BATHYMETRIC MAPS AND GEOMORPHOLOGY OF THE MIDDLE ATLANTIC CONTINENTAL SHELF

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ABSTRACT

Large-scale bathymetric maps covering the northern two-thirds of the Middle Atlantic Continental Shelf have recently been published. They were compiled at a scale of 1:125,000 from 39 smooth sheets and are contoured in 1-fm. (1.8 m.) intervals on the shelf and in 10-fm. (18.3 m.) intervals on the upper slope.

Part 1 of this report discusses the construction and reliability of these maps. In addition, a short review of surveys made in the mapped area is given, a few uses for the maps are suggested, and the reliability diagrams (which appear on each map) are explained.

Part 2 discusses the past geologic history, the general distribution of sediments, and the major geomorphic processes at work in the area. In addition, the several physiographic regions and features on the Middle Atlantic Shelf are described in terms of their topography and sediments.

The Middle Atlantic Continental Shelf is one of the world's most studied shelf areas. The 60,000 square nautical miles [1] of drowned coastal lowland making up its surface have long been of interest to mariners, commercial fishermen, and scientists. Numerous nautical chart surveys, oceanographic studies, and geophysical, geological, and biological investigations have been made in the area (Geyer, 1948; Drake, Ewing, and Sutton, 1959; Heezen, Tharp, and Ewing, 1959; Murray, 1961; Drake, Heirtzler, and Hirshman, 1963; Stearns, 1963; Uchupi, 1963; Livingstone, 1965; and Emery, 1966b).

The Middle Atlantic Continental Shelf borders one of the world's largest concentrations of human activity. Called Megalopolis by Gottmann (1961), this region contains almost one-fifth of the population of the United States and is a vast market for marine resources of all kinds. The shelf supplies Megalopolis with commercial and sport fisheries, recreation on the seashores, mineral resources, and space for waste disposal. The need for detailed bathymetric maps in the study of Continental Shelf geology, geomorphology, and mineral resources is well known (Veatch and Smith, 1939; Emery and Schlee, 1963; Emery, 1966b). Less widely appreciated, but equally important, are the uses of such maps in the synthesis and study of physical and biological data.

The shape of the sea floor can influence the movement of water masses on the shelf, and this movement can affect the distribution of such oceanographic properties as temperature, salinity, and nutrient elements (Bigelow, 1931; Hachey, Lauzier, and Bailey, 1956; Trites, 1956). Although only a few benthonic animals are known to respond directly to the shape of the bottom (e.g., see Yonge, 1962), all marine animals respond to the distribution of water-mass properties, which are affected by the bottom. Hence, definite correlations exist between the shape of the bottom and the locations of marine animals (see Parker and Curray, 1956), and detailed studies of environmental relations on the shelf require a detailed knowledge of bathymetry.

[1] I use English fathoms and nautical miles throughout the paper because all the data were collected in English rather than metric units. For conversion, 1 fm. equals 1.83 m., and 1 nautical mile equals 1.85 km.

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Large-scale bathymetric maps covering the northern two-thirds of the Middle Atlantic Continental Shelf (fig. 1) have recently been published by Stearns and Garrison (1967). These maps are contoured in 1-fm. intervals from the shore to 100 fm. and in 10-fm. intervals from 100 to 500 fm. and are drawn on a Mercator projection at a nominal scale of 1 : 125,000.

The present maps can be used in a variety of ways, such as (1) interpolation aids when mapping physical data, (2) foundations for the analysis of relations between physical features and biological distributions, and (3) sources of information for the efficient planning of stratified sampling programs and surveys.

The purpose of this paper is to describe these maps, their construction and reliability, and to discuss the geomorphology of the mapped region.

PART 1. BATHYMETRIC MAPS

The proper use of bathymetric maps requires some knowledge of how they were made, as well as an estimate of their reliability. These topics are discussed in this part of the report.

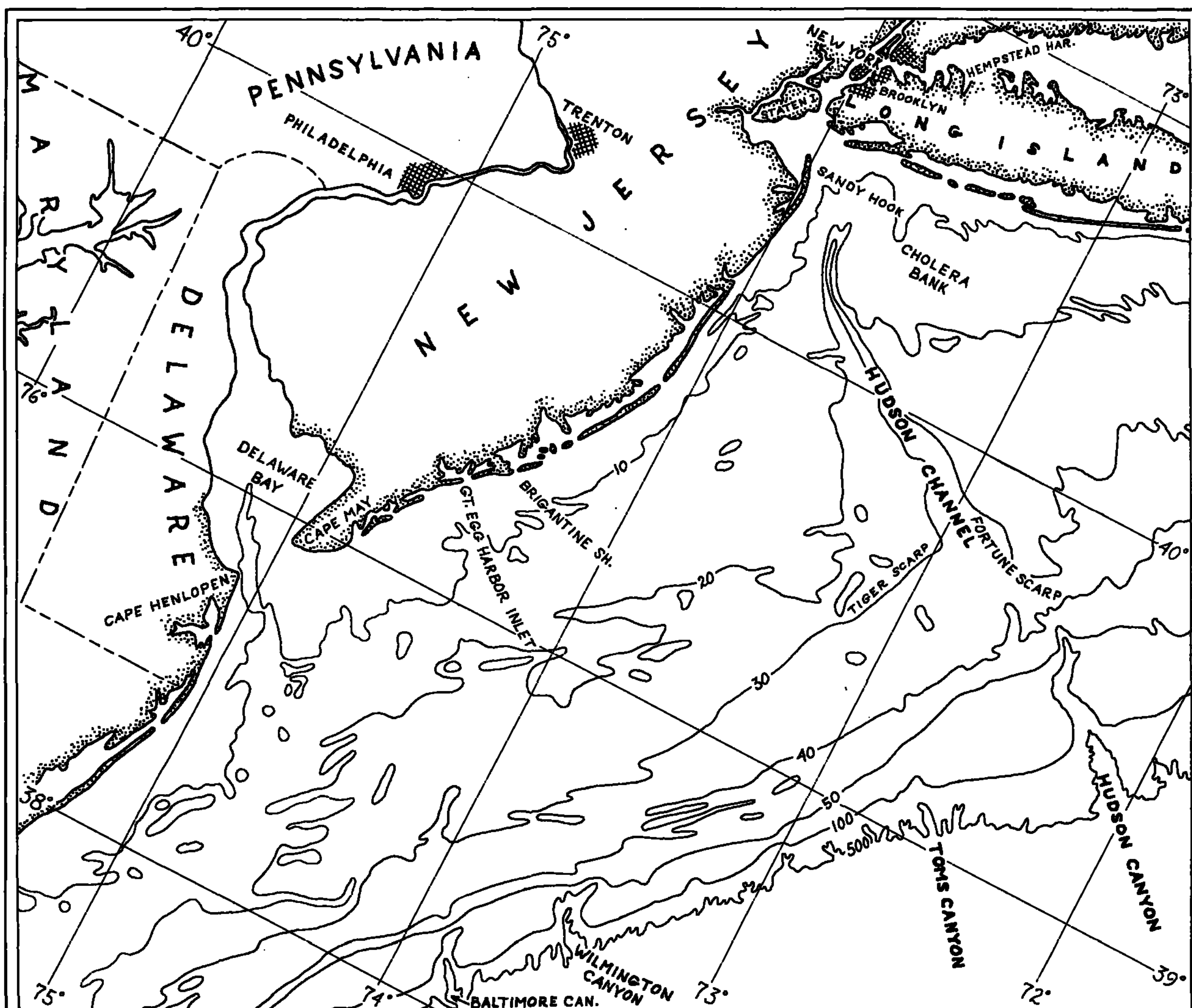


FIGURE 1.—Generalized bathymetry of the Middle Atlantic Continental Shelf and locations of major features discussed in the text. Depth contours in fathoms. Sources: USCGS Chart 1000 (13th ed., 1949) and Stearns and Garrison (1967).

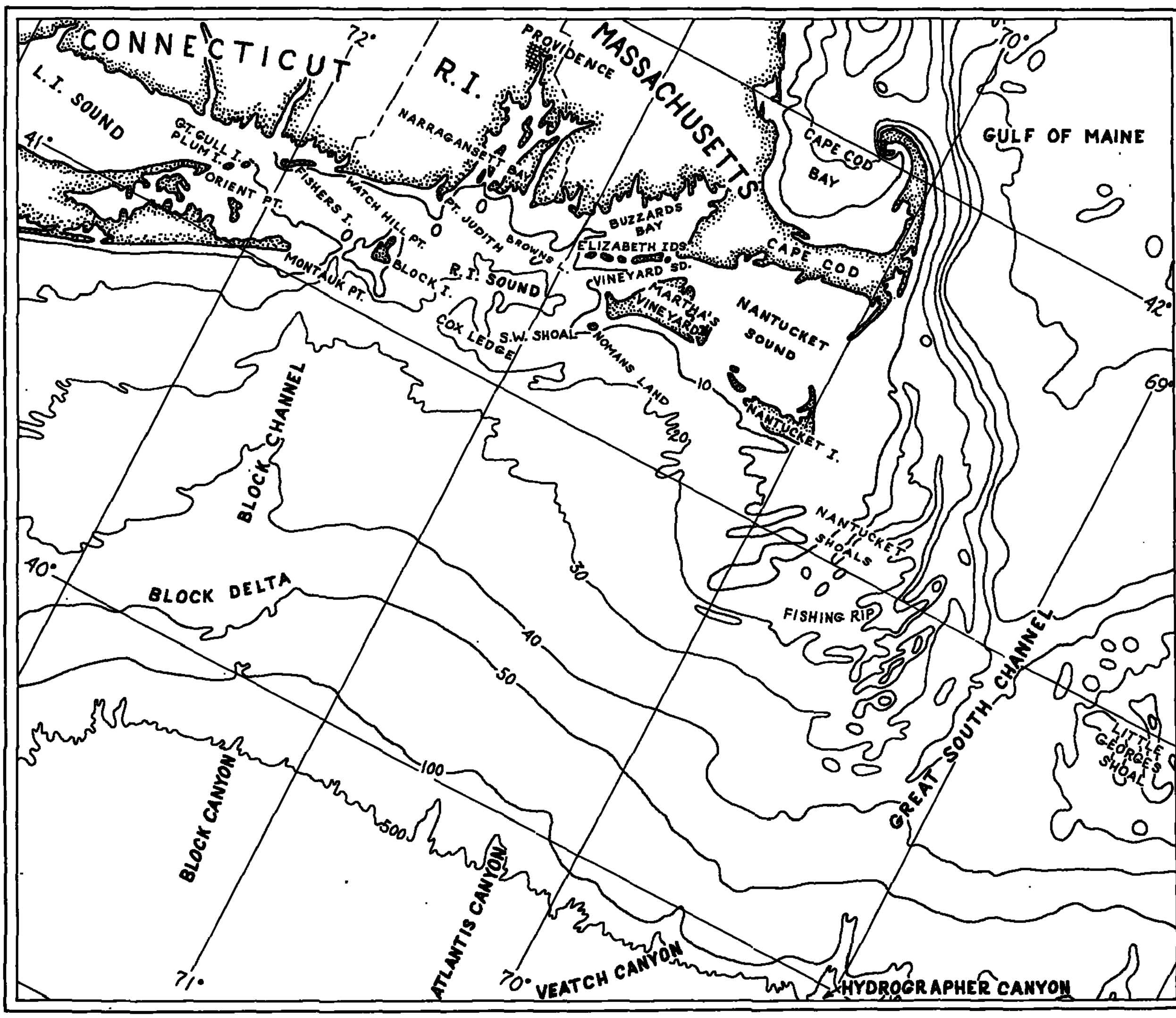
CONSTRUCTION OF THE MAPS

Construction of the maps is discussed from three aspects: (1) history of past surveys, (2) study of present surveys, and (3) methods of construction.

Past Bathymetric Surveys

The first systematic bathymetric survey of the entire width of the Middle Atlantic Continental Shelf was made by the U.S. Coast Survey in 1842 (USCGS Hydrographic Survey no. 100, scale 1:400,000). Previously, only some inshore areas had been systematically surveyed, and charts of the offshore regions were based on a few isolated soundings. The 1842 survey covered the area between Rhode Island Sound and Cape May and from near shore to a little over 100 fm. It was supplemented in 1844 by a survey covering much the same area (no. 101, scale 1:400,000) and again in 1859 by a survey extending from Martha's Vineyard to slightly south of Cape Henlopen, Del. (no. 670, scale 1:400,000).

No surveys were made during the Civil War, but in the 1870's and 1880's much sounding was



done on the Continental Slope and in the adjacent ocean basins, largely as a result of (1) an increased interest in the life of abyssal regions, (2) increasing activity in the laying of submarine telegraph cables, and (3) the development of deep sea wire-sounding machines (Agassiz, 1888; Tanner, 1897). From 1877 to 1880 Alexander Agassiz (1888) directed surveys aboard the Coast Survey ship *Blake* along the Atlantic Continental Slope, but it was not until 1882 that the shelf itself was again surveyed, this time from Montauk Point, Long Island, to Cape Henlopen, Del. (no. 1558, scale 1:300,000). This survey was extended south to Cape Charles in 1886 (no. 1720, scale 1:200,000) and to the east as far as Georges Bank during 1887–1889 (nos. 1782, scale 1:300,000; and 1837, scale 1:400,000). In all of these early surveys, the soundings were by lead line and the navigation was by shore sightings, astronomical fixes, and dead reckoning.

Except for a few isolated investigations of shoal areas, the Middle Atlantic Shelf was not again systematically surveyed until the 1930's, when new sounding and navigational methods had been developed. These surveys, from Georges Bank to Cape Henry and from the shore to the Continental Slope and Rise, are the principal sources used for constructing the maps discussed in this paper.

Several earlier bathymetric maps were based on the surveys of the 1930's. The first and most famous are the maps of Veatch and Smith (1939)—see also Smith (1939). These authors compiled a series of charts of the Continental Slope from Georges Bank to Chesapeake Bay and of the Hudson Channel region of the shelf (scale 1:120,000). Uchupi (1965), in cooperative work by the Woods Hole Oceanographic Institution and the U.S. Geological Survey, used the surveys to compile a 1:1,000,000 scale map of the shelf, slope, and rise from southern Canada to the Straits of Florida. In addition, the USCGS has used the surveys to construct nautical charts of the region at scales of 1:80,000 and 1:400,000 (see the 1100 and 1200 series of nautical charts). The surveys have also been used for small maps, published as text illustrations (e.g., Elliott, Myers, and Tressler, 1955; Garrison and McMaster, 1966).

Present Data Sources

The data from 39 USCGS hydrographic surveys, made between 1932 and 1961, were used for making the present maps. (The smooth sheets of these surveys vary in scale from 1:20,000 to 1:120,000.) In addition, 25 published USCGS nautical charts (scales 1:10,000 to 1:80,000) were used for some nearshore areas, bays, sounds, and harbors. The land contours which appear on some sheets were compiled from U.S. Geological Survey and Army Map Service topographic quadrangle maps (scales 1:24,000 and 1:62,500). The Long Island contours are from a topographic map of the Island, scale 1:125,000, appearing in Fuller (1914).

More bathymetric information exists than was used in the present compilation. Many miles of sounding lines have been run on the Middle Atlantic Continental Shelf by the research ships of various government agencies, private research institutions, and universities. Many of these data are equal in quality to those used, but most have not been reduced and plotted in a form that can be readily contoured.

The new developments in the surveys of the 1930's were echosounding and radio-acoustic ranging. Echosounding was developed in both the United States and Europe during the first part of this century, and by 1923 the USCGS had installed their first echosounder. This method of measuring depths was rapidly improved and soon replaced the older lead line and wire-sounding machine. Before the 1930's, positions were determined in much the same manner as they were in 1842 and before. During the early 1920's, offshore positioning had developed into an elaborate system of precise dead reckoning, but it was not until the USCGS introduced radio-acoustic ranging in 1924 that methods of navigation were changed fundamentally (Adams, 1942). This new method was continually improved throughout the surveys of the 1930's and was replaced by wholly electronic systems during the 1940's.

Methods of Construction

Bathymetric contour lines were drawn directly on either (1) full-scale, corrected copies of the original surveys (smooth sheets), or (2) on nautical charts of nearshore areas. Louis E. Garrison contoured the area between about long. 69°25′ and 72°00′ W. and shallower than about 100 fm. (US CGS Hydrographic Surveys 6331, 6347, 6440, 6441, and 6447). I contoured the rest of the area.

This contoured source material was transferred by pantograph to dimensionally stable plastic compilation sheets at a uniform scale of 1:125,000 (Mercator projection, scale of 1:125,000 at lat. 40° N.); each sheet covered 1° of latitude and longitude. Transfer was done in stages for each piece of source material; small quadrangles were transferred independently to minimize distortion of scale and paper. Adjustment and matching between surveys, corrections, and final smoothing of the isobaths were done on the compilation sheets. The USCGS made the final map layout and design.

RELIABILITY OF THE MAPS

Present technology makes it impractical to observe large areas of the sea floor directly; thus, bathymetric maps are necessarily interpretive drawings of an invisible surface (for discussions of this subjective element in bathymetric mapping see Veatch and Smith, 1939; Jones, 1941; and Shepard, 1943). Such maps are usually made from discrete soundings, between which assumed depths must be interpolated before contour lines of constant depth (isobaths) can be drawn. The uncertainty of these assumed depths, plus observational and positional errors in the original soundings, makes exact correspondence between a bathymetric map and the real sea floor an impossibility. The user of a map, however, should know what accuracy to expect.

The following paragraphs of this section discuss the evaluation of the reliability of the maps, the reliability diagrams which appear on each map, and the spatial distribution of the map errors.

A general method for quantitative estimate of the reliability of isoline maps has been presented by Stearns (1968). In this general method the reliability of isolines (expressed as a variance) is related to (1) observational errors, (2) positional errors, (3) interpolation errors, (4) errors in the time of an observation, (5) synopticity errors (errors due to lack of simultaneity in the observations), and (6) the space-time rates-of-change and the directions of the gradients of the mapped variable.

In applying the method to the present bathymetric maps, I considered all the above factors, with the exception of time and synopticity errors. I omitted the time-dependent errors, first, because little exact information is available on the rates-of-change of bottom topography, and, second, because such changes, except in limited areas, are likely to be very small during the period of useful life of the maps.

The reliability equations (Stearns, 1968), with the time-dependent terms omitted, are as follows:

$$\bar{\epsilon}_3=\bar{e}_0+\bar{e}_p\bar{g}_p\,\overline{\mathrm{Cos}}\,\gamma_p+\bar{e}_l\bar{g}_l\,\overline{\mathrm{Cos}}\,\gamma_l+\bar{e}_l{}'\bar{g}_l{}'\,\overline{\mathrm{Cos}}\,\gamma_l{}' \tag{1}$$

which expresses the expected bias of the values of the isobaths at any point on the map or within any subarea of the map, and

$$\begin{aligned} V_{\epsilon_3}=\,&V_{e_0}+V_{e_p}(V_{g_p}+\bar{g}_p^2)\,(V_{\mathrm{Cos}\,\gamma_p}+\overline{\mathrm{Cos}^2}\,\gamma_p)\\ &+\bar{e}_p^2(V_{g_p}[V_{\mathrm{Cos}\,\gamma_p}+\overline{\mathrm{Cos}^2}\,\gamma_p]+\bar{g}_p^2V_{\mathrm{Cos}\,\gamma_p})\\ &+V_{e_l}(V_{g_l}+\bar{g}_l^2)\,(V_{\mathrm{Cos}\,\gamma_l}+\overline{\mathrm{Cos}^2}\,\gamma_l)\\ &+\bar{e}_l^2(V_{g_l}[V_{\mathrm{Cos}\,\gamma_l}+\overline{\mathrm{Cos}^2}\,\gamma_l]+\bar{g}_l^2V_{\mathrm{Cos}\,\gamma_l})\\ &+V_{e_l}{}'(V_{g_l}{}'+\bar{g}_l{}'^2)(V_{\mathrm{Cos}\,\gamma_l}{}'+\overline{\mathrm{Cos}^2}\,\gamma_l{}')\\ &+\bar{e}_l{}'^2(V_{g_l}{}'[V_{\mathrm{Cos}\,\gamma_l}{}'+\overline{\mathrm{Cos}^2}\,\gamma_l{}']+\bar{g}_l{}'^2V_{\mathrm{Cos}\,\gamma_l}{}') \end{aligned} \tag{2}$$

which expresses the variance of the values of the isobaths at any point, or within any subarea, on the map.

These equations may be evaluated for a map as a whole (in which case a single average reliability value would be obtained), or for any arbitrarily selected small portion of a map. For the present maps, the equations were evaluated for each adjacent unit area of 5 geographical minutes to a side. This unit area was selected as a compromise between the geographic diversity of the map's reliability and the time available for manual computation. Over 1,600 unit areas were involved in the evaluation.

Evaluation of the Reliability

The evaluation of the terms in equations 1 and 2 are discussed in this section.

Observational errors (e_0).—The echosoundings made during the surveys of the 1930's and used as the basis for constructing most areas of the present maps were evaluated by Veatch and Smith (1939)—see also Adams (1942). They concluded (p. 60) that the accuracy of these soundings was within 1 part in 100 for areas deeper than 100 fm. and within 1 part in 200 for areas shallower than 100 fm. To approximate maximum errors on the shelf proper, I used their larger estimate, 1 part in 100, for all depths (0 to 500 fm.) and for all surveys and nautical charts used in the compilation.

Because of lack of data on bias in the soundings, I assumed unbiased work; hence, $\bar{e}_o$ was taken to be zero. The variance of the observational errors was estimated by assuming that the errors are normally distributed and that the value, 1 part in 100, represents 99 percent of the total distribution (this assumption implies that systematic and personal errors have been removed from the data and that any reduction errors have a random distribution). Therefore,

$$\pm d/100 = \pm 2.576\sqrt{V_{e_o}};\text{ hence } V_{e_o} = 0.000015d^2$$

where the variable d equals the maximum depth, in fathoms, within each 5-minute unit area.

To account for round-off errors, I added a constant factor to each variance value. This factor was 0.083 fm. when the soundings were recorded to the nearest fathom and 0.0023 fm. when recorded to the nearest foot. I assumed a rectangular, or uniform, distribution of these errors; hence, the variance equals $E^2/3$ (see Weatherburn, 1961, p. 14), where E equals one half of the round-off interval.

Positional errors (e_p).—Veatch and Smith (1939) discussed the accuracy of positioning for the radio-acoustic ranging methods used in the surveys of the 1930's (see also Adams, 1942). They concluded (p. 65) that the accuracy was 1 part in 200 for distances less than 100 nautical miles from the control (reference) points used in a survey. To approximate a maximum estimate of positional errors, I used 1 part in 100 for all of the surveys (except for a few recent ones which cover a large part of Nantucket Shoals) and all the nautical charts.

Again, because of lack of data, I assumed unbiased work; hence $\bar{e}_p$ was taken to be zero. The variance of the positional errors was determined in the same way as described above for observational errors; hence $Ve_p = 0.000015D^2$, where the variable D equals the maximum distance in nautical miles between each 5-minute unit area and the nearest control point (sonobuoy or station vessel) used in a survey. For nearshore nautical charts the distance D was measured to the nearest prominent shore feature.

To each variance value I added a constant factor—0.0045 nautical mile, to account for such cartographic errors as paper distortion and misalignments in tracing and printing. This factor was calculated by assuming a normal distribution of cartographic errors with a 99 percent limit of ± 0.1 inch or ± 0.17 nautical mile at a scale of 1 : 125,000.

For the recent surveys on Nantucket Shoals (1959–61), during which electronic positioning systems were used, I assumed a 99 percent error of ± 0.066 nautical mile (± 400 feet) and a normal error distribution; hence $Ve_p = 0.0007$ nautical mile. To this was added the cartographic error variance of 0.0045 nautical mile giving a constant total error variance of 0.0052 nautical mile for these surveys.

Interpolation errors (e_I *and* e_I').—If we were concerned with maps showing only the depths of soundings, the total error would be a simple combination of the positional and observational errors discussed above. Because, however, we are dealing with isobath maps, interpolation errors must also be considered. These errors are of two kinds: (1) those associated with depths interpolated along axes between actual soundings (primary interpolation error, e_I) and (2) those associated with depths interpolated between the primary interpolation axes (secondary interpolation error, e_I').

The equations for computing these interpolation errors are (Stearns, 1968):

$$\bar{e}_I = \bar{e}_{I'} = 0 \tag{3}$$

$$V_{e_I} = \tfrac{1}{6}(V_I + \bar{l}^2) \tag{4}$$

$$V_{e_{I'}} = \tfrac{1}{6}(V_{I'} + \bar{l}'^2) \tag{5}$$

These are based on a simple two-point linear interpolation scheme.

The evaluation of V_{e_I} and $V_{e_{I'}}$ depends on the particular survey pattern used. The quantity $(V_I + \bar{l}^2)$ in equation 4 is the mean sum of the squares of the distances between the soundings. For a rectangular array of discrete soundings along more or less parallel track lines, as is the situation for most of the hydrographic surveys of the Middle Atlantic Continental Shelf, this quantity equals $\tfrac{1}{3}(a^2 + b^2)$, where a is the distance between track lines and b is the distance between soundings on each line. By taking the mean of five systematic samples of the two distances, I estimated the quantities a and b for each 5-minute unit area.

The quantity $(V_{l'}+\bar{l}'^2)$ in equation 5 is the mean sum of the squares of the distances between the primary interpolation axes. Several choices are possible for secondary interpolation axes (Stearns, 1968). The correct choices are those axes actually used by the cartographer in drawing the map. A human being, however, in his subjective approach to contouring, is seldom fully aware of just what axes he has used. Therefore, in computing the reliability of the present maps, I assumed that the shortest axes were used, which, in the rectangular trackline surveys of the Middle Atlantic Continental Shelf, equaled the distance between soundings. These distances are usually equal within any unit area, so the quantity $(V_{l'}+\bar{l}'^2)$ equals $\bar{b}^2$.

The topographic slopes.—Positional and interpolation errors (which are expressed in distance units) are converted into depth errors, by multiplying them by g Cos γ, where g is the positive topographic slope in the vicinity of the soundings (or the interpolated point) and γ is the angle between the errors and the local slope.

The slopes g_p, g_l, and $g_{l'}$ were assumed to be equal and were estimated from five systematic samples taken in each 5-minute unit area. Each sample consisted of the maximum slope measured in a circle 1 nautical mile in diameter. The mean slope, $\bar{g}$, was taken as the mean of the five samples, and the variance of the slopes, V_g, was approximated by $(0.43\ \omega)^2$, where ω was the range of the five samples. This estimate of the variance assumed that the slopes have a normal distribution within each 5-minute unit area and was used as a computational expedient (see Dixon and Massey, 1957, pp. 273, 404).

The cosines.—In estimating the cosines in equations 1 and 2, I assumed that all angles had an equal probability of occurrence; thus γ_p, γ_l, and $\gamma_{l'}$ range from zero to π radians (from 0° to 180°), and the probability functions of the angles equal $1/\pi$. Hence,

$$\overline{\mathrm{Cos}}\,\gamma=\frac{1}{\pi}\int_0^\pi \mathrm{Cos}\,\gamma d\gamma=0$$

and

$$V_{\mathrm{Cos}\,\gamma}=\frac{1}{\pi}\int_0^\pi \mathrm{Cos}^2\,\gamma d\gamma=\tfrac{1}{2}$$

This assumption may be true for positional errors, because I assumed that these errors are unbiased. It is not strictly true, however, for interpolation errors, and a more accurate, although more time-consuming method could have been used; i.e., the final map could have been matched with the interpolation networks actually used and the angles measured.

The Source Diagram

The source diagram on each map shows the number, scale, and date of the USCGS hydrographic surveys and nautical charts used in the construction of the maps.

The maps depict the sea floor at the dates of the various surveys, and the user must draw his own conclusions as to changes that may have taken place since then. Significant changes are likely only along some portions of the coast above about 10 fm., in offshore shoal areas, and along the upper Continental Slope where slumping may have occurred (see Lucke, 1934a, 1934b; Howard, 1939; Heezen, 1963; Miller and Zeigler, 1964; Stewart and Jordan, 1964; Uchupi, 1967). In such areas the maps and their reliability diagrams should be used with caution.

Those who wish to study the actual soundings may examine or purchase copies of the original hydrographic survey sheets from the USCGS, Washington, D.C.

Diagram of the Mean Distance Between Track Lines

The mean distance between track lines is a common device for indicating the reliability of bathymetric maps. Reliability is usually assumed to be better where the lines are closely spaced. Trackline spacing also indicates the resolution of a survey; i.e., the minimum size of features consistently discoverable from the survey. Surveys with many different trackline spacings were used in drawing the maps. Consequently, the isobaths are more detailed in some areas than in others.

Diagram of the Standard Deviation of the Isobath Depth Error

The standard deviations in the isobath depth error diagram are estimates of how much and how frequently the depths indicated on the maps may depart from the true depths. The diagram is based on the square root of the variance given by equation 2 and shows the average standard deviation in unit areas of 5 geographical minutes to a side. It applies to depths as indicated on the maps, not to the original soundings. A more detailed diagram of the entire mapped area is reproduced in figure 2.

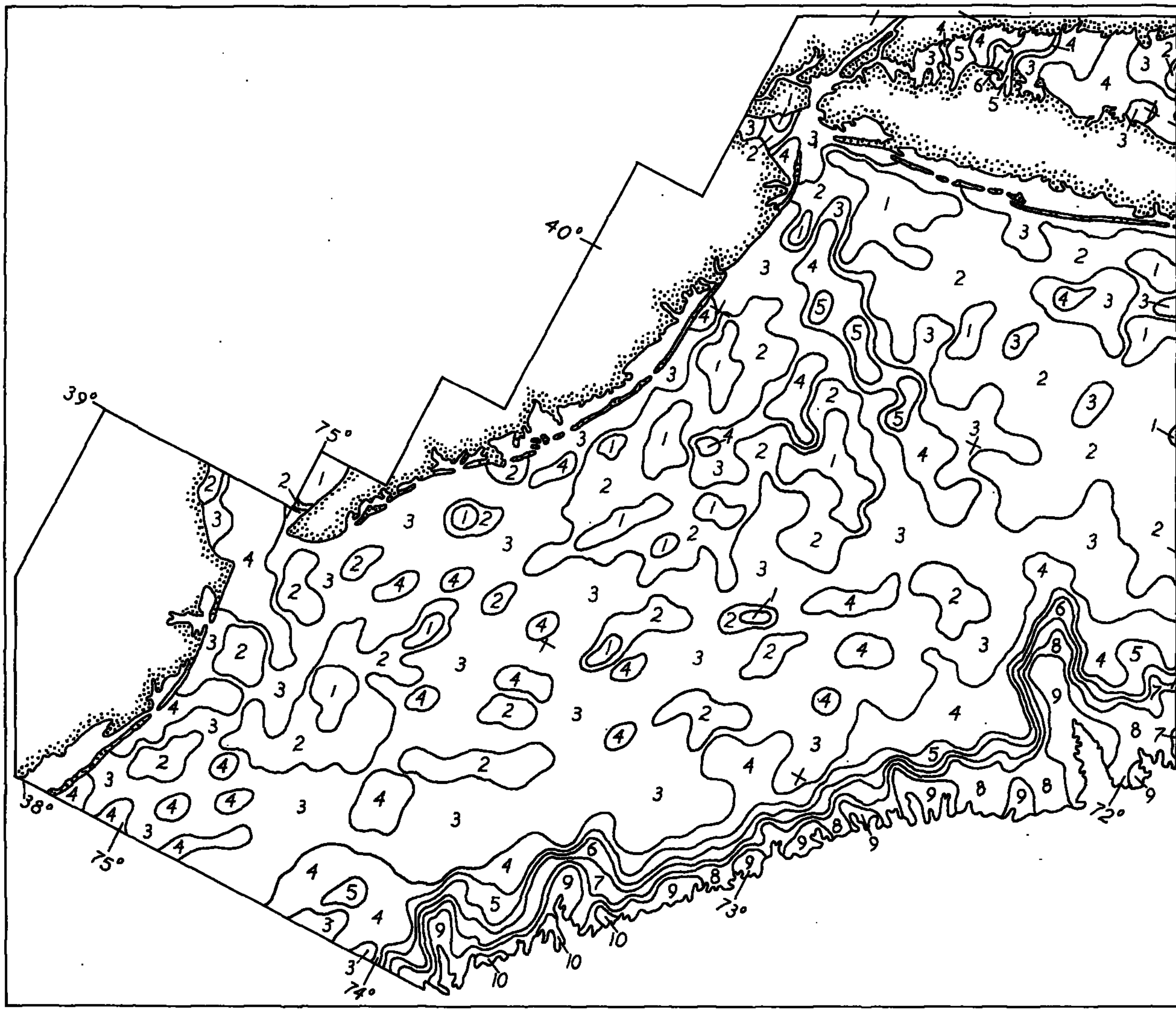
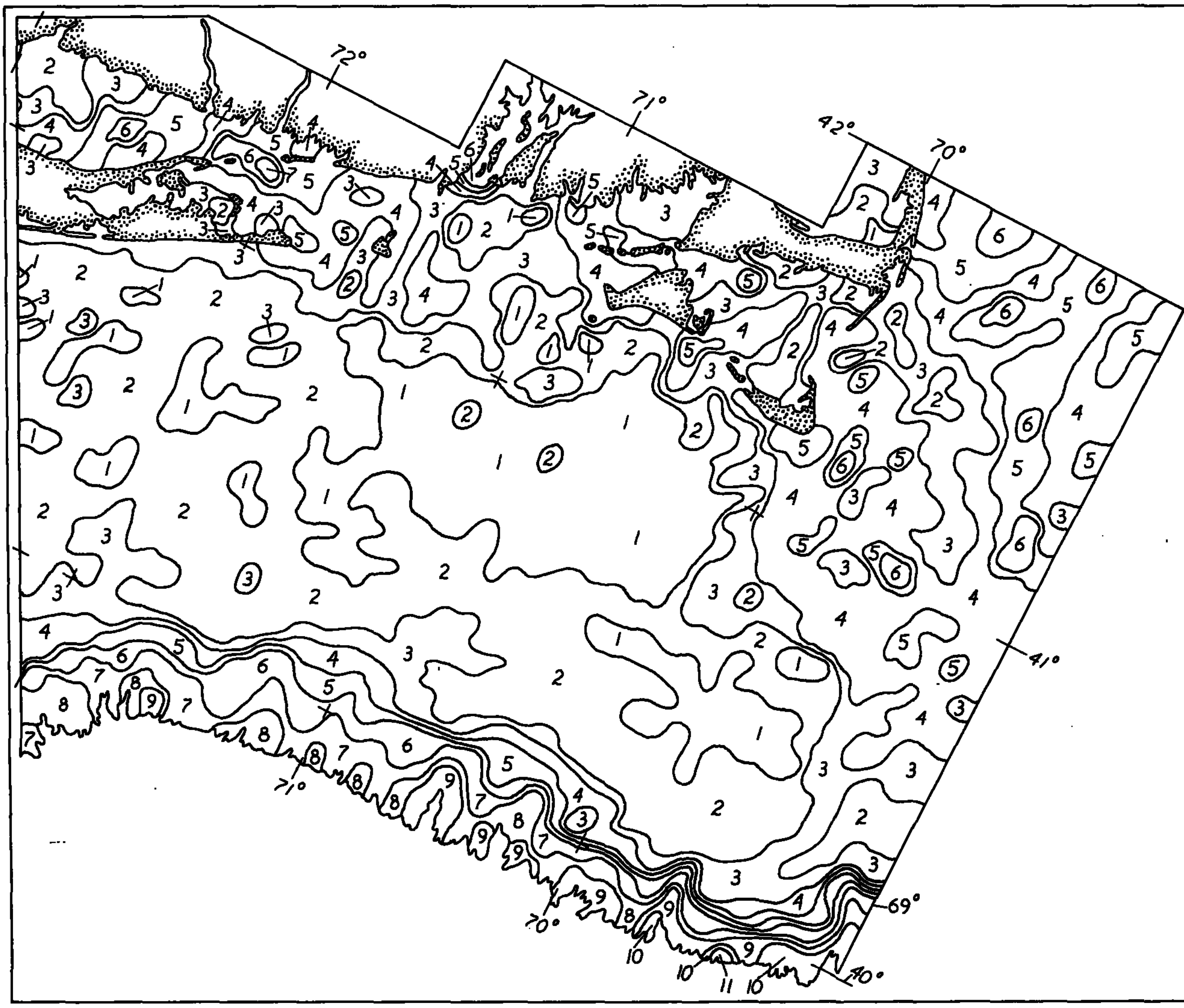


FIGURE 2.—Standard deviation of the isobath depth error. (1) Less than 0.25 fm. (2) 0.25–0.49 fm. (3) 0.50–0.99 fm. (4) 1.00–1.99 fm. (5) 2.00–3.99 fm. (6) 4.00–7.99 fm. (7) 8.00–15.99 fm. (8) 16.00–31.99 fm. (9) 32.00–63.99 fm. (10) 64.00–127.99 fm. (11) 128.00 fm. and more.

The figures in the diagram may be used to estimate the expected correspondence between the mapped depths and the true depths. This expected correspondence is expressed as a probability that the true depth falls between certain limits. For example, if we assume a normal distribution of depth errors in an area where the standard deviation of the depth error is 1 fm., then the probability is 99 percent that the indicated depth is correct to within ±2.6 fm., 90 percent that the depth is correct to within ±1.6 fm., or 50 percent that the depth is correct to within ±0.7 fm. The depth of any isobath as shown on the maps should be thought of as representing a probable range of depths rather than as a single exact depth.

The above limits were computed by the formula $r = Z_i \sigma$, where r is the expected range of depths, σ is the standard deviation taken from the depth error diagram (fig. 2), and Z_i is a number that depends upon the probability i and upon the kind of error distribution (see Dixon and Massey, 1957, or other statistics textbooks).

The above formula gives the expected range due only to errors in the map. To find the expected range when the maps are being used aboard a ship to search for a given bathymetric feature, the



standard deviation would have to include the ship's errors; i.e., $\sigma=\sqrt{\sigma_m^2+\sigma_s^2}$, where σ_m is the map standard deviation taken from the depth error diagram, and σ_s is the ship standard deviation. The ship standard deviation may be estimated as the square root of the first three terms on the right-hand side of equation 2.

Diagram of the Standard Deviation of the Isobath Position Error

The standard deviations in the isobath position error diagram are estimates of how much and how frequently the positions of the depths as indicated on the maps may depart from the true positions. This diagram is also based on the square root of equation 2; it shows the average standard deviation in 5-minute unit areas and applies only to indicated depths—not to the original soundings. The values in the diagram were computed by dividing the standard deviations of the isobath depth error (fig. 2) by $\sqrt{V_g+\bar{g}^2}$, where $\bar{g}$ is the mean topographic slope of the sea floor in a given 5-minute unit area, and V_g is the variance of the topographic slope within the same 5-minute unit area. A more detailed diagram of the entire mapped area is reproduced in figure 3.

The figures in this diagram may be used to estimate the expected correspondence between the mapped positions of the depths and their true positions. This expected correspondence is expressed as a probability that the true position falls between certain limits. For example, if we assume a normal distribution of position errors in an area where the standard deviation of the position error is 0.2 nautical mile then the probability is 99 percent that a given depth will be found within ± 0.5 nautical mile of its indicated position (i.e., will be found within a circle 1.0 nautical mile in diameter centered on the given depth), 90 percent that it will be found within ± 0.3 nautical mile of its indicated position, or 50 percent that it will be found within ± 0.1 nautical mile of its indicated position. The position of any isobath as shown on the maps should be thought of as the center of a probable range of positions rather than as a single exact position.

The above limits were computed by the same formula as was the probable range of depths, except that here r is the expected range of positions, and σ is the standard deviation taken from the position error diagram (fig. 3).

This computation also applies only to map errors. To find the expected range when the

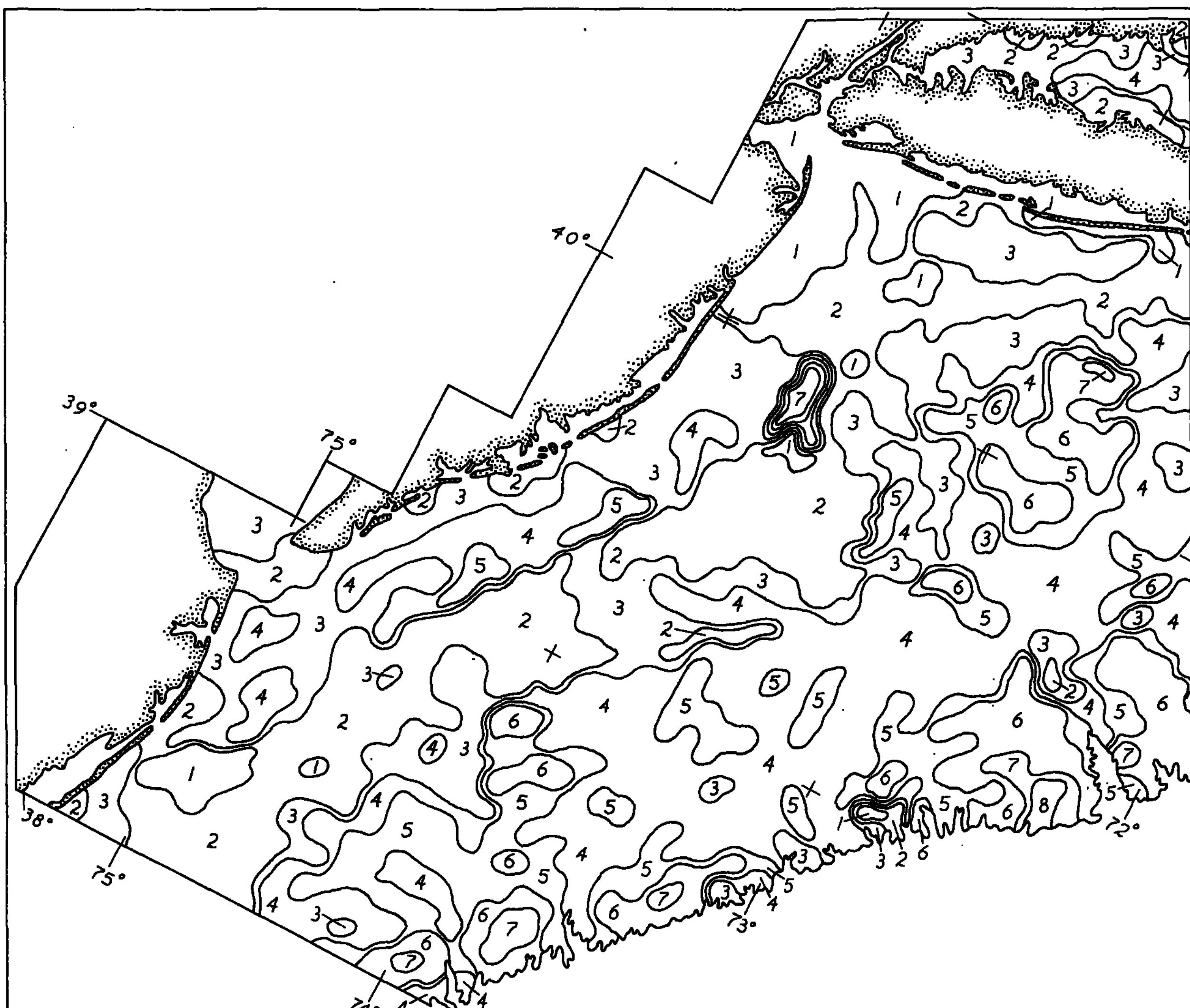


FIGURE 3.—Standard deviation of the isobath position error. (1) 0.05–0.09 nautical mile. (2) 0.10–0.14 nautical mile. (3) 0.15–0.19 nautical mile. (4) 0.20–0.24 nautical mile. (5) 0.25–0.29 nautical mile. (6) 0.30–0.39 nautical mile. (7) 0.40–0.49 nautical mile. (8) 0.50–0.59 nautical mile. (9) 0.60–0.69 nautical mile. (10) 0.70–0.79 nautical mile. (11) 0.80–0.89 nautical mile.

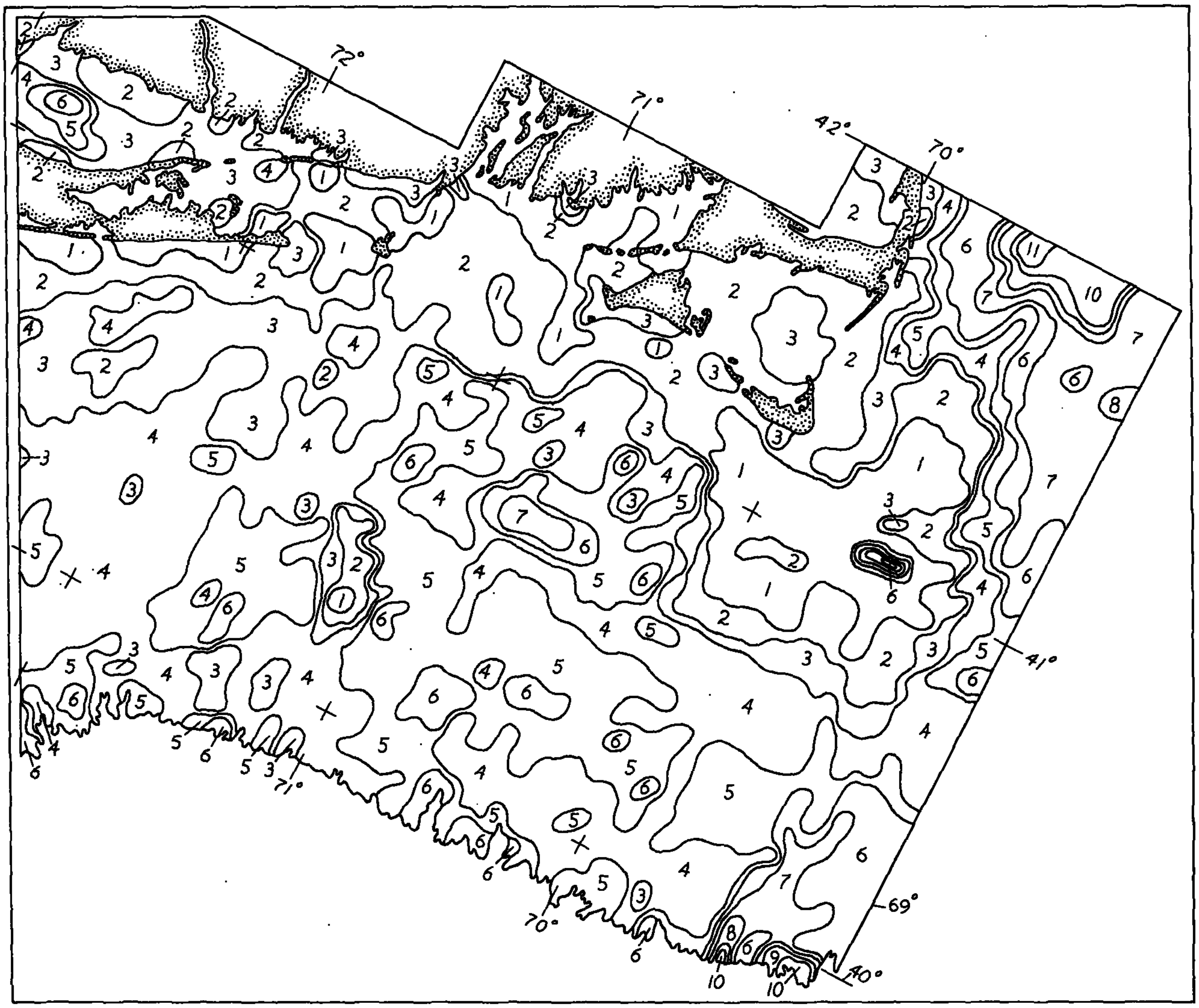
maps are being used aboard a ship, σ must be equated to $\sqrt{\sigma_m^2+\sigma_s^2}$, where σ_m is taken from the position error diagram, and σ_s is computed by dividing the first three terms on the right-hand side of equation 2 by $V_g+\bar{g}^2$, for the area in which the ship is working, and then taking the square root of the quotient.

Distribution of the Map Errors

The standard deviations of the isobath depth error (fig. 2) generally increase in an offshore direction. Most of this increase is due to the steeper topographic slope on the outer shelf and upper slope which makes interpolation of depths between soundings less certain in these regions. A part of the increase is also due to a wider spacing between tracklines offshore.

Most of the large inshore standard deviations are also caused by locally steep topographic slopes (e.g., the Hudson Channel, Long Island Sound, Delaware Bay, and Nantucket Shoals); however, the large deviations east of Cape Cod are due both to wide trackline spacing and to steep slopes.

Figure 4 shows the percentage of the total variance of the depth error which can be attributed to observational, positional, and interpolation errors.



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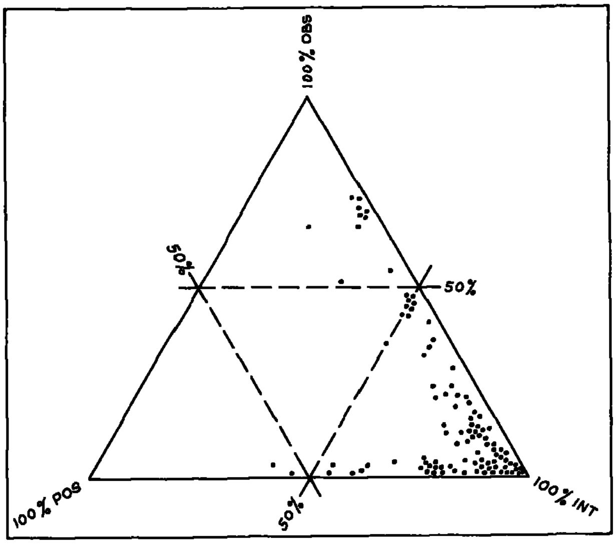

FIGURE 4.—Percentage of the variance of the isobath depth error that can be attributed to observational errors (OBS), positional errors (POS), and interpolation errors (INT).

The figure is based on the variance in 100 representative 5-minute unit areas. In most of these unit areas more than half of the total variance results from uncertainty in interpolations of assumed depths between the original soundings.

Interpolation errors are very sensitive to topographic slope and spacing between soundings. To achieve the same reliability of isobath depths, the spacing of soundings must be much closer in areas of steep slopes than in areas of gentle slopes. For many surveys, not only of bathymetry but of other variables as well, the observations are so widely spaced (usually for reasons of economy) that ordinary positional and observational errors have little effect on the reliability of the final isolines.

Figure 5 shows the relation of the standard deviation of the isobath depth error to the mean topographic slope in a few selected unit areas. The dispersion of the points results largely from variations in the spacing between tracklines.

The standard deviations of the isobath position error (fig. 3) also increase offshore, mostly because of wider spacing between tracklines. Figure 6 shows the relation of these standard deviations to the mean spacing between tracklines. The dispersion of the points is due mainly to variations in the observational and positional errors of the original soundings.

PART 2. GEOMORPHOLOGY

A description of the configuration of the Middle Atlantic Continental Shelf, along with a general discussion of its evolution, of the processes involved in its formation, and of its sediments, is presented in this part of the report.

GENERAL CONSIDERATIONS

The general appearance, geological history, sediment distribution, and geomorphic processes of the Middle Atlantic Shelf are discussed in this section.

General Appearance and Past Geologic History

The present continental border of eastern North America can be divided into five geomorphic zones which roughly parallel the present shoreline (fig. 7): (1) a hilly to mountainous system of parallel valleys and ridges (the Newer, or Folded, Appalachian Mountains), (2) a flat to hilly upland region (the Older Appalachian Mountains), (3) a coastal lowland, in places submerged below present sea-level (the Atlantic Coastal Plain and Continental Shelf), (4) a submerged slope about 1,500 fm. high (the Continental Slope), and (5) a very gently sloping surface merging seaward with the deep ocean floor (the Continental Rise). For a discussion of these geomorphic divisions see Fenneman (1938), Heezan et al. (1959), and Hammond (1964).

Before the Cretaceous Period (some 136 million years ago) a succession of evolving highlands occupied the present sites of the Older Appalachians and the Coastal Plain. According to Dietz and Holden (1966), these highlands were formed when material uplifted from an ancient Continental Slope and Rise and from the adjacent deep-sea floor was added to a then smaller continent. This process of accretion is supposed to have started in the late Ordovician Period (about 445 million years ago) and to have continued until the end of the Permian Period (about 225 million years ago), eventually adding some 150 to 400 or more miles to the continent. (Dates are from Kulp, 1961, and Harland, Smith, and Wilcock, 1964.) The eroded remnants of these old highlands now underlie Cretaceous and younger sediments on the present Coastal Plain; they outcrop in a belt of greatly deformed and altered rocks throughout the Older Appalachian Mountains.

The region west of the Older Appalachians was occupied in pre-Ordovician times by an ancient

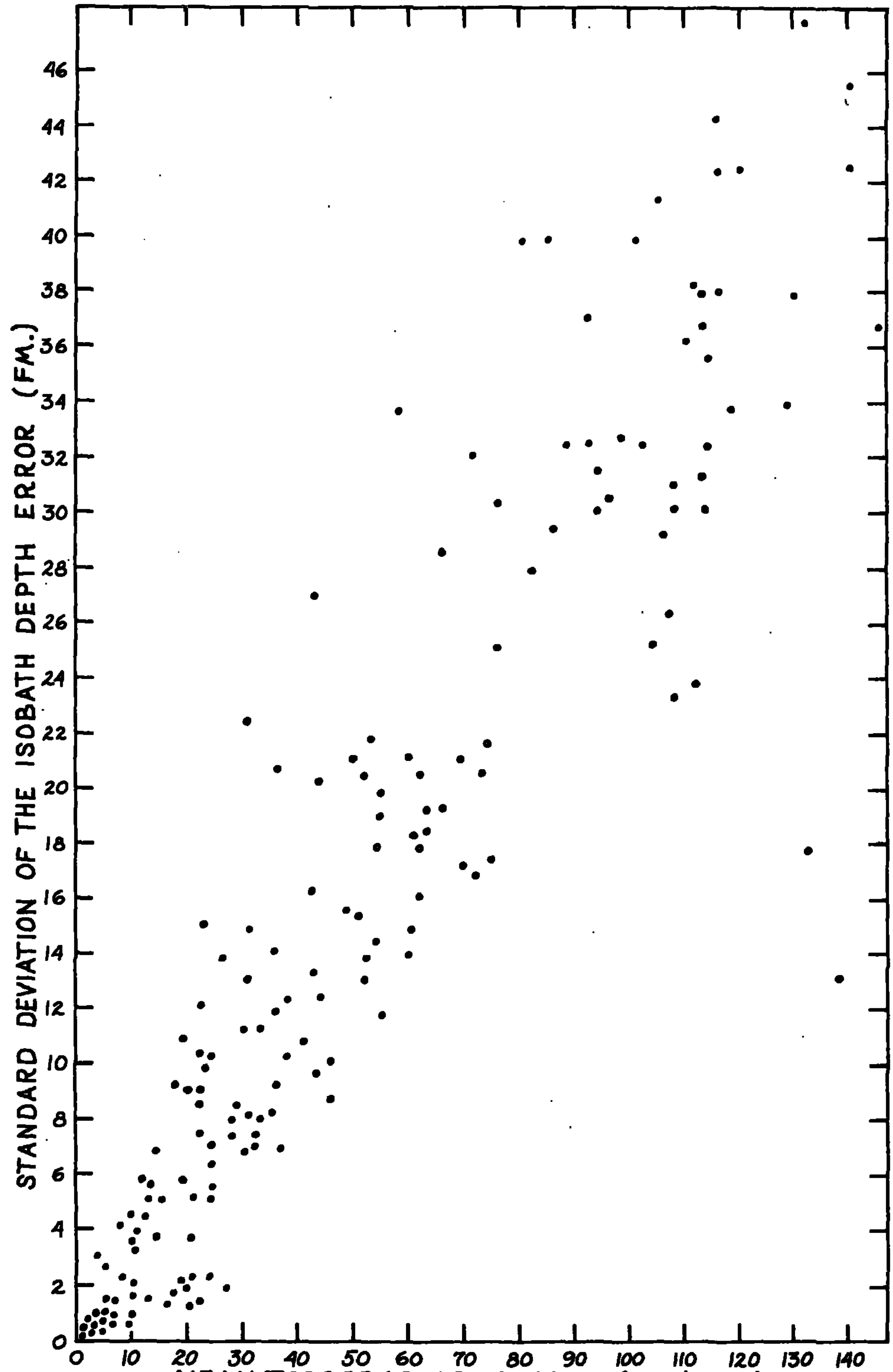

FIGURE 5.—Variation of the standard deviation of the isobath depth error with respect to the mean topographic slope.

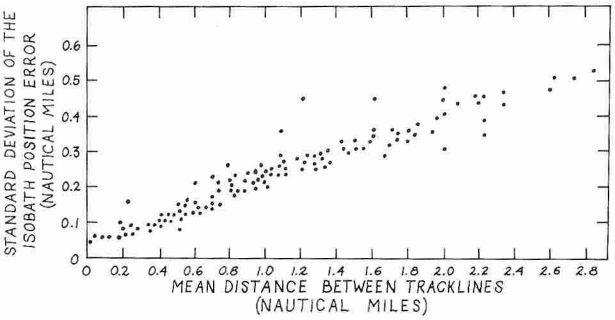

FIGURE 6.—Variation of the standard deviation of the isobath position error with respect to the mean distance between tracklines.

coastal plain and continental shelf. This plain became an epicontinental inland sea in post-Ordovician times, and its bottom was progressively folded until the Appalachian Revolution of middle and late Permian times finally forced it and its sediments into the present Folded Appalachian Mountains. The above sequence of events is only one recent inference from available evidence; for other interpretations of the geologic history of the region see Schuchert (1923), Kay (1951), Drake et al. (1959), Wilson (1966), and Harland (1967); see also the criticism by Hsu (1965) of earlier ideas of Dietz (1963a) and the reply by Dietz (1965).

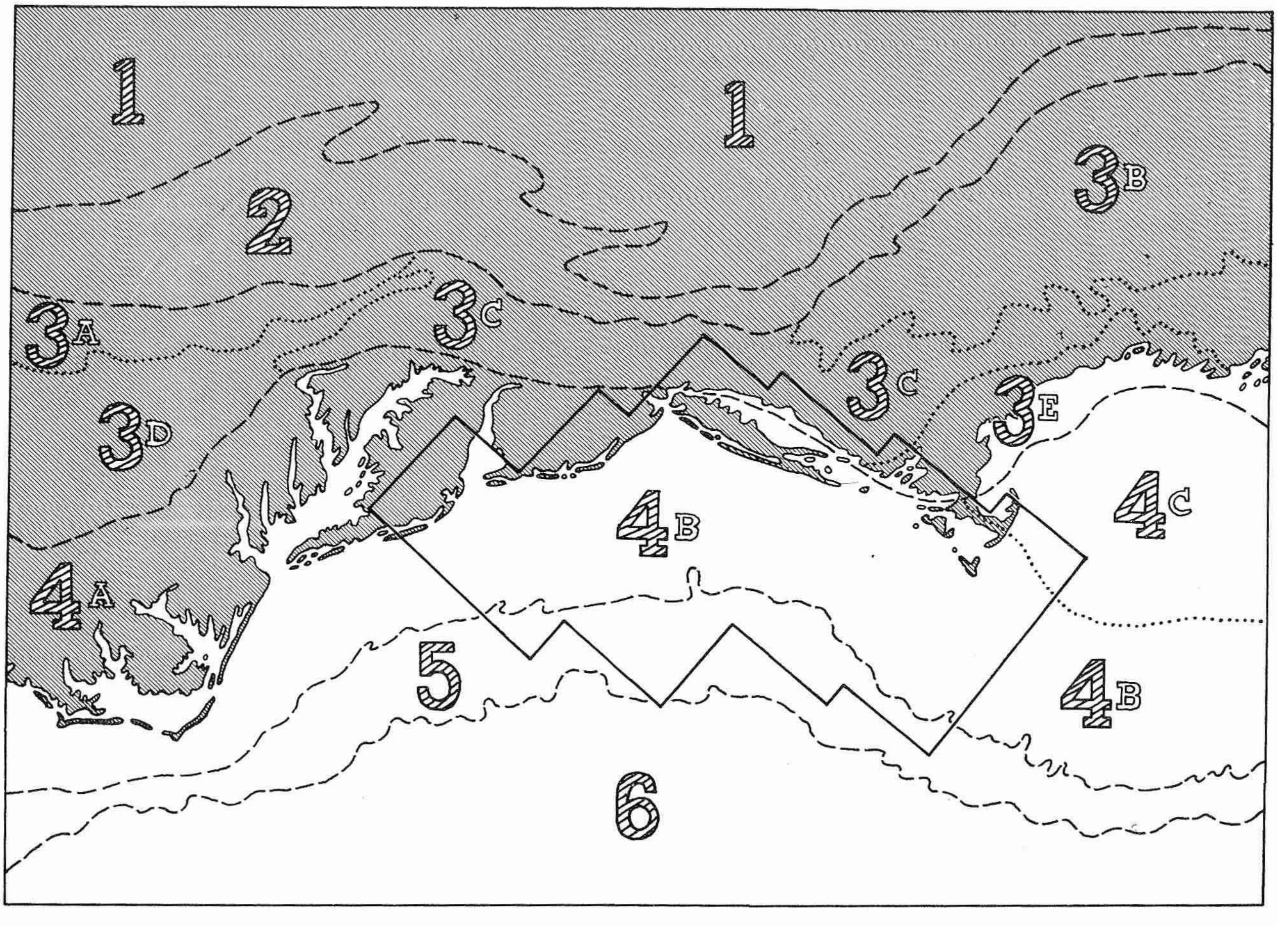

FIGURE 7.—Physiographic regions of the Middle Atlantic Coast. (1) Appalachian Plateaus and Interior Lowlands. (2) Folded Appalachian Mountains. (3) Older Appalachian Mountains, including (3A) Blue Ridge Mountains, (3B) New England-Acadian Mountains, (3C) Piedmont-New England Hills, (3D) Piedmont Plain, and (3E) New England Plain. (4) Emerged and Submerged Coastal Plain, including (4A) Emerged Coastal Plain, (4B) Submerged Coastal Plain or Continental Shelf, and (4C) Gulf of Maine Basin. (5) Continental Slope. (6) Continental Rise. Boundaries are approximate. Sources: Fenneman (1938); Heezen et al. (1959); and Hammond (1964). The heavy solid line is the boundary of the mapped area.

Since the Cretaceous Period, the eroded roots of the old coastal highlands have experienced successive invasions of the sea, and a large wedge of sediment has been deposited on their surfaces. The most recent submergence was between about 4,000 and 20,000 years ago. (For discussions of terrestrial conditions on the shelf in the recent past see Emery, 1966a; Emery, Wigley, and Rubin, 1966; and Wigley, 1966). The presently submerged surface of this sedimentary wedge is the Continental Shelf of eastern North America.

General Sediment Distribution

The surface of the Middle Atlantic Continental Shelf is covered only in part by contemporary sediments. These are mainly in a narrow nearshore zone (Emery, 1961; Uchupi, 1963). The largest part of the shelf is covered by relict deposits formed during lower stands of sea level in the Ice Age.

Relict shelf features and sediments were recognized as early as 1850 by Austen who suggested that the English Channel was once a subaerial river valley. Dana (1863) extended Austen's idea to the Middle Atlantic Continental Shelf by his discovery on an 1852 Coast Survey chart of both the Hudson and Block submarine channels which, he concluded, were once occupied by the Hudson and Connecticut Rivers. Taylor (1872) later suggested that evidence of dry land, rivers, and shoreline features should be found within the 100-fm. line, and during the same period Louis Agassiz taught his Harvard classes that the offshore fishing banks consisted superficially of glacial drift (Upham, 1894). Most recent authors accept the idea of relict deposits, although emphasis shifted somewhat after Gulliver (1899) and Johnson (1919) introduced the concept of an inner shelf which had been cut by waves and an outer shelf which had been built up by wave deposition (for a discussion of this concept see Dietz, 1963b, 1964; and Moore and Curray, 1964).

The Middle Atlantic Shelf is covered by modified glacial outwash and moraines, river channel and flood plain deposits, ancient deltas, offshore bars, and old coastal beach-lagoon complexes (Uchupi, 1968). Some smaller areas may contain materials formed in place by submarine chemical processes (Uchupi, 1963; Emery, 1966b). Superimposed on these primary sediments are patches of both contemporary and ancient shell debris (Merrill, Emery, and Rubin, 1965; Emery, Merrill, and Trumbull, 1965).

The subsurface sediments of the Shelf and Coastal Plain consist of layer after layer of much the same type of deposit that occurs today on their surface (with additions of other types such as peat and limestone). These sediments have been accumulating at least since the Cretaceous Period and now form a thick prism which ranges from a few feet at the landward border of the Coastal Plain to over 15,000 feet (4.6 km.) thick at the edge of the shelf. An even greater thickness has accumulated at the foot of the Continental Slope, and some 25,000 feet (7.6 km.) of sediments now lie under the Continental Rise (for a discussion of this deeper structure see Dietz, 1952; Drake et al., 1959; Heezen et al., 1959; Murray, 1961; Emery, 1966b; Krause, 1966; Hoskins, 1967; and Uchupi and Emery, 1967).

Geomorphic Processes

The nearshore breaking of waves is the most important cause of erosion on the landward edge of the shelf, but is apparently effective only above about 5 to 10 fm. (Dietz, 1963b; see also the discussion by Moore and Curray, 1964 and the answer by Dietz, 1964). Some controversy exists, however, concerning the ability of contemporary processes to alter significantly the relict terrains and sediments seaward of the surf-zone. Several authors have thought that present waves and currents can scour the shelf intensely to great depths (Dana, 1890; Gulliver, 1899; Johnson, 1919; Alexander, 1934; and Jones, 1941). Other workers have suggested that the present shelf surface is drowned and entirely out of adjustment with present conditions (Lindenkohl, 1891; Dietz, 1963b, 1964). Still others have believed that a thin surface layer (6–24 inches, or 15–60 cm.) is in adjustment with contemporary sea level (Donahue, Allen, and Heezen, 1966), or that fine sediments are being either moved across the shelf or deposited in certain restricted areas (Shaler, 1881; Shepard and Cohee, 1936; Stetson, 1938b; and Emery, 1966b). Uchupi (1968) suggested that some linear sand bodies on the inner shelf may have been formed by large modern storm waves. It is also possible that with a long-continued stand of the sea at its present level, the shoreline would build out over a large portion of the inner shelf (Curray, 1964; Emery, 1966b) or that existing bottom sediments and relict land forms would eventually become completely adjusted to present sea level (Stetson, 1938b, 1939; Moore and Curray, 1964).

A distinction must be made between gross land forms and surficial sediments. All of the relict surface sediments above the late Wisconsin low stand of the sea (about 65 or 70 fm.) have been modified during the last 20,000 years or so by the active surf-zone, as this zone migrated shoreward across the shelf with the latest postglacial (or Holocene) rise of sea level. Thus, the surface sediment layer is a direct product of the Holocene marine transgression. Large terrain features, however, are not likely to have been obliterated by the Holocene rise; hence, much of the present gross morphology on the shelf is probably related to pre-Holocene events.

Between the nearshore surf-zone and the land a complex of barrier beaches, lagoons, and coastal marshes has developed along most of the Middle Atlantic Coast. This complex traps much of the sediment load now brought to the ocean by rivers and other runoff. A large volume of recent sediment is also deposited in bays or sounds, and the small amount of suspended fine material that escapes is often removed from the shelf by currents or deposited in such depressions as the Hudson and Block Channels (Stetson, 1955; Curray, 1964).

As changes have occurred in sea level, the shoreline (along with a complex of barrier beaches, lagoons, coastal marshes, and estuaries) has migrated scores of miles back and forth across what is now the shelf and the emerged coastal plain (Emery, 1967). As early as 1881 Shaler suggested that the net effect of this repeated migration, combined with a slow subsidence of the continental margin, has been the deposition of the series of layers that now form the thick sedimentary wedge of the Continental Shelf.

REGIONAL PHYSIOGRAPHY

The physiographic regions and features on the Middle Atlantic Shelf are described in terms of their topography and sediments in the following paragraphs. The major regions and features discussed are (1) nearshore terrains, (2) terrains southwest of the Hudson Channel, (3) the Hudson Channel, (4) terrains northeast and east of the Hudson Channel, and (5) terraces and ancient shore features on both the inner and outer shelf. The bathymetric maps of Stearns and Garrison (1967) serve as illustrations for this section and should be available; features mentioned in the text are keyed to these maps by chart number. The locations of some of the larger features are also shown in figure 1.

Nearshore Terrains

Nearshore terrains are easily accessible and have been much studied (see, for example, Shaler, 1893, 1895; Johnson, 1919, 1925; Shepard, 1948; and Guilcher, 1958). In the mapped area they may be divided into three types.

The surf-zone.—Parallel to the shoreline is a relatively smooth concave slope, in some places interrupted by one or more offshore bars, extending from the beach to a depth of 5 or 10 fm. The width of the surf-zone rarely exceeds 2 nautical miles (its average width is about one-half mile) and it appears to be deepest off New Jersey and eastern Long Island. The sediments of the surf-zone are mostly clean, coarse to fine sand, with a few patches of gravel and rock. Some black mud that lies between 4 and 11 fm. off New Jersey and Long Island may indicate places where the surf-zone has exposed old coastal marsh deposits such as underlie the present barrier beaches (see Fischer, 1961).

The barrier beach-lagoon complex.—Shoreward of and parallel to the surf-zone, throughout most of the mapped area, are extensive linear barrier beaches forming the seaward margin of shallow bays, lagoons, and coastal marshes. This terrain is especially well developed along the whole of the Maryland, Delaware, New Jersey, and southern Long Island Coasts. The width of the lagoon-coastal marsh terrain usually varies from 1 to 6 nautical miles. Except for tidal channels, the depth of lagoons seldom exceeds 2 fm. and is generally less than 1 fm. The marshes are at sea level, between the high- and low-tide marks; and sediments there are mud and organic plant debris. Tidal-delta sands are around inlets. Barrier beaches are clean sand often formed into sand dunes by the wind (see Lucke, 1934a, 1934b; and Fischer, 1961).

Glacial moraines.—Running across the northern part of the mapped area is a zone of low hills separated from the southern New England shore by a series of bays and sounds. This region of old glacial moraines forms numerous submerged features as well as the backbones of Long Island, Block Island, and the islands south of Massachusetts (Schafer and Hartshorn, 1965). Long Island has two moraines: the Harbor Hill Moraine extends along the north shore to Orient Point and then across Long Island Sound through Plum, Great Gull, and Fishers Islands to Watch Hill Point in Rhode Island and along the shore (where it is called the Charlestown Moraine) to Point Judith; the Ronkonkoma Moraine runs through central Long Island to Montauk Point. These two moraines are considered to have formed during the last advance of the late Wisconsin ice-sheet some 20,000 years ago (Flint, 1957; and Donner, 1964). They merge to the west, south of Hempstead Harbor, and continue across Brooklyn to Staten Island and New Jersey.

Where the Harbor Hill Moraine crosses Long Island Sound there is a ridge of coarse rocky sediments (chart 0808N–53 of Stearns and Garrison, 1967). Between the high points on this ridge are elongated depressions and channels, some as deep as 55 fm., containing finer sediments. Some of these depressions may be kettles formed by the melting of buried blocks of ice (Elliott et al., 1955), or they may have been cut by either ice-scour or subglacial drainage streams (Dana, 1870, 1875, 1883, 1890; Loring and Nota, 1966, suggested this origin for similar features in the Gulf of St. Lawrence). These pre-Holocene depressions would have become fresh-water lakes shortly after being uncovered by the melting ice-sheet (Antevs, 1922, 1928; Lougee, 1953); evidence for these lakes, in the form of fresh-water clay concretions, has been found in one depression south of Fishers Island (Frankel and Thomas, 1966). Some other depressions may have been formed or at least modified, by river erosion, during the period which followed the retreat of the ice-sheet. All the depressions probably have been scoured by tidal currents which became effective in this area when the sea had risen to 10 to 15 fm. below present sea level.

The Ronkonkoma Moraine extends beyond Long Island, from Montauk Point to Block Island, and its crossing is marked by a broad ridge of coarse rocky and bouldery sediments (charts 0808N–51 and –53). Near its center this band is breached by a channel, which contains several 25- and 30-fm. holes. This breach probably represents one of the ancient channels for the rivers of Connecticut and western Rhode Island. It was later eroded by tidal currents when sea level rose to within 10 or 15 fm. of its present level.

East of Point Judith, R.I., the Harbor Hill (or Charlestown) Moraine appears to bend southward around Narragansett Bay and to join with the Buzzards Bay Moraine of western Cape Cod by way of Browns Ledge and the Elizabeth Islands (chart 0808N–51). This bend is marked by a submerged ridge of coarse gravelly sediments. East of Block Island the Ronkonkoma Moraine also appears to bend to the south and to join with moraines on the north shores of Martha's Vineyard and Nantucket Island by way of Nomans Land, the Southwest Shoal, and Cox Ledge. The bottom in this area is marked by a broad rocky and gravelly ridge (Schafer, 1961; and Kaye, 1964).

Between Block Island and Martha's Vineyard this ridge is breached by a channel with depths as great as 35 fm. The sea bottom between the two moraines in this area contains an east-west channel with depths that approach 30 fm. to the north of Block Island. This east-west channel continues westward through Block Island Sound and eastward as far as the entrance to Vineyard Sound. This channel probably represents an early Holocene drainage system for much of southern New England. Presumably, late Holocene drainage from Connecticut broke through the moraine east of Montauk Point, while Rhode Island and Massachusetts drainage continued down the channel east of Block Island. It appears that both these systems entered the Block Channel across the shelf. The channels have been modified by tidal scour and tidal delta deposition which would have started when the sea rose to about 25 fm. below present sea level.

The moraines on Martha's Vineyard, Nantucket Island, and Cape Cod cannot be traced to the east with certainty (see chart 0708N–51). They probably merge with the lateral moraine of an ice-sheet lobe that once extended southward through the Great South Channel (see Zeigler, Tuttle, Tasha, and Giese, 1964). Between Martha's Vineyard and Nantucket Island is a double tidal delta which appears to have been built in an old tributary of the Block Channel that once ran between the Islands.

Terrains Southwest of the Hudson Channel

Off the coasts of New Jersey, Delaware, and Maryland, the bottom above about 50 fm. consists of alternate ridges and longitudinal depressions, which generally run northeast-southwest and are interspaced by flat areas, escarpments, embayments, and former channels. The sediments on this part of the shelf are predominantly sands with some coarser material. Muds are infrequent above about 50 fm. and are not dominant shallower than the shelf break.

The terrains in this area are similar to present nearshore and modified subaerial alluvial terrains; this similarity is not surprising because the surf-zone, the complex of lagoons and coastal marshes, and the subaerial river regimes must have repeatedly migrated back and forth across the shelf. Flint (1940) noted that north of the James River the Pleistocene formations on the emerged coastal plain are typical of compound alluvial deposits. It seems that this is also true of the submerged shelf, with the addition of numerous transgressive marine features (see also MacClintock, 1943, and Schlee, 1964).

Delaware River channels.—From the mouth of Delaware Bay a channel may be traced southeastward about 40 nautical miles (Lindenkohl, 1891; charts 0807N–56 and –57). Below 20 fm. this channel is lost in a series of what appear to be old lagoons and barrier beaches which continue down to about 40 fm. To the northeast the channel is bounded by a scarp as much as 15 fm. high. A well-defined ridge backing this scarp can be traced 30 nautical miles southeastward from Cape May, and its remnants extend for another 30 or 40 nautical miles.

Northeast of this ridge is a shallow embayment that has a diffuse channel below 5 to 7 fm. (charts 0807N–55 and –56). Deeper than 20 fm. this embayment flattens out and merges with what appears to be a series of lagoons and barrier beaches. Possibly this bay represents an older Delaware River estuary which might be correlated with a post-Sangamon channel in the Cape May Formation on the Cape May Peninsula (Richards, 1962).

Great Egg Harbor River channel.—Running southeast from near Great Egg Harbor Inlet is a smooth embayment that extends to a depth of 12 or 14 fm., where a bar has been built across its mouth (chart 0807N–55). Beyond this bar the bay narrows and a shallow channel continues south-southeastward. Between 18 and 22 fm. a ridge, about 20 nautical miles long, appears to have been a large barrier beach. It encloses what was probably a former lagoon, now as much as 2 or 3 fm. deeper than the surrounding bottom. Below this feature, the channel is lost in a deeper series of what seem to be lagoons and barrier beaches. The northeast boundary of the embayment off Great Egg Harbor Inlet is a low ridge extending southeasterly from Brigantine Shoal; it appears to be composed of a series of submerged sand spits and barrier beaches.

The old and new Delaware embayments and the Great Egg Harbor embayment are each well defined between about 10 and 20 fm. Below about 20 fm., however, the new Delaware embayment is lost, and the old Delaware and Great Egg Harbor embayments are combined, first into a large shallow depression (about 35 nautical miles long) between 24 and 27 fm. and then into a single open embayment between 27 and 29 fm. (charts 0807N–55 and –56). Below about 28 fm., this open embayment narrows into a slender channel which continues southward to about 35 fm., where it is lost in what may be a complex of former lagoons.

The Shelf northeast of Brigantine Shoal.—Northeast of Brigantine Shoal the shelf is dominated by several large northeastward trending embayments, and by two north-south trending channels, which are associated with a submerged alluvial gravel deposit (Schlee, 1964; charts 0807N–54 and –55). One of the north-south trending channels heads offshore near lat. 39°45′ N. and may be traced southward for about 30 nautical miles, roughly along long. 73°50′ W.

West of this channel is a very smooth and flat plain, whose shallow limit is defined by the 10- or 11-fm. isobath. On the east it is bounded by a low scarp and backed by a north-south ridge with a minimum depth of less than 9 fm. This ridge is distinct for at least 35 nautical miles along the bottom, and remnants of it extend even farther both north and south.

East of this ridge is the second of the north-south channels mentioned above. It originates near lat. 39°50′ N. and runs southward for about 30 nautical miles between long. 73°28′ and 73°33′ W. This channel is defined by the 19- to 21-fm. isobaths and is extensively barred throughout its length at those depths.

West of this second channel is another plain, somewhat dissected by northeasterly trending depressions; to the east is a broad flat-topped ridge with minimum depths of between 17 and 18 fm. Most of the channels on the east side of this ridge trend northeastward toward the Hudson Channel. North of lat. 39°50′ N., all of the old shelf channels run eastward or northeastward toward the Hudson Channel.

The gravel deposits near these north-south channels seem to have added about 5 fm. to the shelf surface off the coast of northern New Jersey. When compared to the surface south of Long Island this buildup is shown by a greater offshore extent of the 20- to 30-fm. isobaths (compare charts 0807N–54 and 0808N–54 and –55). According to Schlee (1964), these deposits are at least 10,000 years old and were probably deposited by the ancestral Hudson River.

The northernmost and largest of the northeastward trending embayments runs roughly along a line between lat. 39°05′ N., long. 74°04′ W. and lat. 39°24′ N., long. 73°20′ W. (chart 0807N–55). It is well defined between about 20 and 25 fm. and occurs immediately below the submerged gravel deposit described by Schlee (1964). It can be traced for some 50 nautical miles across the shelf and apparently connects with the 37- to 38-fm. depression below Tiger Scarp (chart 0807N–52). Southeast of this largest embayment are four similar but smaller embayments. All of these embayments are bounded on their northwest sides by low scarps and all lead into a north-northeast trending series of apparent lagoons and channels below about 35 fm. To the south these embayments are defined by the 24- to 26-fm. isobaths, but they are progressively less well formed as the end of the Brigantine Shoal Ridge is approached.

The Hudson Channel

The Hudson Channel is the best defined of the old river valleys on the shelf. It was first discovered during the 1842–44 surveys and originally mapped as a series of discrete "mud holes." Dana (1863) later suggested that these holes were part of a continuous valley that had been eroded by the Hudson River. The survey of 1882 demonstrated the continuity of the channel.

The Hudson Channel extends some 85 nautical miles across the shelf from off the entrance to New York Harbor to the head of the Hudson Canyon (charts 0807N–52 and –54, and 0808N–55). It is very shallow at its upper end, but some 10 nautical miles southeast of Sandy Hook it deepens abruptly, runs about 15 nautical miles southward, and then turns southeastward across the shelf. It is divided into a series of basins which are floored with mud and muddy sand. It becomes partially lost in an elongated flood plain and delta below about 40 fm., but several buried channels have been traced through this area, the youngest of which connects to the present head of the Hudson Canyon (Ewing, LePichon, and Ewing, 1963).

According to Ewing et al. (1963), the present Hudson Channel and Delta and the upper slope portion of the Hudson Canyon have all been in much the same position throughout the late Pleistocene. Very likely, however, the present head of the canyon is only one of the latest feeder channels for the lower canyon. Ewing et al. (1963) showed some old buried discontinuities (possibly erosion surfaces) which head northeast of the present canyon. Robertson (1964) suggested that the Georges Bank canyons were eroded during a Pliocene emergence, filled during an upper Pliocene or very early Pleistocene submergence, and then re-excavated during the Pleistocene. Some of the canyons which are immediately northeast of the Hudson Canyon, and which have their present heads below 100 fm. may be of Pliocene age and have not had their heads re-excavated because the Hudson drainage moved out of the area.

Terrains Between the Hudson Channel and the Block Channel

The shelf surface south of Long Island (charts 0808N–53, –54, and –55) has at least three types of relict terrains. Between about 15 and 35 fm. it is characterized by low ridges and shallow channels and appears to be a stream-dissected alluvial plain modified by minor features formed during the Holocene transgression. It is not covered by extensive late Pleistocene alluvial gravels like the shelf southwest of the Hudson Channel.

The shelf surface above about 15 fm. is dominated by Wisconsin glacial outwash and appears as a sand plain in front of the old moraines on Long Island. It has been much modified by early Holocene stream erosion, the late Holocene marine transgression, the modern surf-zone, and possibly by present-day storm wave action (see discussions of this region by Dana, 1875; Lindenkohl, 1885, 1891; Shepard and Cohee, 1936; Stetson, 1938b, 1949; Lougee, 1953; Elliott et al., 1955; Garrison and McMaster, 1966; and Uchupi, 1968). Below about 35 fm. the surface appears to be dominated by deltaic and alluvial deposition rather than by erosion.

As Garrison and McMaster (1966) pointed out, two major directions of past drainage are apparent on the present shelf surface south of Long Island; one (north of about lat. 40°20′ N.) is eastward into Block Channel, and the other east and southeastward into a large embayment (well defined between about 40 and 45 fm. on charts 0807N–52 and 0808N–54) near lat. 40°00′ N. and long. 72°10–15′ W.

The Block Channel

The Block Channel was discovered during the same surveys of 1842–44 that found the Hudson Channel. This broad and shallow channel extends some 70 nautical miles across the shelf, from inside Block Island Sound to its delta at the shelf break (charts 0807N–51, and 0808N–51 and –52). Block Channel has several minor tributaries entering from the west and two major tributaries entering from the east—one from Rhode Island Sound and Buzzards Bay, and the other from the area south of Nantucket Sound. The Channel and its Rhode Island Sound tributary contain what are apparently well-developed tidal deltas between about 23 and 26 fm.

Dana (1863) suggested that the Block Channel had been eroded by the Connecticut River. Garrison and McMaster (1966) considered it to have been the main trunk for southern New England drainage during late Wisconsin and Holocene times, and Krause (1966) suggested that its delta was forming throughout the Pleistocene. These authors noted that the delta's present form was reached during the early Holocene when sea level was about 45 fm. below the present one. This level is similar to the depth of formation of about 43 fm. proposed by Veatch and Smith (1939) for the Hudson Delta.

Surficial sediments in the Block Channel consist of about 16 inches (41 cm.) of fine fluvial and estuarine sands and silt, probably of Holocene age. These overlie clean medium sands of Wisconsin age and of fluvial origin. The upper 1 inch (2 cm.) or so is sandy silt, with a very high water content; it is probably late Holocene or modern sediment (McMaster and Garrison, 1966; Garrison and McMaster, 1966).

Terrains Between the Block Channel and the Great South Channel

The sea floor east of the Block Channel (exclusive of Nantucket Shoals) is zoned much the same as to the west, although it is very much smoother, contains fewer stream channels and other well-defined offshore features, and is partly covered by considerably different sediments (charts 0807N–51, and 0808N–51 and –52).

Above about 20 fm. the bottom is rough and is composed of Wisconsin glacial outwash and morainal deposits modified by stream erosion, by the late Holocene transgression, and by the present surf-zone. Between about 20 and 35 fm. the shelf is of very low relief and appears to be an alluvial plain modified by a few transgressive features.

The surficial sediments on this plain are fine to coarse sands, which Garrison and McMaster (1966) considered to be pre-Holocene fluvial deposits later reworked by the Holocene transgression. To the east, around the margin of Nantucket Shoals, these authors believed these fluvial sands to be covered by fine sand derived from the Shoals during the late Holocene or present.

The silty region south of Martha's Vineyard.—Below about 30 to 35 fm. evidence of stream erosion is sparse, the bottom is very smooth, and the surface sediments change to sandy silt (chart 0808N–52). This region is unique because it is the only extensive muddy deposit on the entire East Coast Continental Shelf that is not associated with a marked depression. It was first mentioned by Pourtales (1870).

Lindenkohl (1885) considered this muddy area to be a region of Tertiary outcrop that had not been covered by Pleistocene deposits. Shepard and Cohee (1936) thought that the silt was a modern deposit derived from Georges Bank. Stetson (1938b) also thought that silt was now being added to older sand deposits in the area, and Chamberlin and Stearns (1963) have suggested a current eddy to account for this deposition. Garrison and McMaster (1966) noted that the northern edge of the silt deposit is strongly intermixed with older alluvial sands and that the eastern edge appears to be overlain by younger sand derived from Nantucket Shoals. They believed that the silt accumulated in a topographic depression during the Holocene rise of sea level. Furthermore, they suggested silt beds under Nantucket Shoals as the source and placed the age as late Holocene (after the sea had risen to about 35 fm. below present sea level) because the surface appears smooth and uneroded.

The smooth appearance in this area may be a data artifact, resulting from a rather wide spacing of survey tracklines. Just to the east of the Block Delta is a small well-surveyed area (USCGS Hydrographic Survey No. 6659) that shows the bottom finely dissected by many small channels and covered with a few small mounds and depressions. Although this survey may indicate what the surrounding region would look like if surveyed in comparable detail, there is some doubt that it does.[2] The average standard deviation of the isobath position error in the area of USCGS Hydrographic Survey No. 6659 is 0.13 nautical mile and, because the principal tracklines run parallel to the trend of the small channels (i.e., up and down slope), lengthwise line shifts of one or two times this amount would account for much of the fine detail shown. Some of the crosslines run in this survey, however, give evidence of shallow channels, and it seems probable that the true appearance of the bottom lies somewhere between the two extremes indicated.

Nantucket Shoals.—For a distance of 30 to 50 nautical miles to the south and southeast of Nantucket Island is a vast expanse of sand shoals and a tangle of many smaller ridges and depressions (charts 0708N–51 and –52). Collectively, this area is called Nantucket Shoals and has been known since the earliest explorations of the east coast (see Rich, 1929). Two old maps showing Nantucket Shoals, one made about 1656 and the other about 1730, are reproduced in Gottmann (1961).

From geologic mapping of Nantucket Island, Martha's Vineyard, and Cape Cod, it appears that Nantucket Shoals are relict glacial deposits laid down when the sea was 25 fm. below its present level. The large shoals abutting on the Great South Channel contain a few patches of gravel and probably constitute a much modified glacial moraine formed by a late Wisconsin ice-lobe in that channel. Farther to the west, Nantucket Shoals probably were derived by reworking outwash from the west side of this South Channel moraine, or from an interlobate outwash deposit formed between the South Channel ice-lobe and another ice-lobe extending through Cape Cod Bay (Zeigler et al., 1964, suggested that outer Cape Cod is an interlobate deposit formed between these two lobes), or from end moraines of the Cape Cod Bay ice-lobe. Whatever their exact source, these Shoals have been much altered by early Holocene stream erosion and by late Holocene and modern tidal current and surf-zone action (Lindenkohl, 1883; Curtis, 1913).

Old silt beds occur under the Shoals, and Livingstone (1964) considered them to be of Sangamon age. (Athearn (1957) came to the same conclusion for a similar silt layer about 43 fm. below sea level some 60 nautical miles south of Moriches Bay, Long Island.) Groot and Groot (1964) found that samples of the upper 5 feet (1.5 m.) of the silt near Fishing Rip contained a mixture of Cretaceous, Tertiary, and Pleistocene pollen and spores, as well as a marine shell about 11,500 years old. It, thus, seems that the silt layer, at least near Fishing Rip, has been covered by the Shoal sands only in the late Holocene—probably by material washed southwestward from the lateral moraine of the South Channel ice-lobe. This type of winnowing has been invoked by Garrison and McMaster (1966) to account for the band of fine sand covering the silty area to the west of Nantucket Shoals (see also Shaler, 1893). Uchupi (1968) suggested, however, that some of this sand may have come from the erosion of the outer arm of Cape Cod.

The Great South Channel.—The existence of the Great South Channel was inferred from local surface currents by Captain John Smith as early as 1614 (Rich, 1929). It separates Georges Bank from Nantucket Shoals and is a broad and flat but rough-bottomed valley with a sill at about 40 fm. (lat. 40°36′ N. on chart 0708N–52). It is divided into a number of shallow basins by low sills. This Channel was probably occupied by a lobe of the late-Wisconsin ice-sheet, from which outwash and moraines contributed to both Little Georges Shoal to the east and Nantucket Shoals to the west (see Zeigler et al., 1964). In pre-Pleistocene time Great South Channel may have been a stream valley

[2] Personal communication from John S. Schlee, U.S. Geological Survey, Washington, D.C.

(Johnson and Stolfus, 1924; Shepard, Trefethen, and Cohee, 1934; Emery and Uchupi, 1965; and Uchupi, 1966a, 1966b).

Terraces and Shore Features on the Outer Shelf

Below about 40 fm. the outer shelf is characterized by (1) an alternation of discontinuous scarps and relatively flat terraces, some with superimposed linear ridges of coarse sands and gravels (especially well developed off New Jersey and Delaware) and (2) by ancient river deltas (especially south of New England). Most authors describe the scarps and terraces as old shoreline features, developed during lower Pleistocene sea levels (Taylor, 1872; Newberry, 1878; Lindenkohl, 1891; Shepard, 1932; Stetson, 1938b; Veatch and Smith, 1939; Dietz, 1952; and Emery, 1961).

Old shore lines.—Three sets of terraces with bars and spits are observable throughout the area. The deepest set is between 82 and 90 fm. and averages about 85 fm. Remnants of this set may be seen between Veatch Canyon and Atlantis Canyon (86–90 fm. on chart 0708N–53), just to the east of the head of Block Canyon (82–84 fm. on chart 0807N–51), and to the northeast of Hudson Canyon (82–86 fm. on chart 0807N–52). In addition, Ewing et al. (1963) discovered an 80- to 90-fm. buried erosion surface near the Hudson Canyon (their 165-m. terrace).

A shallower set, from 73 to 81 fm. and averaging about 77 fm., may be seen between Veatch Canyon and Atlantis Canyon (a double set at 78–81 and 73–76 fm. on chart 0708N–53), and to the northeast of Toms Canyon (73–78 fm. on chart 0807N–53). The 85- and 77-fm. sets of terraces south of New England have been combined by Garrison and McMaster (1966) into what they call the 80-fm. terrace.

These terraces are backed by a discontinuous scarp, whose foot is at an average depth of about 77 fm.; this scarp is the Nicholls Shore of Veatch and Smith (1939). It is well defined in the subsurface (Ewing et al., 1963) and, for the most part, appears to be a constructional escarpment formed by younger sediments deposited on an older surface. A more poorly developed deeper scarp, with its foot at about 86 fm., can be seen between Veatch Canyon and Atlantis Canyon (chart 0708N–53), and just to the west of Atlantis Canyon where it merges with the higher Nicholls Shore (chart 0807N–51).

The next set of terraces is between 56 and 71 fm. and averages about 64 fm.; it may be seen between Hydrographer Canyon and Veatch Canyon (59–62 fm. on chart 0708N–53), as well as to the west of Atlantis Canyon (64–70 fm. on chart 0807N–51), and to the northeast of Hudson Canyon (59–62 and 62–70 fm. on chart 0807N–52), Toms Canyon (64–71 fm. on charts 0807N–52 and –53), Wilmington Canyon (56–59 and 63–65 fm. on chart 0807N–56), and Baltimore Canyon (62–66 fm. on chart 0807N–56). Referring to the region south of New England, Garrison and McMaster (1966) called this set the 65-fm. terrace. It is backed by a poorly developed scarp whose foot is at an average depth of about 64 fm. Called the Franklin Shore by Veatch and Smith (1939), this scarp appears to be partly constructional and partly destructional in origin. Ewing et al. (1963) could not find a clear subsurface indication of the Franklin Shore near the Hudson Canyon.

Although these three sets of terraces and scarps were certainly formed when the sea was at various lower levels than at present, it is not easy to determine the exact levels. The difficulty was made plain by Johnson (1910, 1932), Johnson and Winter (1927), and Miller (1939) in discussions of the problems involved in correlating old shorelines now above sea level. These authors concluded that at a given sea-level shoreline features can be developed at different elevations and that determination of former sea levels by physiographic methods alone is, consequently, very inaccurate. Johnson (1932) has also pointed out that a distinction must be made between the elevations of erosional and depositional features formed at the same sea level. All of these conclusions are also applicable to submerged features

Numerous estimates of former sea levels on the outer shelf have been based on appraisals of the eustatic lowering of sea level during the formation of the Pleistocene ice-sheets (e.g., Maclaren, 1842; Taylor, 1872; Shaler, 1875; Daly, 1925; Fairbridge, 1960; Curray, 1961; and Shepard, 1961). Donn, Farrand, and Ewing (1962) give double estimates for this eustatic lowering which correspond with two different estimates of the present thickness of the Antarctic ice-cap. These, combined with dates taken from Emiliani (1961, 1964, 1966) and

Broecker (1966), are: (1) a maximum Illinoian lowering of about 75 or 88 fm. (some 110,000 years ago), (2) a maximum early Wisconsin lowering of about 63 or 74 fm. (some 53,000–60,000 years ago), and (3) a maximum late Wisconsin lowering of about 58 or 68 fm. (some 18,000–20,000 years ago).

In addition to these three terraces, Garrison and McMaster (1966) have noted the existence of another terrace formed when sea level stood at about 45 fm. This level seems to have been the latest episode in (1) large delta formation, especially south of New England, and (2) extensive barrier beach-lagoon formation off New Jersey and Delaware. The 45-fm. terrace is well developed near the Block Delta, where there is also evidence of small lagoons to the east (chart 0808N–52), and of a large spit and a barrier beach-lagoon complex to the west (charts 0807N–51 and 0808N–54). The terrace is also well developed between the Block Delta and the Hudson Canyon (chart 0807N–52) and between Toms and Wilmington Canyons where a large embayment and an extensive series of barrier beaches and lagoons seem to have formed (chart 0807N–53).

Deltas.—Old river deltas along the 45-fm. terrace are especially well developed northeast of the Hudson Channel. The 45-fm. level was the most recent episode in a long history of large-scale deltaic deposition on this part of the outer shelf. The most typical and best preserved of the old deltas is associated with Block Channel (Garrison and McMaster, 1966). From seismic profiles Krause (1966) has concluded that this delta probably existed throughout the Pleistocene. Where it bulges out over the edge of the shelf and onto the upper Continental Slope, Krause's profiles revealed a large area of bottomset beds.

Between the Block and Hudson Deltas a small delta is associated with the southeasterly drainage pattern south of Long Island. Probably of late Wisconsin or Holocene age, this delta appears to lie almost completely above the 64-fm. terrace northeast of the Hudson Canyon (chart 0807N–52).

The Hudson Channel disappears below about 40 fm. in what Veatch and Smith (1939) have called the Hudson Apron, a large delta whose latest stage of construction occurred when sea level stood at about 43 fm. The large bar, or spit, just to the northeast of the Hudson Canyon, may represent the remains of an earlier delta built during or shortly after the late Wisconsin maximum sea level regression (which probably formed the 64-fm. surface under this feature). Similar large spits to the northeast of both Wilmington and Baltimore Canyons (chart 0807N–56) may also be remnants of early or late Wisconsin deltas—probably built in this area by the Delaware River. Little evidence exists of delta formation at the 45-fm. level east of Block Channel.

Canyons and the slope complex.—The Continental Slope of Eastern North America was discovered in the early 19th century, but it was not studied in detail until the 1870's, when the first successful wire-sounding machines were introduced. The Coast Survey steamer *Blake* surveyed the slope during 1877–80 (Agassiz, 1888), and the Fish Commission steamers *Fish Hawk* and *Albatross* did extensive deep-water biological dredging, especially south of New England, during the 1880's.

Although the upper parts of canyons on the edge of the Scotian Shelf and Grand Banks had long been known to commercial fishermen (see Collins, 1885, and Johnson, 1885), no evidence of Middle Atlantic canyons was obtained until the 1842 work of the Coast Survey. After the soundings from the 1842 surveys were plotted, nautical charts carried notations of a "145-fathom hole" near the head of Hudson Canyon. Dana (1863) used an 1852 chart to trace the Hudson and Block Channels across the Shelf, but the new surveys of 1882 were required to show the immense size of the Hudson Canyon and its extension to the bottom of the Continental Slope (Lindenkohl, 1885). The upper part of another canyon, later named the Atlantis Canyon, was discovered by the *Albatross* in 1884 (Tanner, 1886). After the discoveries of the 1880's the canyons were much discussed (see Upham 1890a, 1890b, 1894; and Spencer, 1890, 1903, 1905a, 1905b)—usually in attempts to support theories of a vast uplift of the North American continent during the late Tertiary or early Pleistocene, which was supposed to have caused the ice age—but little new field work was done until the surveys by the USCGS in the 1930's (discussed by Shepard, 1931, 1933a, 1933b, 1934, 1938; Daly, 1936; Shepard and Beard, 1938; and Stetson, 1938a, 1938c). This work culminated in the report and charts of Veatch and

Smith (1939)—see also Smith (1939, 1940a, 1940b, 1941).

The origin of these canyons is still an open question, but most recent authors believe that they were formed by a combination of fluvial processes delivering sediment during lower stands of the sea and submarine transport of the sediment by mass movement and turbidity currents seaward of the shelf. Review articles on the canyons as well as on the Continental Slope and Rise have been made by Johnson (1938–1939, 1939), Veatch and Smith (1939), Stetson (1949), Deitz and Menard (1951), Dietz (1952, 1963a), Kuenen (1953), Drake et al. (1959), Heezen et al. (1959), Shepard (1963), Guilcher (1963a, 1963b), Heezen (1963), Moore and Curray (1963), Hoskins and Hersey (1965), Emery (1966b), Krause (1966), and Heezen, Hollister, and Ruddiman (1966).

The surface sediments of the slope and canyons consist of rock outcrops, deltaic deposits, and slumping debris, all of which are more or less covered by a veneer of late Pleistocene and present-day muds and organic oozes.

Terraces and Shore Features on the Inner Shelf

For the most part the inner shelf is made up of alluvial plains that have been modified by glacial outwash and by the Holocene transgression. Much of this has been discussed in preceding sections, but some of the better defined features deserve further mention. Although transgressive features occur on the inner shelf at almost every level between the present shore and about 40 fm., they seem to be concentrated in at least four major bands that occur at about 6 to 15, 15 to 27, 28 to 33, and 33 to 40 fm.

The shallowest of these bands (6–15 fm.) has been described by McMaster and Garrison (1967) who noted evidence of a barrier spit and lagoon south of Block Island at about 13 fm. (chart 0808N–51). Similar spits can also be found at about 13 fm. southeast of Cape May (chart 0807N–56), across the Great Egg Harbor River Channel and east of Brigantine Shoal (chart 0807N–55), southeast of Montauk Point (chart 0808N–53), east of Point Judith and south of Nomans Land (chart 0808N–51). Furthermore, Elliott et al. (1955) have noted a ridge, which crosses the Delaware Channel at a depth of about 15 fm., and have suggested that this ridge may be the remains of a submerged coastal terrace (chart 0807N–57).

The 6- to 15-fm. band is also well represented by channel bars and small depressions off the coasts of Delaware and New Jersey, by the barred terrace below Cholera Bank south of western Long Island (chart 0808N–55), by the tidal delta between Martha's Vineyard and Nantucket Island (chart 0808N–51), and by the higher parts of Nantucket Shoals. Most of these features are probably of late Holocene age.

The second band (15–27 fm.) is represented by: many apparent channel bars, barrier beaches, and lagoons off the coasts of Delaware and southern New Jersey; by spits and bars above Tiger Scarp (chart 0807N–52); by Cox Ledge south of Narragansett Bay and the tidal deltas in the Block Channel system (chart 0808N–51); and by a platform with numerous sand ridges south of the southeastern part of Nantucket Shoals (chart 0708N–52). These features are probably of Holocene age, with the possible exception of the platform south of Nantucket Shoals. This platform may represent the old silt beds under the Shoals and may be as old as the Sangamon (Livingstone, 1964); however, its covering of sand ridges is probably Holocene (Groot and Groot, 1964).

A Holocene age estimate for the features in this band is supported by the discovery of fossil oysters, *Crassostrea virginica*, some with radiocarbon ages of 7,300 to 10,300 years, at depths of 18 to 24 fm. throughout the mapped area (Merrill et al., 1965; Emery and Garrison, 1967). Living oysters of this species are found almost entirely in shallow inshore waters. Old fresh-water peat deposits, with radiocarbon ages of 8,600 to 11,000 years, have also been found in this band on Nantucket Shoals (Emery, Wigley, Bartlett, Rubin, and Barghoorn, 1967).

The third band (28–33 fm.) is represented by bars and lagoons off southern New Jersey and by barred terraces south of Long Island and Massachusetts. These features are also probably of Holocene age. Fossil oysters, some with radiocarbon ages of 9,800 to 10,800 years, have been found concentrated in this band throughout the area (Merrill et al., 1965; Emery and Garrison, 1967). An old peat deposit has been found at a depth of about 32 fm. on Georges Bank, just to the east of the region discussed in the present report; this has a radiocarbon age of about 11,000 years (Emery et al., 1966, 1967).

The fourth band (33–40 fm.) is marked by several terrace remnants, some with extensive bars and lagoons. For example, the foot of Fortune Scarp (northeast of the Hudson Delta) lies at about 37 to 38 fm. and the foot of Tiger Scarp at about 33 to 36 fm. (chart 0807N–52). Garrison and McMaster (1966) also noted that a significant percentage of what appear to be Holocene ridge tops south of New England are at depths of 34 to 39 fm. and an old fresh-water peat deposit has been discovered at 36 fm. just south of the mapped region (Emery et al., 1967). This peat has a radiocarbon age of 13,500 years.

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