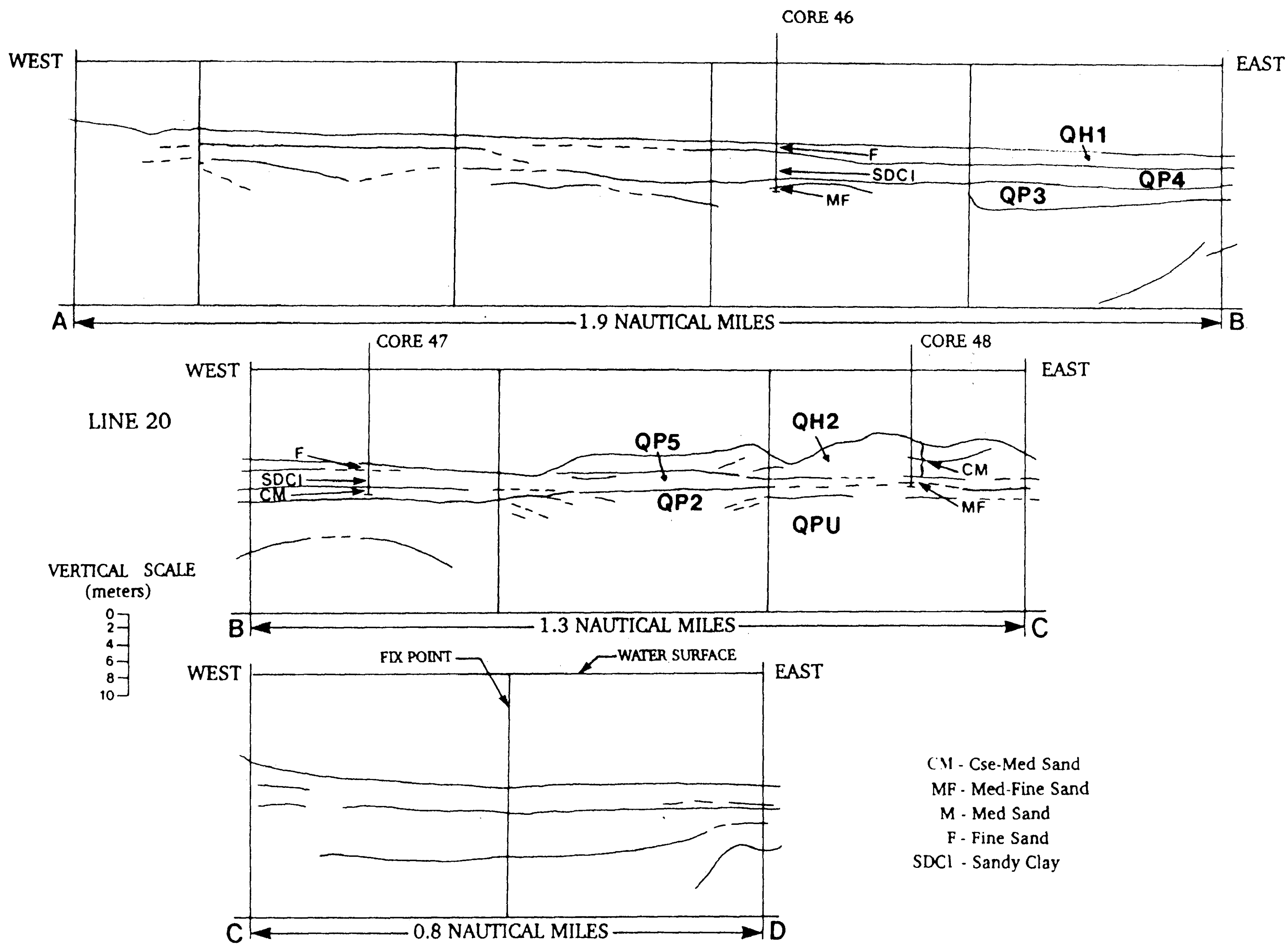

WEST
EAST
A
1.7 NAUTICAL MILES
B
WATER SURFACE
QH1
QP4
WEST
EAST
B
1.7 NAUTICAL MILES
C
FIX POINT
QH2
QP5
QPU
WEST
EAST
C
0.8 NAUTICAL MILES
D
LINE 11
0
2
4
6
8
10
VERTICAL
SCALE
(meters)

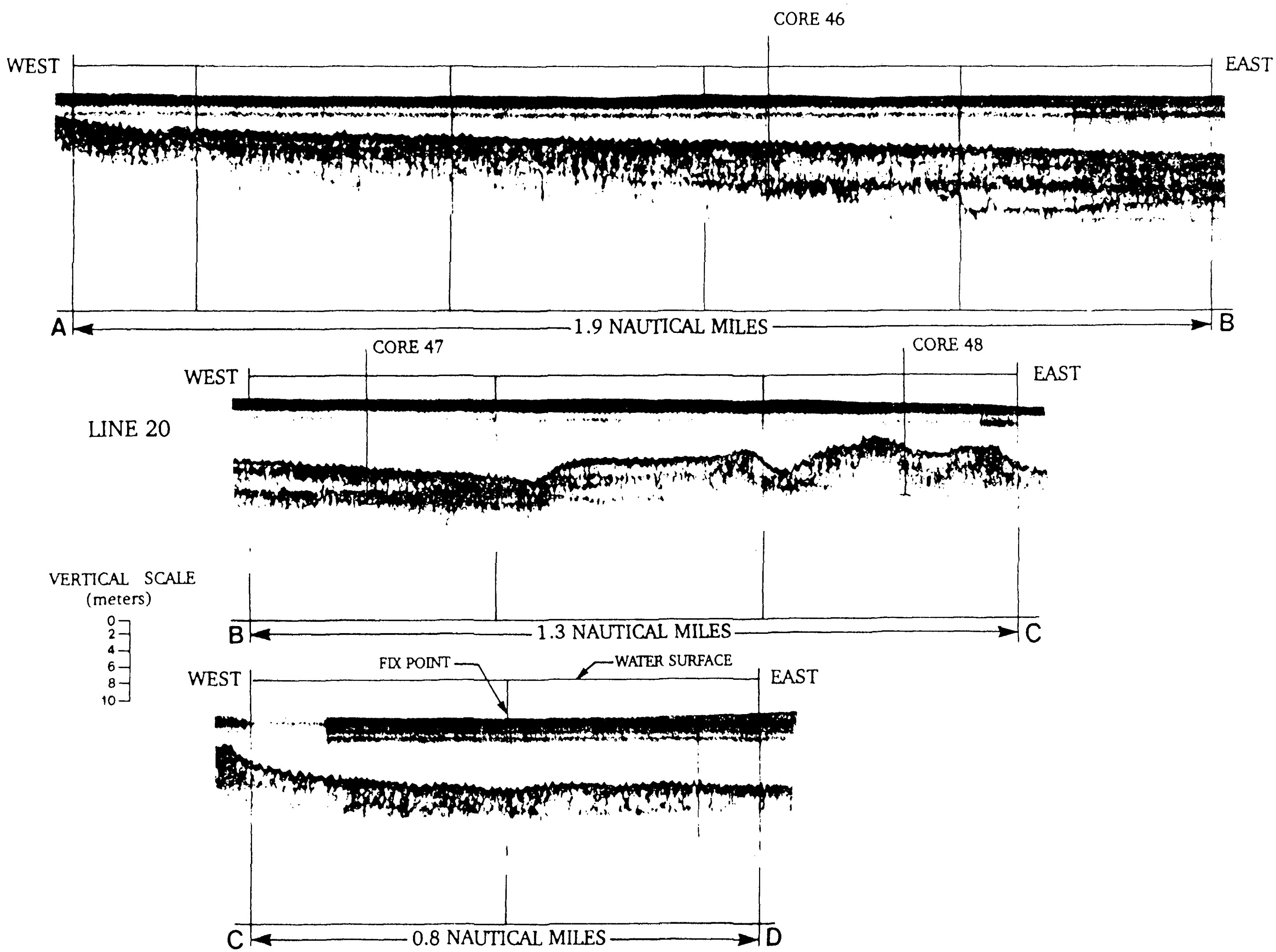

WEST
EAST
A
B
1.7 NAUTICAL MILES
WATER SURFACE
WEST
EAST
B
C
1.7 NAUTICAL MILES
FIX POINT
WEST
EAST
C
D
0.8 NAUTICAL MILES
0
2
4
6
8
10
VERTICAL
SCALE
(meters)

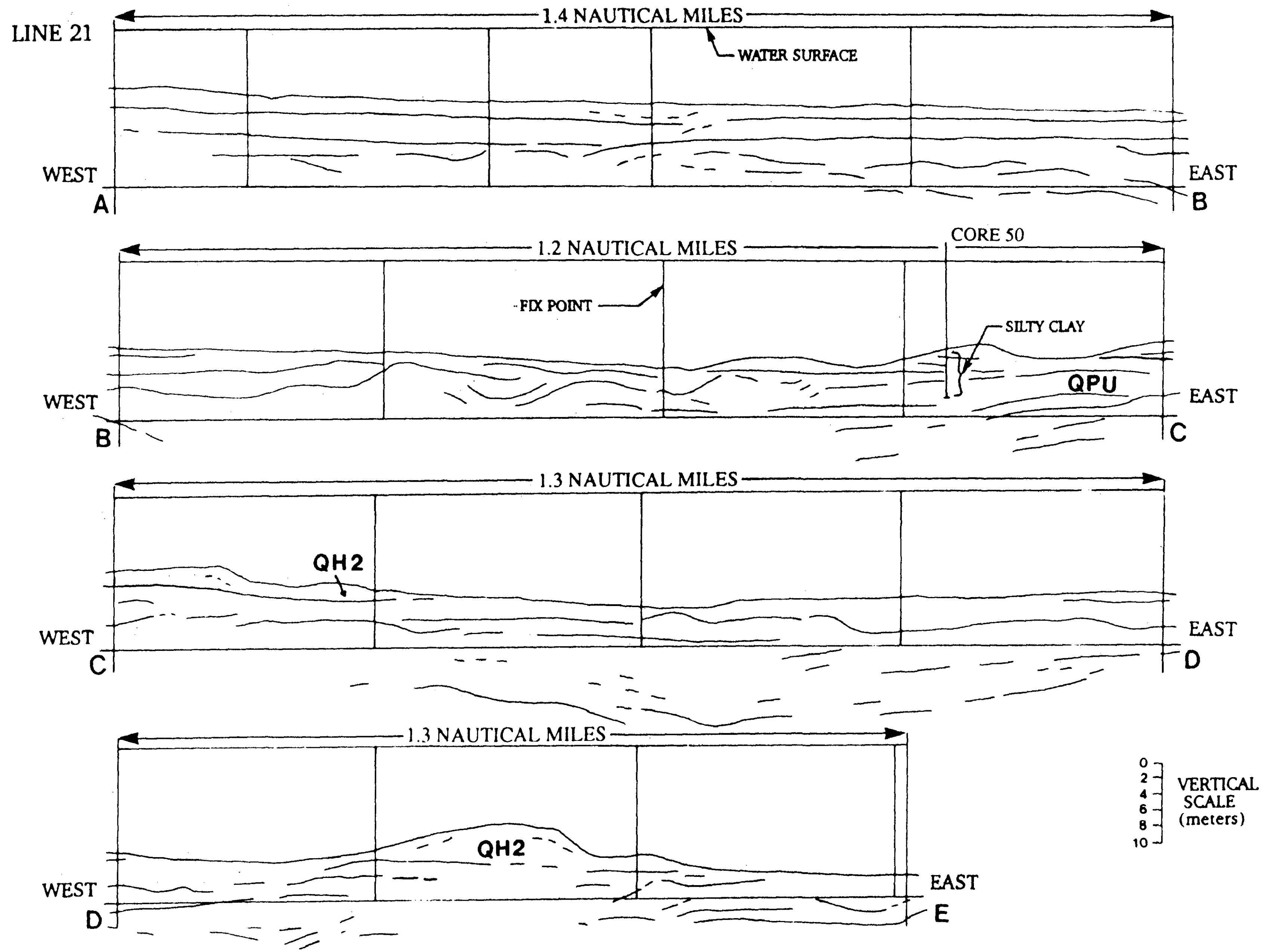
LINE 11

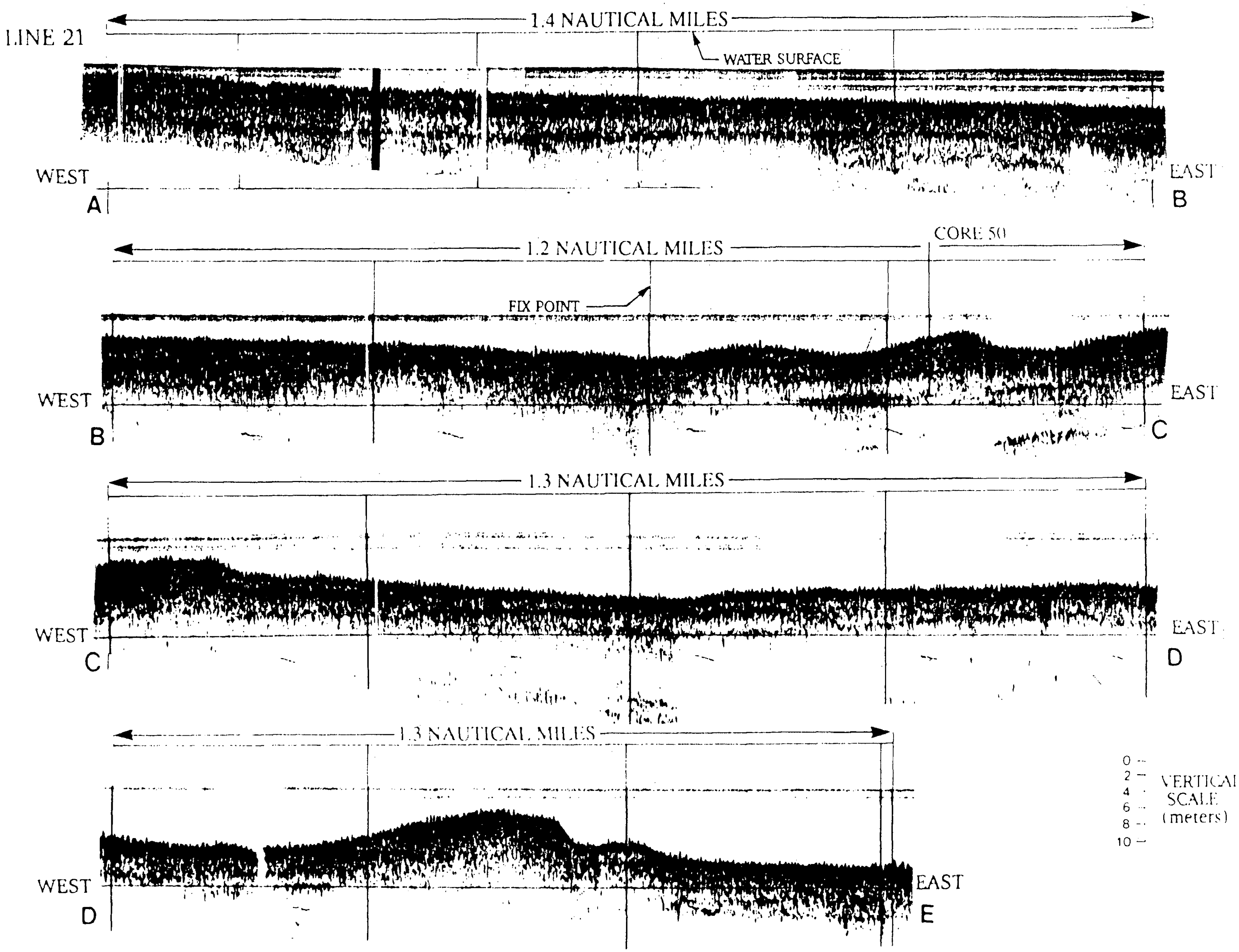

WATER SURFACE
QP4
WEST
EAST
A
1.5 NAUTICAL MILES
B
FIX POINT
QH1
QP4
QH2
QP5
QPU
WEST
EAST
B
2.0 NAUTICAL MILES
C
LINE 19
VERTICAL SCALE (meters)
0
2
4
6
8
10
CHANGE DIRECTION (SEE MAP VIEW)
EAST
WEST
EAST
C
1.3 NAUTICAL MILES
D

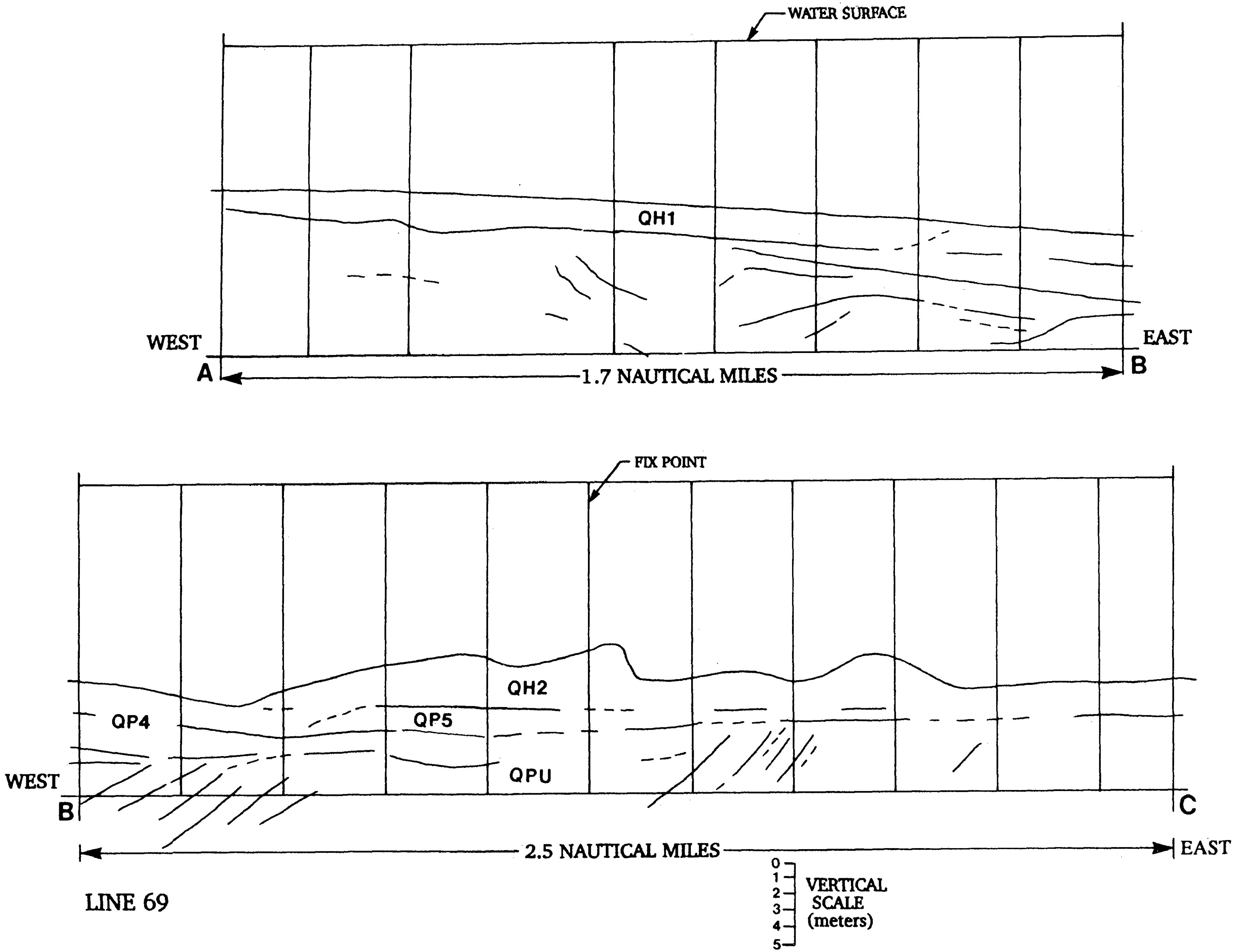

WATER SURFACE
WEST
EAST
A
1.5 NAUTICAL MILES
B
FIX POINT
WEST
EAST
B
2.0 NAUTICAL MILES
C
LINE 19
VERTICAL
SCALE
(meters)
0
2
4
6
8
10
CHANGE
DIRECTION
(SEE MAP VIEW)
EAST
WEST
EAST
C
1.3 NAUTICAL MILES
D


CORE 46
WEST
EAST
QH1
F
SDCI
MF
QP4
QP3
A
1.9 NAUTICAL MILES
B
CORE 47
CORE 48
WEST
EAST
LINE 20
QP5
QH2
F
SDCI
CM
CM
MF
QP2
QPU
VERTICAL SCALE
(meters)
0
2
4
6
8
10
B
1.3 NAUTICAL MILES
C
FIX POINT
WATER SURFACE
WEST
EAST
C
0.8 NAUTICAL MILES
D
CM - Cse-Med Sand
MF - Med-Fine Sand
M - Med Sand
F - Fine Sand
SDCl - Sandy Clay

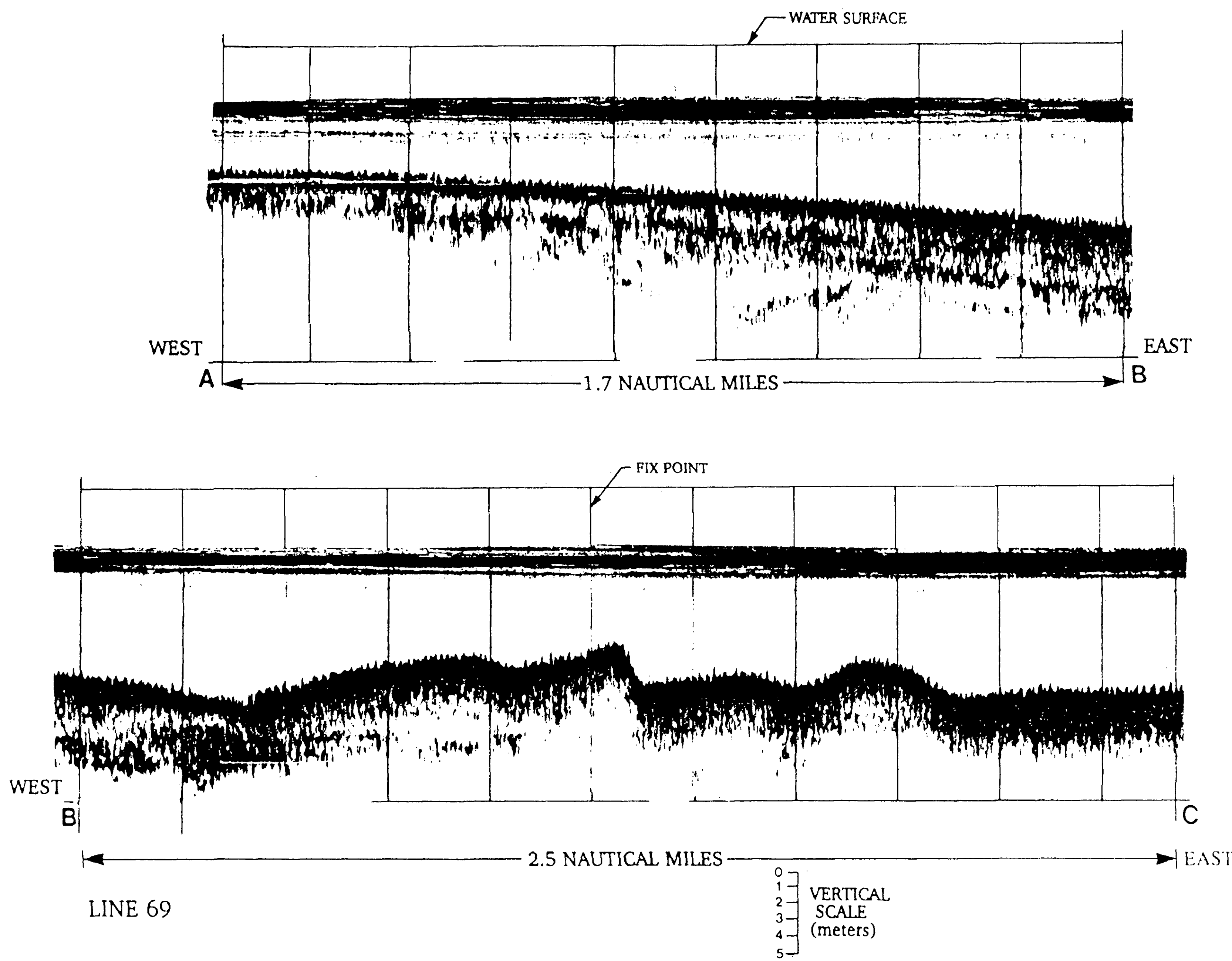

CORE 46
WEST
EAST
A
1.9 NAUTICAL MILES
B
CORE 47
CORE 48
WEST
EAST
LINE 20
VERTICAL SCALE
(meters)
0
2
4
6
8
10
B
1.3 NAUTICAL MILES
C
FIX POINT
WATER SURFACE
WEST
EAST
C
0.8 NAUTICAL MILES
D


LINE 21
1.4 NAUTICAL MILES
WATER SURFACE
WEST
A
EAST
B
1.2 NAUTICAL MILES
CORE 50
FIX POINT
SILTY CLAY
QPU
WEST
B
EAST
C
1.3 NAUTICAL MILES
QH2
WEST
C
EAST
D
1.3 NAUTICAL MILES
QH2
WEST
D
EAST
E
0
2
4
6
8
10
VERTICAL
SCALE
(meters)

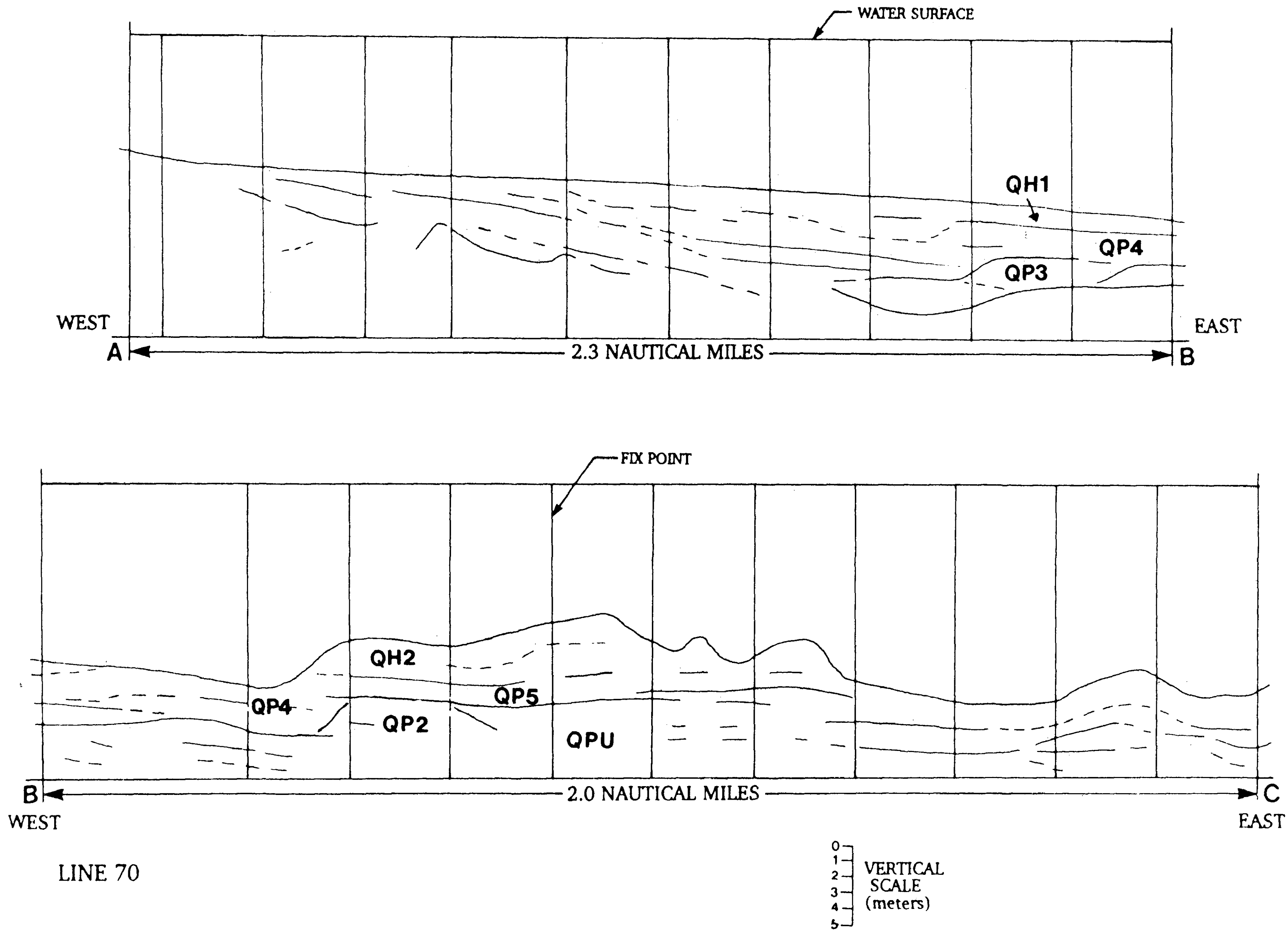

LINE 21
1.4 NAUTICAL MILES
WATER SURFACE
WEST
EAST
A
B
1.2 NAUTICAL MILES
CORE 50
FIX POINT
WEST
EAST
B
C
1.3 NAUTICAL MILES
WEST
EAST
C
D
1.3 NAUTICAL MILES
WEST
EAST
D
E
0
2
4
6
8
10
VERTICAL SCALE (meters)


WATER SURFACE
QH1
WEST
EAST
A
B
1.7 NAUTICAL MILES
FIX POINT
QH2
QP4
QP5
QPU
WEST
EAST
B
C
2.5 NAUTICAL MILES
0
1
2
3
4
5
VERTICAL
SCALE
(meters)

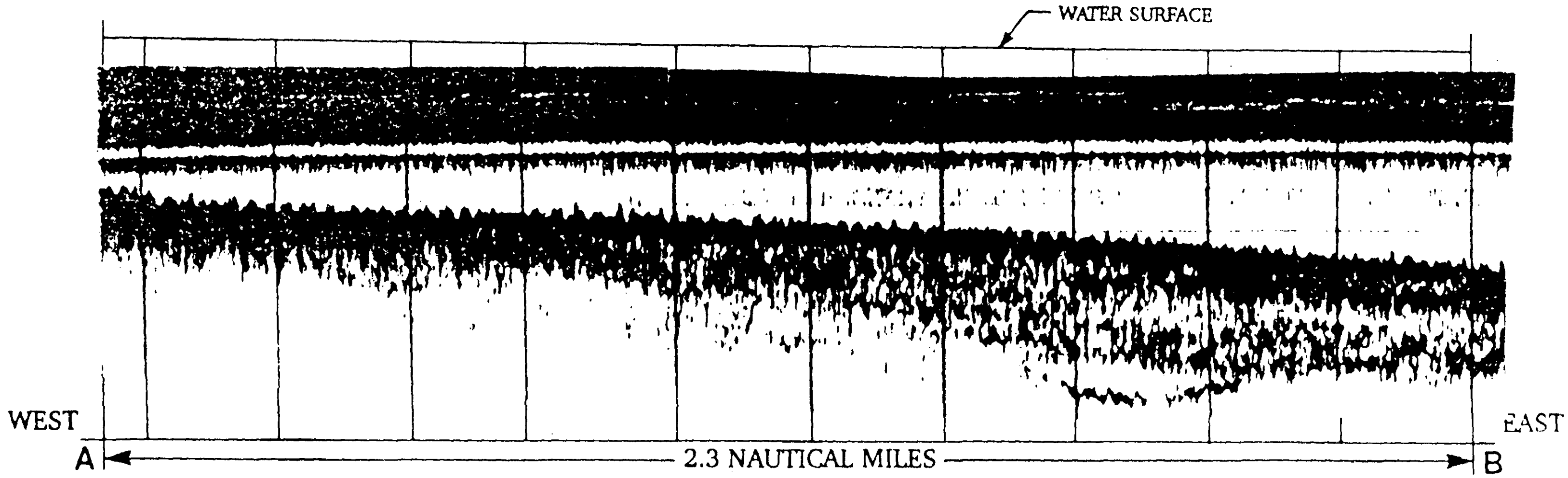
LINE 69

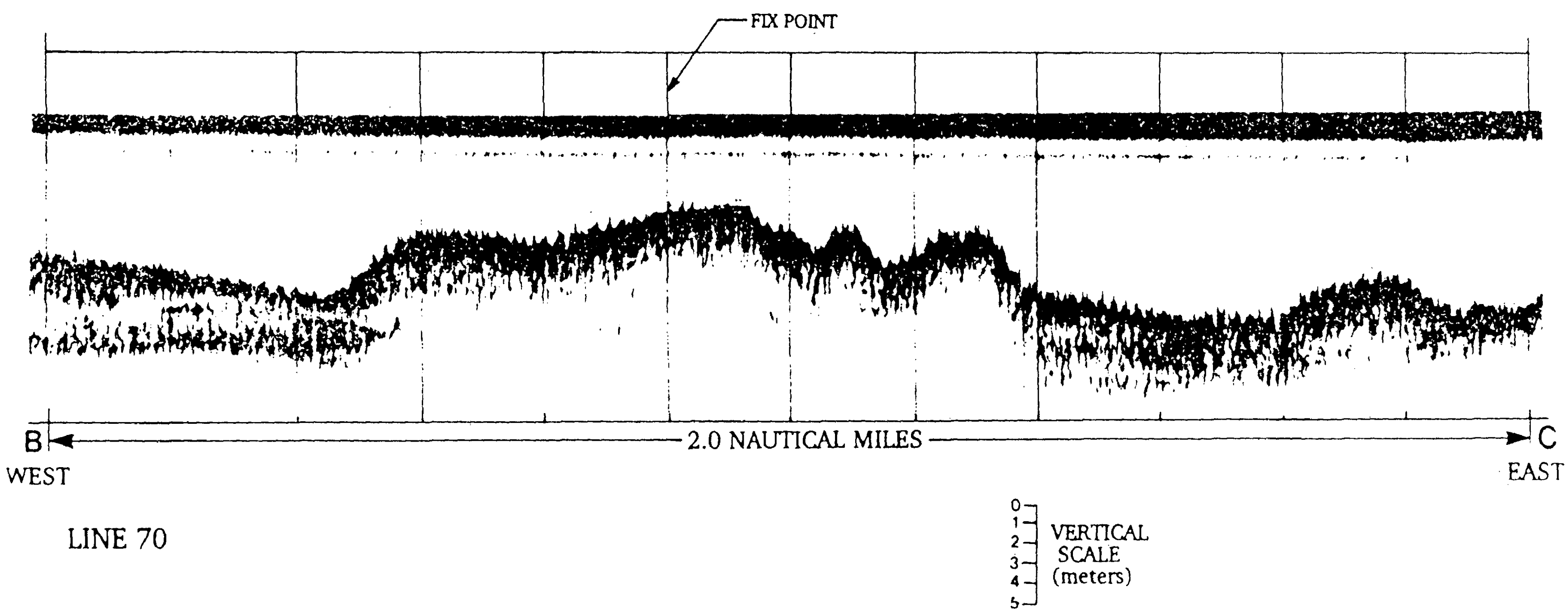

WATER SURFACE
WEST
EAST
A
B
1.7 NAUTICAL MILES
FIX POINT
WEST
B
C
2.5 NAUTICAL MILES
EAST
0
1
2
3
4
5
VERTICAL
SCALE
(meters)

LINE 69


WATER SURFACE
QH1
QP4
QP3
WEST
EAST
A
B
2.3 NAUTICAL MILES
FIX POINT
QH2
QP5
QP4
QP2
QPU
B
C
WEST
EAST
2.0 NAUTICAL MILES
0
1
2
3
4
5
VERTICAL
SCALE
(meters)

LINE 70


WATER SURFACE
WEST
EAST
A
2.3 NAUTICAL MILES
B


FIX POINT
B
2.0 NAUTICAL MILES
C
WEST
EAST
0
1
2
3
4
5
VERTICAL
SCALE
(meters)

LINE 70

LEGEND FOR PLATES

STRATIGRAPHIC UNITS

(see Table 1 for description)

QH1 - Holocene sand sheet

QH2 - Upper unit of Sandbridge Shoal

QPU - Upper Pleistocene undivided

QP5 - Lower unit of Sandbridge Shoal

QP4 - Upper Pleistocene estuarine

QP3 - Upper Pleistocene tidal channel

QP2 - Upper Pleistocene baymouth or tidal shoal

QP1 - Upper Pleistocene estuarine

QPL - Lower Pleistocene undivided

TP - Pliocene

REFLECTORS

R1 - Reflector at top of TP

R2 - Reflector separating QPU & QPL

R3 - Reflector at base of Sandbridge Shoal

R4 - Reflector separating QH2 & QP5

GRAB SAMPLE SEDIMENT DESCRIPTIONS

(see Appendix A for vibracore descriptions)

VGC - Very gravelly coarse sand

GMC - Gravelly medium to coarse sand

MC - Medium to coarse sand

MF - Medium to fine sand

VSM - Very silty medium to coarse sand

F - Fine sand

SNS - Sandy silt

SC - Silty clay

5 AA - Indicates sample number of dated material and method used

PLATE 1A

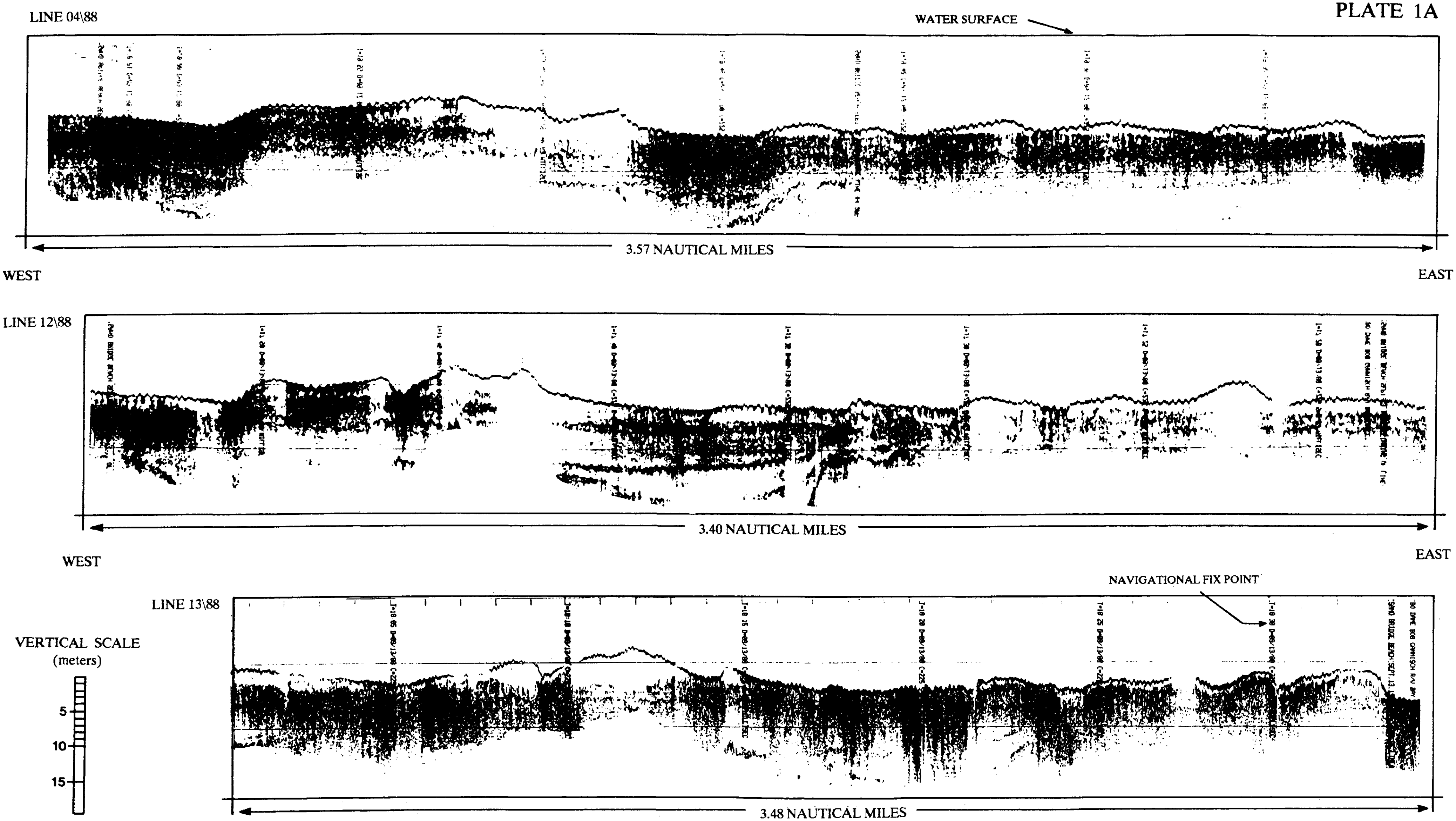

LINE 04\88
WATER SURFACE
3.57 NAUTICAL MILES
WEST
EAST
LINE 12\88
3.40 NAUTICAL MILES
WEST
EAST
NAVIGATIONAL FIX POINT
LINE 13\88
VERTICAL SCALE
(meters)
5
10
15
3.48 NAUTICAL MILES

PLATE 1B

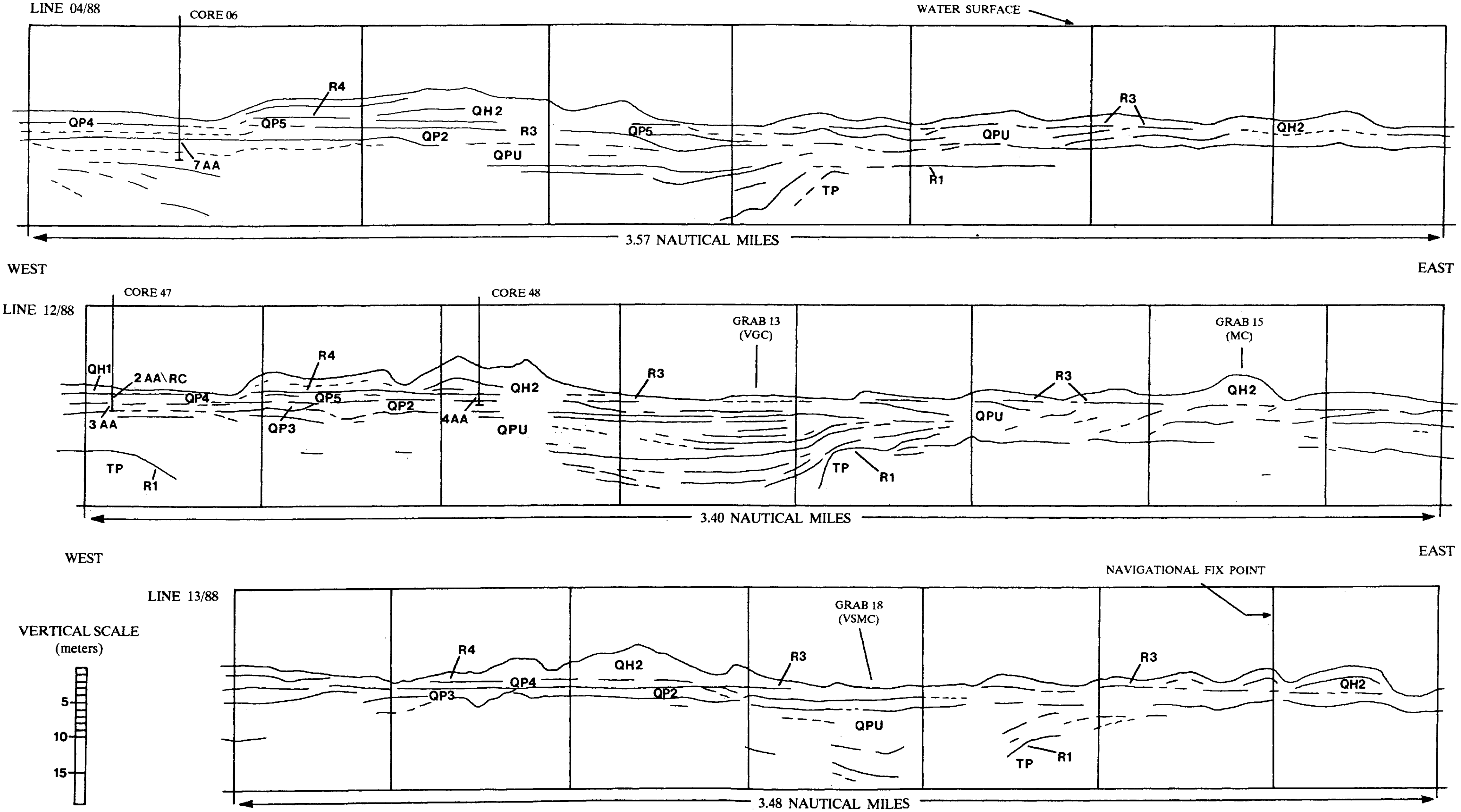

LINE 04/88
CORE 06
WATER SURFACE
R4
QH2
QP4
QP5
QP2
R3
QPU
7 AA
QP5
R3
QPU
QH2
R1
TP
3.57 NAUTICAL MILES
WEST
EAST
LINE 12/88
CORE 47
CORE 48
GRAB 13
(VGC)
GRAB 15
(MC)
QH1
2 AA\RC
QP4
R4
QP5
QP2
3 AA
QP3
4AA
QH2
QPU
R3
R3
QPU
QH2
TP
R1
TP
R1
3.40 NAUTICAL MILES
WEST
EAST
NAVIGATIONAL FIX POINT
LINE 13/88
GRAB 18
(VSMC)
VERTICAL SCALE
(meters)
5
10
15
R4
QP4
QP3
QH2
QP2
R3
QPU
R3
QH2
TP
R1
3.48 NAUTICAL MILES

PLATE 2A

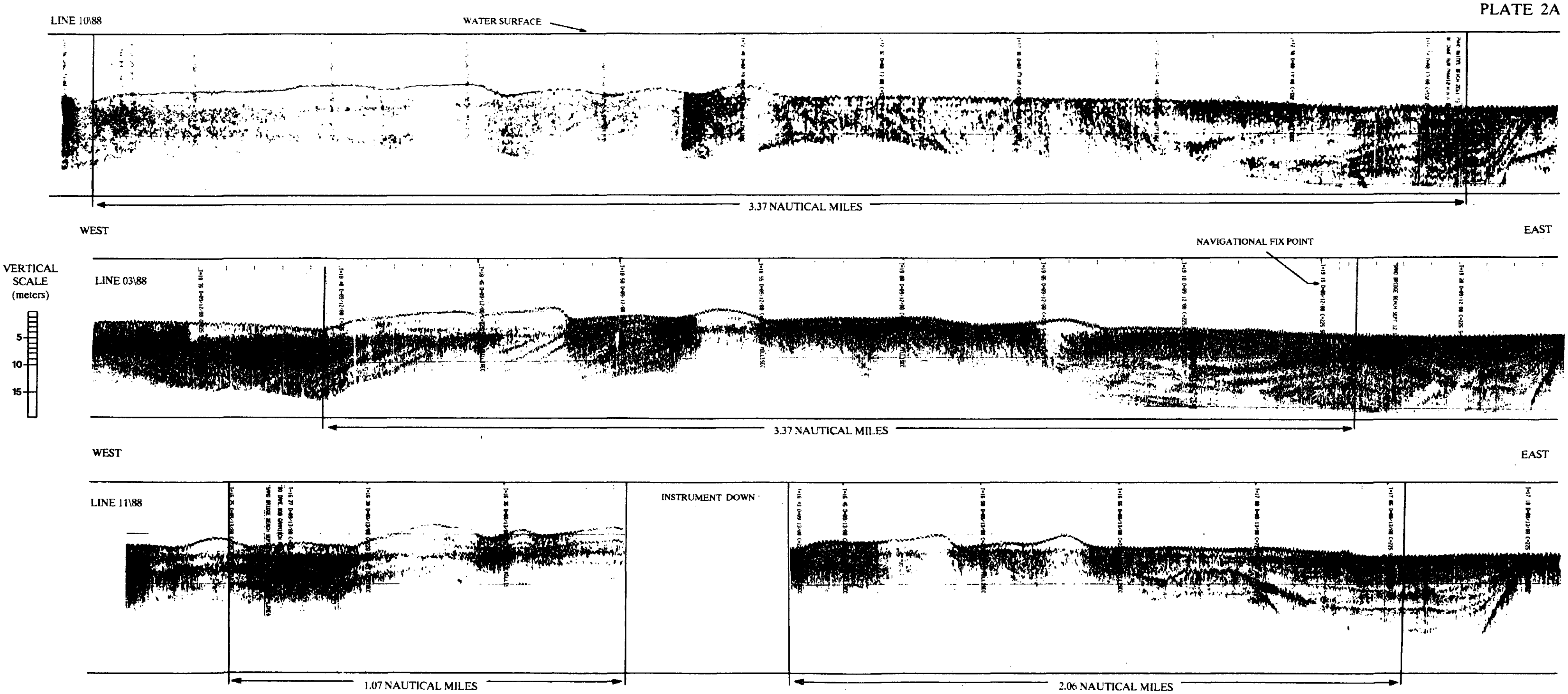

LINE 10\88
WATER SURFACE
3.37 NAUTICAL MILES
WEST
EAST
VERTICAL
SCALE
(meters)
5
10
15
LINE 03\88
NAVIGATIONAL FIX POINT
3.37 NAUTICAL MILES
WEST
EAST
LINE 11\88
INSTRUMENT DOWN
1.07 NAUTICAL MILES
2.06 NAUTICAL MILES

PLATE 2B

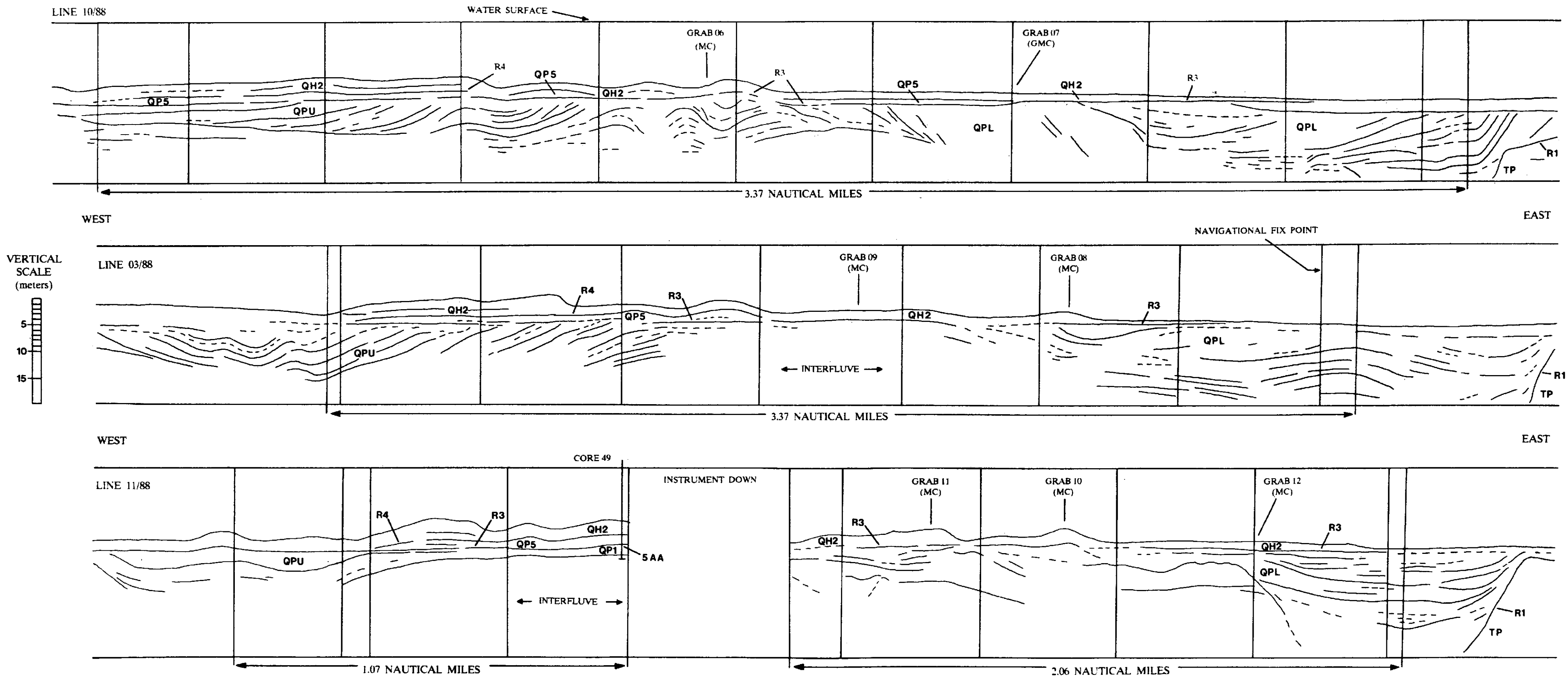

LINE 10/88
WATER SURFACE
GRAB 06
(MC)
GRAB 07
(GMC)
R4
QP5
QH2
QPU
R3
QPL
R1
TP
3.37 NAUTICAL MILES
WEST
EAST
VERTICAL
SCALE
(meters)
5
10
15
LINE 03/88
GRAB 09
(MC)
GRAB 08
(MC)
NAVIGATIONAL FIX POINT
INTERFLUVE
3.37 NAUTICAL MILES
WEST
EAST
LINE 11/88
CORE 49
INSTRUMENT DOWN
GRAB 11
(MC)
GRAB 10
(MC)
GRAB 12
(MC)
QP1
5AA
INTERFLUVE
1.07 NAUTICAL MILES
2.06 NAUTICAL MILES

PLATE 3A

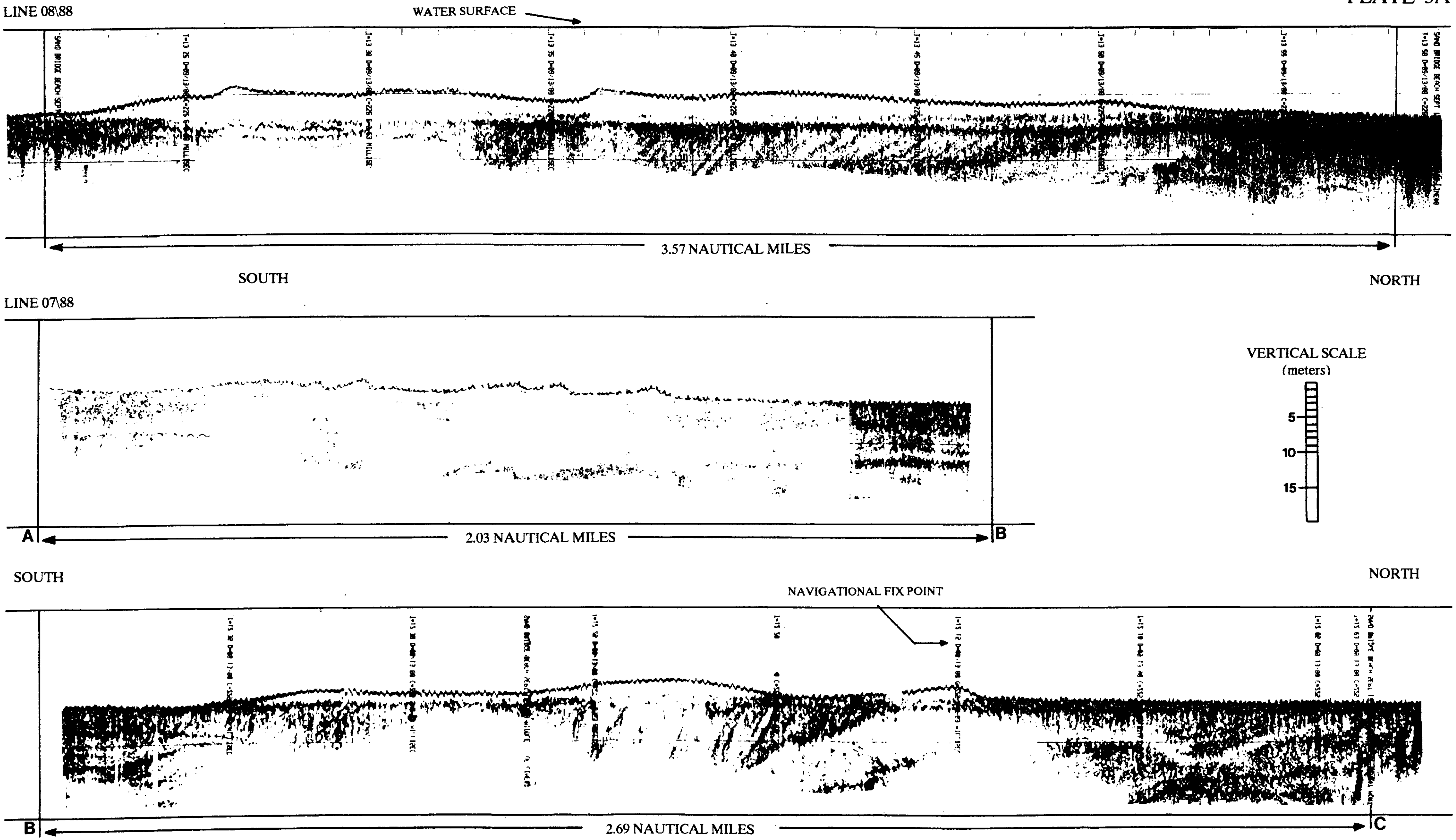
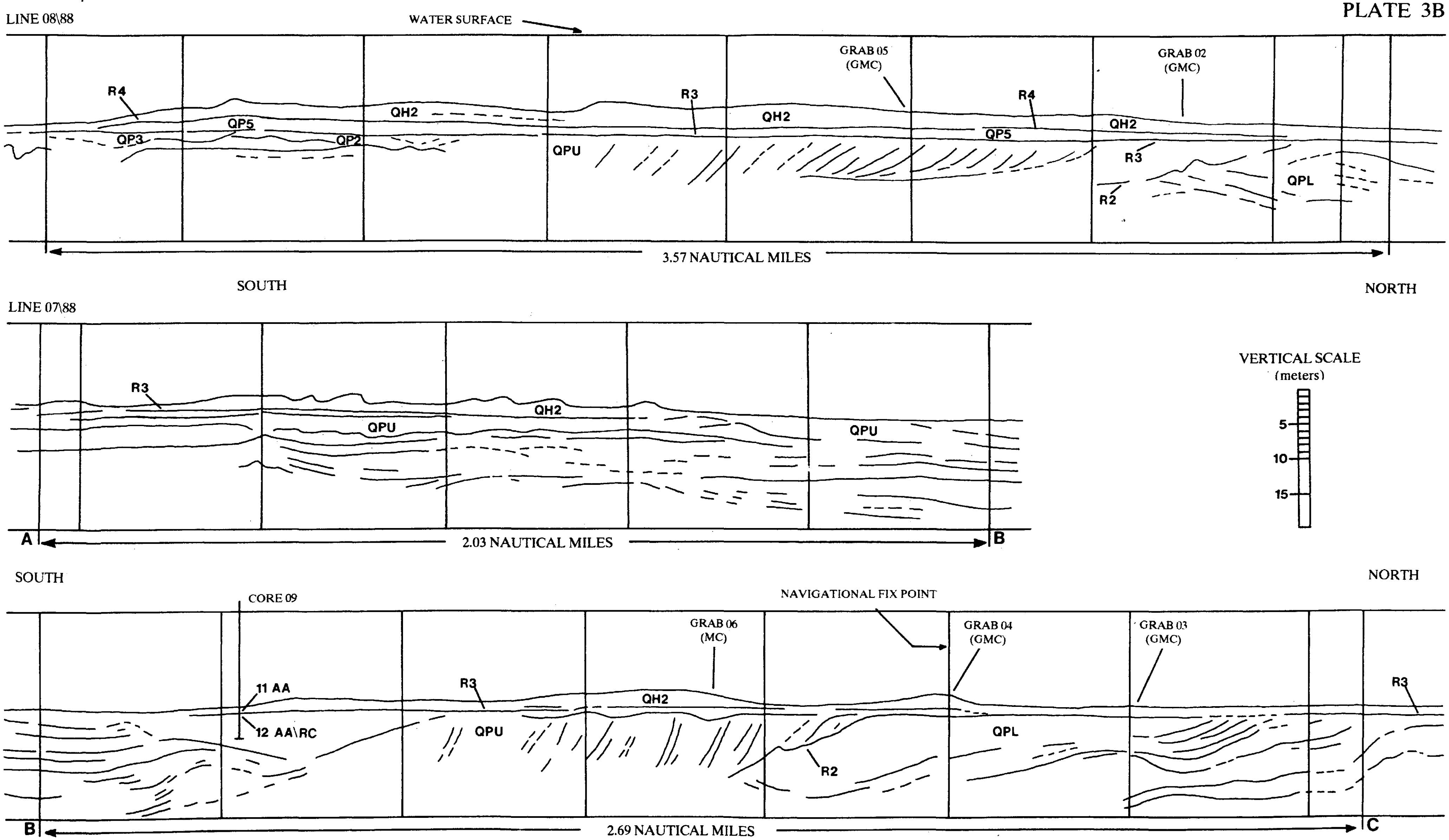

LINE 08\88
WATER SURFACE
3.57 NAUTICAL MILES
SOUTH
NORTH
LINE 07\88
VERTICAL SCALE
(meters)
5
10
15
A
2.03 NAUTICAL MILES
B
SOUTH
NORTH
NAVIGATIONAL FIX POINT
B
2.69 NAUTICAL MILES
C

PLATE 3B



LINE 08\88
WATER SURFACE
GRAB 05 (GMC)
GRAB 02 (GMC)
R4
R3
QH2
QP5
QP3
QP2
QPU
R2
QPL
3.57 NAUTICAL MILES
SOUTH
NORTH
LINE 07\88
QPU
A
B
2.03 NAUTICAL MILES
VERTICAL SCALE (meters)
5
10
15
CORE 09
NAVIGATIONAL FIX POINT
GRAB 06 (MC)
GRAB 04 (GMC)
GRAB 03 (GMC)
11 AA
12 AA\RC
C
2.69 NAUTICAL MILES

PLATE 4A

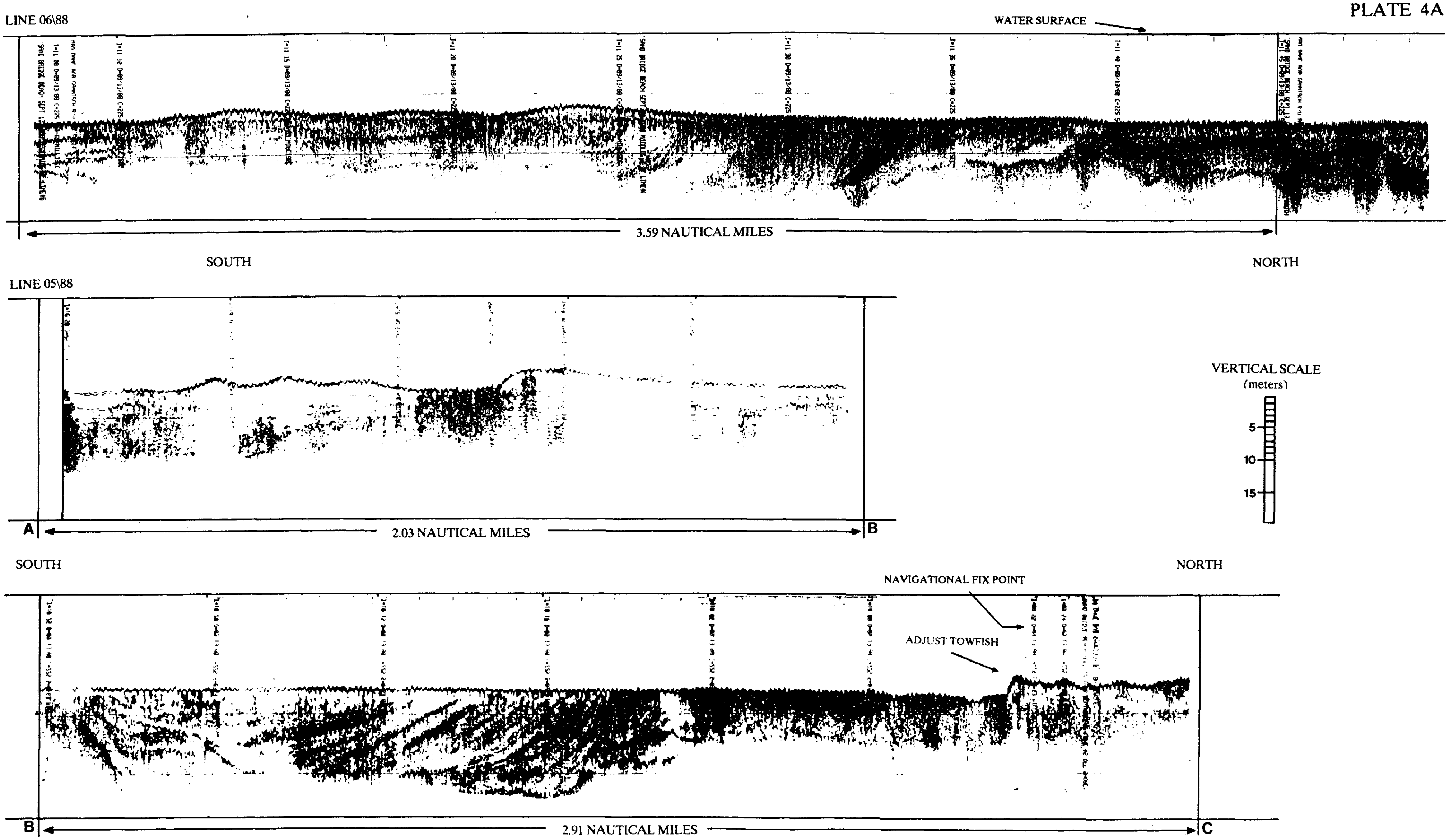
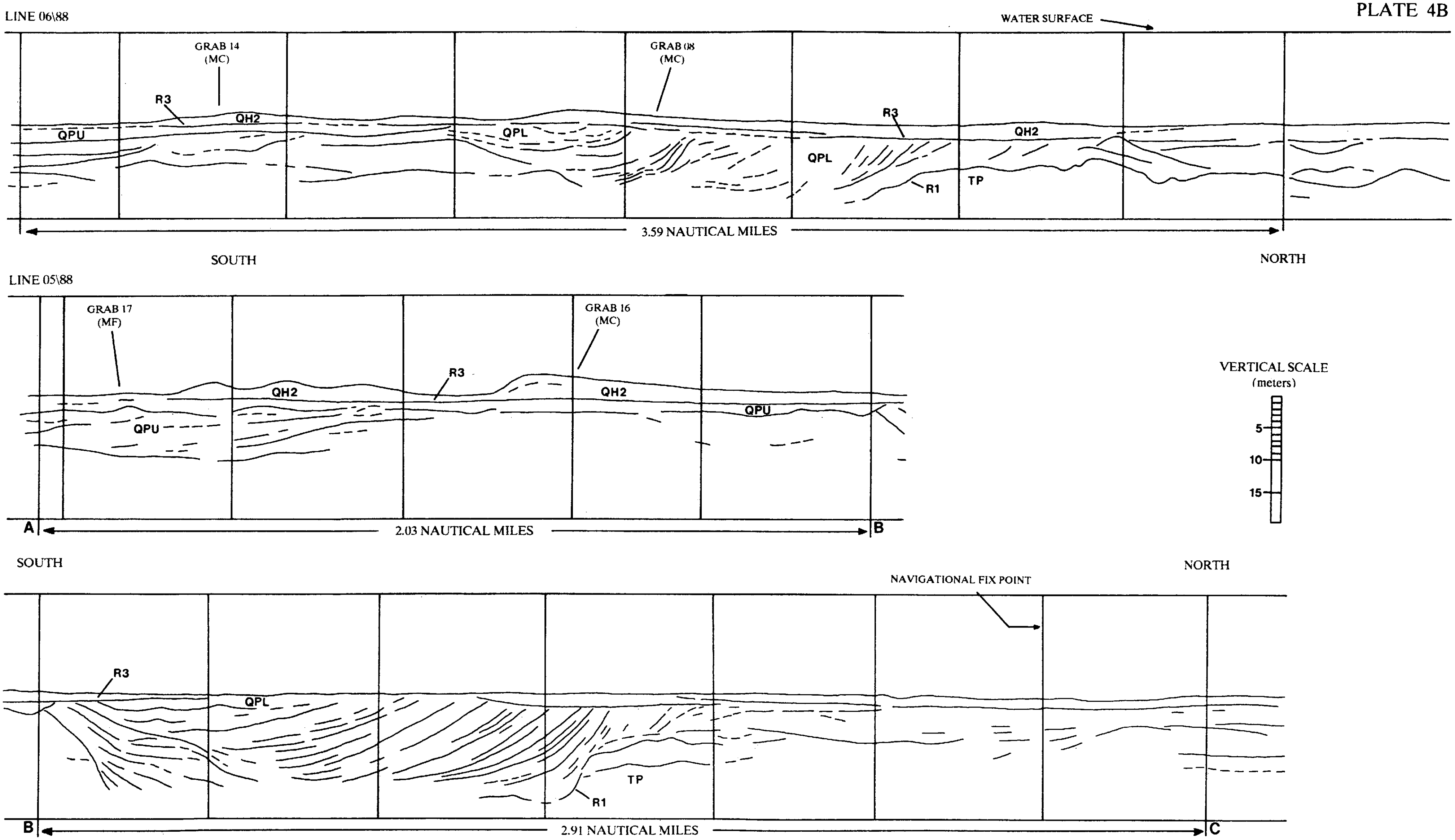
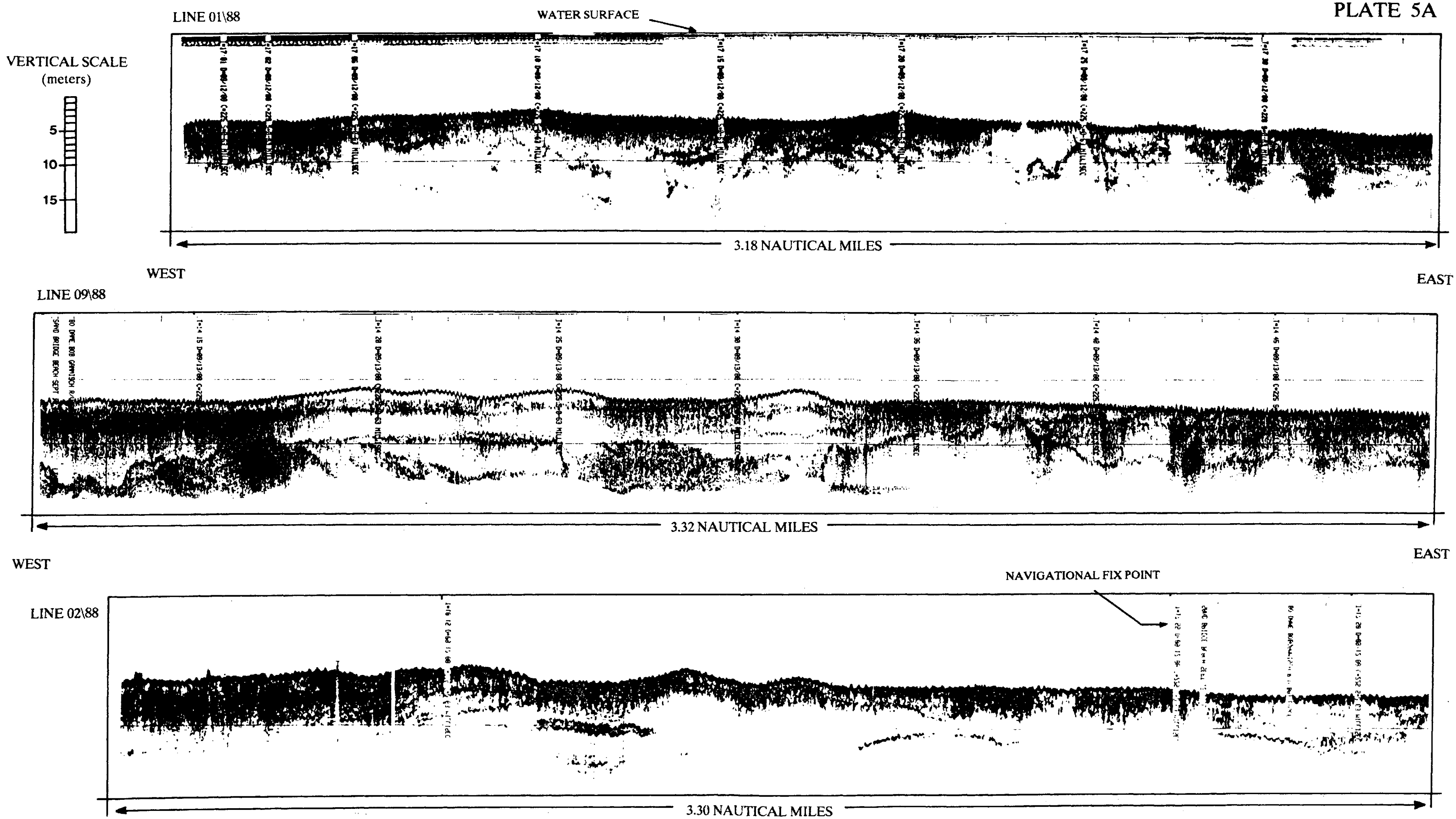

LINE 06\88
WATER SURFACE
3.59 NAUTICAL MILES
SOUTH
NORTH
LINE 05\88
A
2.03 NAUTICAL MILES
B
VERTICAL SCALE
(meters)
5
10
15
SOUTH
NORTH
NAVIGATIONAL FIX POINT
ADJUST TOWFISH
B
2.91 NAUTICAL MILES
C

PLATE 4B



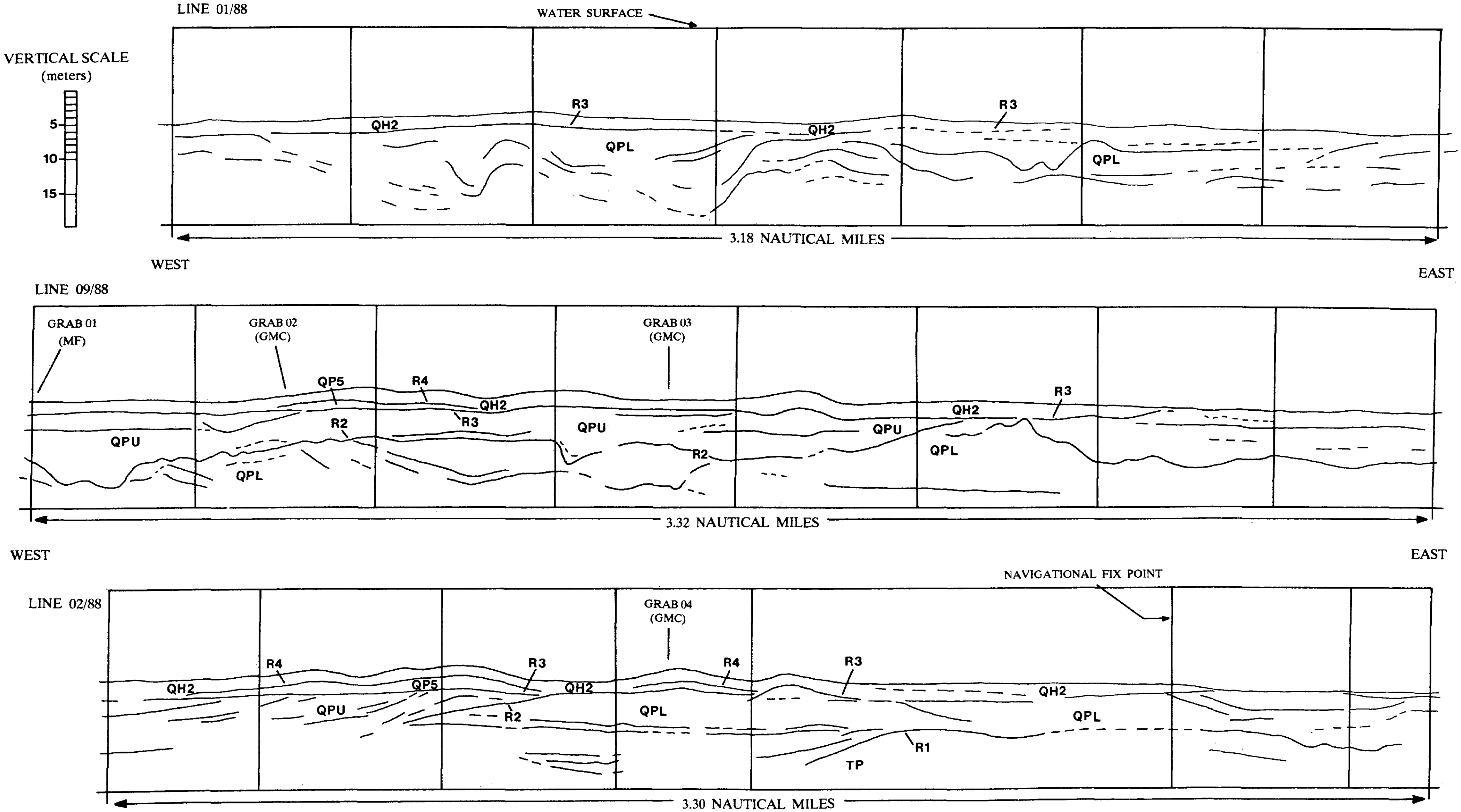
LINE 06\88
WATER SURFACE
GRAB 14
(MC)
GRAB 08
(MC)
R3
QH2
QPU
QPL
R3
QH2
QPL
R1
TP
3.59 NAUTICAL MILES
SOUTH
NORTH
LINE 05\88
GRAB 17
(MF)
GRAB 16
(MC)
R3
QH2
QH2
QPU
QPU
A
2.03 NAUTICAL MILES
B
VERTICAL SCALE
(meters)
5
10
15
SOUTH
NORTH
NAVIGATIONAL FIX POINT
R3
QPL
TP
R1
B
2.91 NAUTICAL MILES
C

PLATE 5A



LINE 01\88
WATER SURFACE
VERTICAL SCALE
(meters)
5
10
15
3.18 NAUTICAL MILES
WEST
EAST
LINE 09\88
3.32 NAUTICAL MILES
WEST
EAST
NAVIGATIONAL FIX POINT
LINE 02\88
3.30 NAUTICAL MILES

PLATE 5B


LINE 01/88
WATER SURFACE
VERTICAL SCALE (meters)
5
10
15
R3
QH2
QPL
QH2
R3
QPL
3.18 NAUTICAL MILES
WEST
EAST
LINE 09/88
GRAB 01 (MF)
GRAB 02 (GMC)
GRAB 03 (GMC)
QP5
R4
QH2
R2
R3
QPU
QPU
R2
QPL
QPU
QH2
R3
QPL
3.32 NAUTICAL MILES
WEST
EAST
NAVIGATIONAL FIX POINT
LINE 02/88
GRAB 04 (GMC)
R4
QH2
QP5
R3
QH2
R4
R3
QPU
R2
QPL
QH2
QPL
R1
TP
3.30 NAUTICAL MILES