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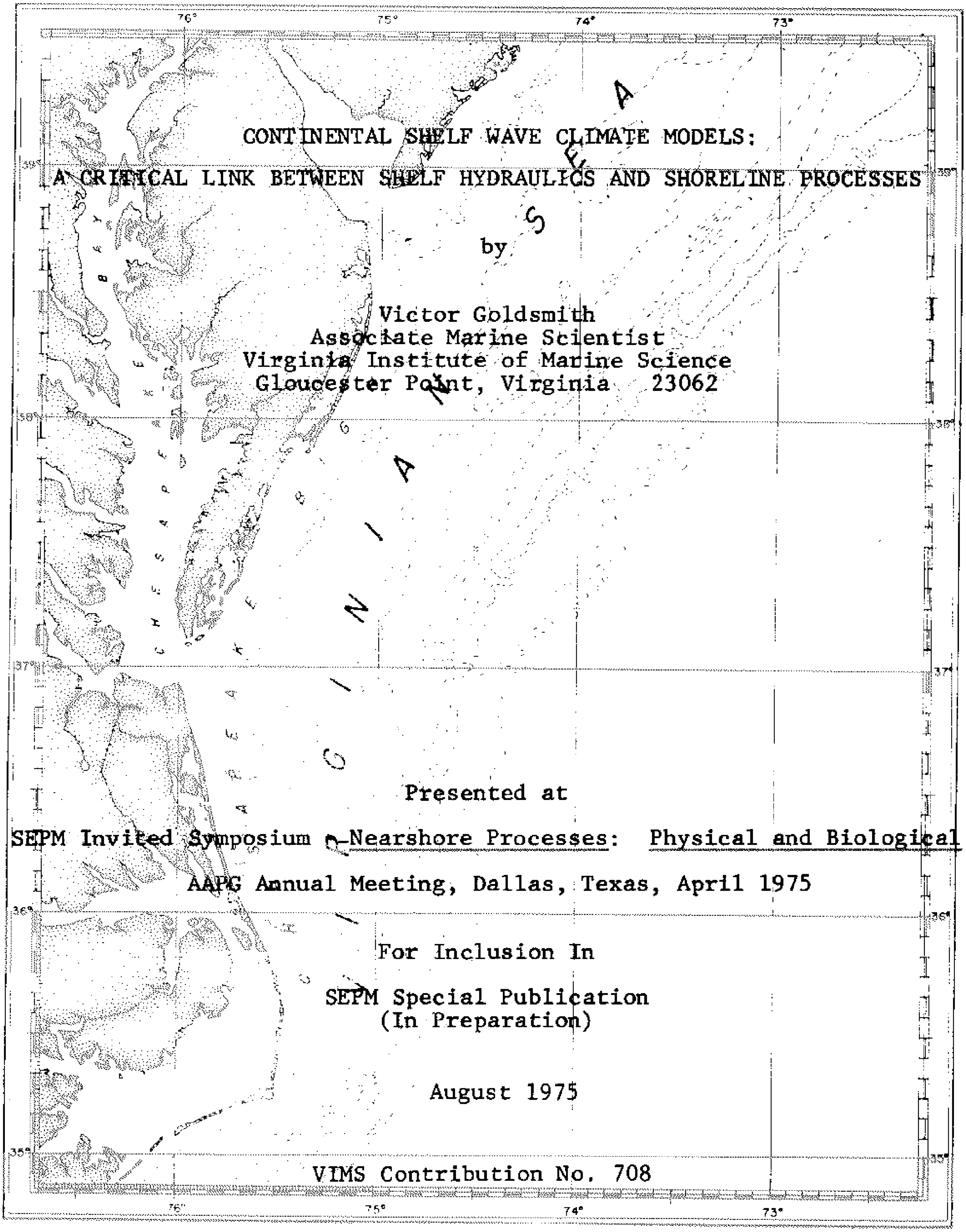

CONTINENTAL SHELF WAVE CLIMATE MODELS: A CRITICAL LINK BETWEEN SHELF HYDRAULICS AND SHORELINE PROCESSES

by

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Presented at

SEPM Invited Symposium - Nearshore Processes: Physical and Biological

AAPG Annual Meeting, Dallas, Texas, April 1975

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Abstract

In 1947, Munk and Traylor's classic paper clearly showed the importance of shelf bathymetry upon surface wave processes, and linked these processes to shoreline changes to the extent "...that wave refraction is the primary mechanism controlling changes in wave height along a beach..." (Munk and Traylor, 1947, p. 1). With the application of high speed digital computers in the 1960's, wave refraction diagrams have become commonplace in shoreline and nearshore studies.

The Virginian Sea Wave Climate Model (Goldsmith, et al, 1974) represents a significant advance in the computation and application of "wave refraction diagrams" through the use of new and more sophisticated techniques: (1) a regional approach in which 52,000 km^2 of continental shelf (out to depths of 300 m), and 160 km of shoreline, are incorporated into one wave ray diagram; (2) voluminous depths are chosen from numerous original hydrographic sounding sheets and interpolated depths are avoided: e.g., 100,000 depths were acquired for the Virginian Sea Model; (3) these depths are transferred to a common grid using a specially computed Transverse Mercator Projection "centered" on the study area in order to minimize distortion caused by the earth's

curvature (i.e., waves travel great circle paths); (4) 19 different ray parameters are computed along each ray including surface wave heights and bottom orbital velocities; (5) an improved understanding of wave behavior in the area of crossed wave rays (available from the theoretical studies of Chao and Pierson, 1972) have been applied to the interpretation of such wave phenomena as curved caustics (over the shelf-edge canyons and ridge and swale bathymetry) and straight caustics (over deep channels off the mouths of Delaware and Chesapeake Bays); (6) this information is then used to delineate areas of "confused seas" and bottom "scour" for specific wave and tidal conditions.

Wave ray diagrams, shoreline histograms and shelf contour maps, of various wave parameters for various combinations of 122 distinct wave conditions, as computed in the Virginian Sea Wave Climate Model, are being used to increase our understanding of shelf sedimentology, historical shoreline changes, and inlet hydraulics, as first suggested by Munk and Traylor 28 years ago.

INTRODUCTION

Wave refraction is essentially the bending of wave crests caused by their slowing down as depth decreases and the waves pass through shallow water in their approach to the shore. Because of the large variation in depths along most coastal areas, the slowing down of the waves occurs differentially. Such wave bending or refraction, is the major determinant of the shoreline wave energy distribution along the East and Gulf Coasts of the United

States because of the wide, shallow continental shelves. Refraction is also critical in understanding the local processes and resulting geomorphology along the United States West coast.

When a series of wave refraction diagrams are computed with the particular wave conditions chosen because they are considered to be the important wave conditions for the area, we may refer to this total series of wave computations as a wave climate model.

In this discussion we will first briefly review the historical development of the "art" of wave refraction, some of the basic behavior patterns of refracted waves, and the consequences to the adjacent shoreline. Secondly, the latest developments and applications of wave climate models will be reviewed, with emphasis on the Virginian Sea Wave Climate Model (VSWCM). Finally, the present state of the art will be briefly reviewed, and some problems necessitating solution will be enumerated.

This review is not meant to be all inclusive, but merely to highlight the state of the art--both the accomplishments and the problems--as it relates to the study of nearshore processes. For a more exhaustive treatment of the subject the interested reader is referred to Goldsmith, et al. (1974), Goldsmith, et al. (1975) and to the standard texts.

Historical Development

The study of wave refraction is thousands of years old Early wave analysts included the Polynesians who navigated their way around the south Pacific by using the crossed wave patterns resulting from waves bending around the numerous islands (Lewis, 1974). The Polynesians constructed the oldest known wave refraction diagrams using bent twigs.

Modern wave refraction studies began in the 1930's and largely owe their origin to M. P. O'Brien and his colleagues at the University of California (Berkeley) who applied Snell's Law to the process of wave slowing down (i.e., wave "refraction"). Some of this early work, discussed in O'Brien (1942, 1947), Anon. (1950), Horrer (1950) and Arthur (1951), relates to breakwater problems of stone displacement, to harbor shoaling at Long Beach and Santa Barbara, California respectively, and to other similar West Coast studies.

Emphasis in the early 1940's shifted to wartime applications-especially surf prediction on proposed Allied landing beaches (Bates, 1949). Experience gained in these applications is summarized in Johnson (1948). The manual construction of wave refraction diagrams, pioneered by O'Brien, is detailed in Johnson, et al. (1948), a basic reference for those seeking instruction on the manual construction of wave refraction diagrams, a practice now discontinued with the development of computers.

The basic relationships between offshore wave refraction, the resulting shoreline wave energy patterns and shoreline processes were most clearly detailed and verified in Munk and Traylor's (1947) classic investigation. Much of the basic wave refraction relationships affecting the beach and nearshore were delineated in their work, and are still valid. Subsequent efforts have developed more sophisticated approaches, but have added little to the basic relationships outlined in Munk and Traylor's (1947) study.

Basic Wave Refraction Patterns

Since early wave refraction studies were mostly on the west coast, emphasis in these studies was on the effects of the canyons which approached quite close to shore; in some cases within less than a kilometer of the beach. Munk and Traylor (1948) noted that for a three kilometer (two mile) stretch of shore, wave rays tended to diverge opposite (and down-wave from) the canyon, whereas along the shoreline opposite from an inter-canyon ridge the wave rays converged (Fig. 1). Many basic wave refraction patterns were delineated within their study: (1) larger measured wave heights occurred along the shoreline near computed wave ray convergences, and lower measured wave heights occurred in shoreline areas of computed wave ray divergences for specific wave conditions (Fig. 2); (2) short wave periods gave smaller variations in shoreline wave heights (this is because the longer waves "feel" the bottom sooner, and are refracted more than the shorter waves); (3) different wave approach directions (for the same wave periods) changed the shoreline locations, but not the spacing of areas of higher and smaller calculated wave heights; (4) crossed-wave fronts, which developed on the downwave margins of steeply decreasing bathymetry (e.g., canyon rims), were detected in the refraction diagrams and verified in photographic studies.

Such commonly-occurring crossed-wave patterns, termed caustics from the application of geometrical optics to wave studies, were further described by Pierson (1951). Wave caustics are one of the major areas of controversy in the interpretation of wave refraction diagrams because of the inability of linear wave theory to mathematically describe the wave caustic.

Many investigators of nearshore processes were quick to apply these aspects of wave refraction to their studies. Shepard and Inman (1950) related nearshore circulation (such as rip currents) and geomorphology (such as spits) to areas of wave ray divergence caused by wave refraction. Bascom (1954) used wave refraction diagrams to help explain how this longshore variation in wave heights, due to wave refraction, controlled the location of stream outlets. This is, in shoreline areas of wave ray divergence, the resulting beach berms were at lower elevations due to the lower impinging wave heights, thereby encouraging streams to enter the ocean at these areas. Bascom (1954) found these relationships to hold for examples of wave refraction around tombolos, headlands and opposite marine canyons.

With the advent and application of high-speed computers, wave refraction really came of age (e.g., Lepetit, 1964; Harrison and Wilson, 1964). There was one change in the theory employed in most of the computer-drawn wave refraction diagrams, however, which is often overlooked by those interpreting these diagrams. This relates to the variation in the spacing between the wave rays, which is used as an indication of wave heights along the wave fronts. In the older, manual-drawn diagrams a simple ratio of the distance between adjacent rays in deep water relative to shallow water was used to calculate the shallow water wave heights, wave energy, and other parameters. In the computer-drawn diagrams a method suggested by Munk and Arthur (1951) has been adopted.

This method assumes that a second ray is spaced an infinitesimal distance from the first ray, and the mathematical expressions relating to "wave intensity" proposed by Munk and Arthur (1951) are used to calculate this ray spacing, and consequently the wave height. Thus, in the wave refraction diagrams employing this technique, wave heights and other related wave parameters are calculated along each wave ray, and each ray is "unaware" of the presence of the other wave rays. Partly for this reason, Chao (1974) suggested reverting back to a variation of the manual method, for the proper interpretation of crossed-waves, even for computer-drawn diagrams. However, Chao, et al. (1975) in a more recent paper have returned to the Munk and Arthur (1951) wave intensity method, with some modification within the wave caustic area. Additional aspects of the interpretation of crossed-wave fronts will be discussed in a later section of this paper.

Recent Applications

Wave refraction diagrams have been used to trace the paths of seismic sea waves across the Pacific (Wilson and Torum, 1968; Keulegan and Harrison, 1970) and in particular, to interpret the high destruction at Crescent City, California relative to adjacent coastal areas (Roberts and Kamper, 1964).

More commonly, wave refraction has been used to understand dramatic longshore variations in shoreline erosion and accretion (Goldsmith and Colonell, 1970), nearshore bottom sediment distribution (Farrell, et al., 1971), the role of wave climate in river delta morphology (Coleman and Wright, 1971), the mysterious loss of two British trawlers in the North Sea (Pierson, 1972), the development and maintenance of nearshore sediment and morphology cells (May and Tanner, 1973), reef design for recreational surfing (Walker, et al., 1972), the development of offset inlets (Goldsmith, et al., 1973), and many other applications.

VIRGINIAN SEA WAVE CLIMATE MODEL (VSWCM)

The Virginian Sea Wave Climate Model differs from previous models in the following important elements:

(1) The model covers a very large geographic area of the continental shelf and shoreline, Cape Henlopen, Delaware to Cape Hatteras, North Carolina, an area of 52,000 km^2 within a single large grid (Fig.3). The importance of this approach is that the resulting graphical display allows the investigator to visually integrate patterns of wave behavior which would escape detection when smaller areas are used; as a result, regional differences in behavior within the grid stand out. More detailed studies can then be made on a finer-mesh grid in specific subareas by using the wave information from the large grid as input to the smaller grid.

(2) Distortions due to flat representations of the spherical earth and problems resulting from the fact that waves travel great circle paths were overcome by constructing a transverse Mercator map projection tangent to the earth along the center of the grid.

(3) An improved understanding of wave behavior in the area of crossed wave rays is now available from the theoretical studies of Chao (1972) and Pierson (1972). These studies have been applied to the interpretation of such wave phenomena as curved caustics (which occur over continental shelf ridge and swale bathymetry) and straight caustics (which occur directly over the margins of the deeply incised channels off the mouths of the Delaware and Chesapeake Bays).

The depth grid utilized an input of 84,420 depths with a unit cell of 0.5 nautical miles on a side. The specified wave input conditions considered nine initial directions for six different wave frequencies, two wave heights, and two tidal conditions (for three approach directions). In all, 122 separate wave conditions were used with 19 different wave parameters computed as output for the entire shelf and adjacent shoreline.

These aspects are thoroughly described in Goldsmith, et al. (1974) from which much of the discussion in this section is taken. Our exhaustive studies have shown that one of the major weaknesses in such an effort is the horizontal and vertical accuracy of depth information on the original hydrographic sounding sheets available for much of the United States East coast. Furthermore, the depth information is considered to be a far more important problem in the efficacy of the methodology than any weaknesses in the wave theory discussed here and elsewhere.

Data Input

Depths--

Despite the wide usage of original sounding sheets, few sources of written information exist on the accuracy criteria desired and met in these surveys as well as the corrections employed or not employed and their justifications. In order to fill this critical information gap a study on the accuracy of the depth and navigational positioning has been made by Sallenger, et al. (1975). Figure 4 taken from Sallenger, et al. (1975) illustrates different criteria set by the U.S. Coast Survey and its successor agencies for surveys of different dates. The depths at which waves of the periods used in this study are first significantly refracted by the sea floor irregularities are plotted over the Coast Survey accuracy criteria to give an indication of the depth errors influencing the wave climate model. Only four of the charts which were used in the depth accumulation were surveyed prior to 1915, and only three of these charts were surveyed prior to 1870. These charts (prior to 1915) used for the model were surveyed where the depths did not exceed 27 meters.

Approximately 100,000 of these original uninterpolated depths were transferred from the 61 sounding sheets and other data, using latitude and longitude onto a transverse Mercator map projection 2.4 by 1.2 meters, specially constructed for the present study. Then 84,420 of these depths were read from the map grid of 0.5 nautical mile squares and punched on cards.

Wave Conditions--

The second major input to the Wave Climate Model is a wide variety of wave conditions. Approximately 200 to 250 wave orthogonals were propagated shoreward from deep water[1] for each

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[1] Waves propagating landward from deep water will be slowed to $0.996C_o$ at $d = \frac{1}{2} L_o$. Similarly, at $d = \frac{1}{4} L_o$, the waves are traveling at $0.92C_o$, and at $d = 1/8\ L_o$, they are traveling at $0.66C_o$. Therefore, the slowing down of the wave is a gradual process, and for the purpose of starting the 14-second waves, deep water was considered to be where the waves were not appreciably affected by the bottom or at depths $\geq \frac{1}{4} L_o$.

of 122 wave conditions. The wide variety of wave conditions (Table 1) was chosen in order to model as many different combinations of wave period, direction, height, and tidal conditions as possible from amongst the infinite variety of conditions that occur in nature.

Thus, a "library file" of a wide variety of wave conditions is accumulated so that it can be used in conjunction with other geological, biological, and chemical studies of the shelf and shoreline and as an aid to resource managers charged with selecting sites for offshore ports and shoreline defense structures.

One might ask the question as to why this "scattergun" approach with respect to wave input conditions. Why not zero in on just the most significant waves for calculating the wave parameters? There are two reasons why a wide variety of wave conditions is calculated. First, anyone can testify to the almost infinite variety of wave conditions that may occur over a long span of time. Second, data for determining the precise percentage of time that a given wave condition will occur are presently unavailable in most areas. The large spectrum of conditions is also needed in order to calculate parameters such as mean wave height at a shelf location and total shoreline wave energy along a stretch of coast during an average year. This could be easily calculated by summing up, based on frequency of occurrence, the data for a given location from each of the calculated wave parameters. Also, in order to determine the effects

TABLE 1.- INITIAL DEEP-WATER WAVE CONDITIONS

Tide		Wave direction, deg	Wave periods, sec	Wave height	
m	ft			m	ft
0	0	0	4, 6, 8, 10	0.61, 1.83	2, 6
		22.5	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
		45 NE	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
		67.5	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
		90 E	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
		112.5	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
		135 SE	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
		167.5	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
		180 S	4, 6, 8, 10, 12, 14	.61, 1.83	2, 6
+1.22	+4.0	45	4, 6, 8, 10, 12, 14	.61	2
		90	4, 6, 8, 10, 12, 14	.61	2
		135	4, 6, 8, 10, 12, 14	.61	2

of storm waves along a shoreline, the sequence of weather fronts and resulting storm-generated waves is needed.

Such data come from four sources: (1) wave measurements by instruments in deep water, (2) wave measurements by instruments in shallow water and along the shoreline (i.e., on piers, anchored buoys, etc.), (3) shipboard wave observations compiled by U.S. Naval Oceanographic Office by 10° squares called Marsden squares, and (4) wave hindcast calculations. None of these methods has produced data considered adequate for the Virginian Sea.

Data from source (1) are quite rare, and where available, are generally of insufficient duration to be statistically valid. Summaries of shallow water wave measurements calculated from coastal wave gages were found to bear little relationship to individual shipboard wave height and period observations off the east coast of the United States (Thompson and Harris, 1972). These authors further concluded that if adequate data were available from shipboard observations, wave refraction methods would be useful in determining shallow water and shoreline wave parameters. Furthermore, no procedures presently exist for propagating waves seaward (incorporating the effects of bottom friction), which use wave parameters determined from coastal gages as input.

Shipboard wave opservation data are not accurate enough for determining the percentage frequency of occurrence for a given wave condition, as there are several inherent biases built into the present data collection system. Several of these biases, such as the awkward computer forms, are discussed by Harris (1972).

Another bias is suspected from the interpretation of summary graphs of shipboard wave observations from the Marsden squares adjacent to Cape Cod, Mass. (Goldsmith, 1972) and the southern portion of the Virginian Sea (Goldsmith, et al., 1974). In these two area summaries, the dominant waves on an annual basis appear to approach from the west, despite the proximity of land to the west and more than 3000 n. mi. of ocean to the east. One possible explanation for this suspected bias is related to the fact that the shipboard wave observations are recorded as part of a voluntary program. Ships tend to avoid extreme wave conditions, and when they do encounter severe conditions, the assigned observer might find that he has more important duties to perform than filling out wave forms. Nevertheless, shipboard observations appear to be the best information available at present for summing up individual wave conditions. These data have been used with some success in making littoral drift calculations along the coast of Florida (Walton, 1973).

The final method used in summarizing wave conditions utilizes wave hindcast calculations. Hindcast calculations using the Bretschneider-revised Sverdrup-Munk (significant wave) method have been computed for four stations along the U.S. East Coast, including one adjacent to the Chesapeake Bay entrance, by using data from weather stations for the 3-year period, 1948-1950 (Saville, 1954). There are large discrepancies between the shipboard wave observations and these wave hindcast data (Goldsmith, et al., 1974). Important considerations in these discrepancies are the two major assumptions used in wave hindcasting: (1) deep water for 360° around the hindcast station and (2) that meteorological conditions in the 3-year period, 1948-1950, are representati of long-term weather conditions.

Verification of Wave Ray Diagrams

A test of the wave ray diagrams in duplicating complex wave conditions was made by Farrell, et al. (1971) and is illustrated in Figure 5. The input for the diagram was based on the actual wave conditions as closely as they could be determined from the lower right margin of the photograph in "deep" water. Note the excellent qualitative comparison, even in the caustic regions down wave from the island.

Shelf Geomorphology

Two important aspects of the shelf geomorphology in this area are the great width and relatively shallow nature of the continental shelf (Fig. 3). The abrupt increase in gradient at the shelf edge is between depths of 61 and 91 meters and is located as much as 60 n. mi. from shore. Thus, a great expanse of the continental shelf, and superimposed relief elements, is available for influencing wave behavior.

A closer examination of the detailed bathymetric map of the sea floor (Fig. 3) reveals that the shelf surface is not a smooth plain but instead consists of numerous irregularities.

These irregularities may be divided into two groups:

(1) Large-scale morphogeometry consists mainly of erosional forms cut into the shelf such as terraces, channels and valleys, and shelf-edge canyons.

(2) Small-scale shelf relief elements consist of low relief features (i.e., less than 9 meters) of probable depositional origin, most notably ridge and swale bathymetry and arcuate (e.g., cape-associated) shoals.

Whereas the origin of group (1) features is directly related to a lowered sea level, group (2) features probably formed since the last rise in sea level under the present shelf hydraulic conditions. The most recent eustatic sea level lowering reached its maximum extent approximately 15,000 years ago on the Atlantic Continental Shelf (Milliman and Emery, 1968).

Large-Scale Morphogeometry--

1. Terraces. The most pronounced terraces adjacent to Chesapeake Bay are at 24, 30, 40 and 86 meters. The presence of these terraces on the sea floor indicates a step-like bathymetric profile. The effect of the steeper portions of the profiles on the incoming waves will depend primarily on the angle of wave approach to these rises. However, even the steepest rises have relatively low-gradient slopes. The slope is 0°07'19" for the rise between depths of 87.8 and 62.2 meters as compared with a slope of 0°01'58" for the total shelf landward of the depth contour of 62.2 meters.

2. Subaqueous stream drainage. The major relief features remaining from the Pleistocene stream drainage are the shelf valleys at the mouths of Delaware and Chesapeake Bays which are generally perpendicular to the strike of the terraces. Swift (1973) has suggested, however, that the Delaware shelf valley is an estuary retreat path and not a drowned river valley. Both these southeastern-oriented valleys have a pronounced influence on the wave refraction patterns, with areas of confused seas forming over the seaward rim of the shelf valleys.

Most of the relict Pleistocene river channel network has been filled in with sediments. However, subtle changes in relief in some areas of the shelf surface of the Virginian Sea are suggestive of former channels. Examples of these transverse shelf valleys are found between the mouth of Chesapeake Bay and Norfolk Canyon (Susquehanna Valley), from the Delaware Bay shelf valley to the shelf edge (Delaware Valley), from the Chesapeake Bay shelf valley southeastward to the shelf edge (Virginia Beach Valley), from the vicinity of Oregon Inlet, N.C., southeastward to the shelf edge (Albermarle Valley), and from the Metomkin-Assawoman Island, Va. vicinity east-southeastward to Washington Canyon. The valley names are adopted from Swift, et al. (1972), see Figure 3.

3. Virginia Beach Massif. The Virginia Beach Massif, between the Susquehanna Valley and the Virginia Beach Valley, is an extensive shallow, relatively level-topped topographic high lying approximately between the depth contours of 18.3 and 21.9 meters (Fig. 3). This imposing large-scale relict feature, of probable

interfluve origin, contains a superimposed irregular ridge and swale bathymetry, which is delineated by the depth contour of 18.3 meters. The Virginia Beach Valley, flanked to the northeast by the Virginia Beach ridges on the topographic high and to the southeast by the False Cape ridges, is indeed suggestive of a series of relict ebb-tidal deltas formed as the sea level rose and the estuary mouth retreated, as hypotehsized by Swift, et al. (1972).

This complex topographic high, originating as an interfluve feature, with subsequent superimposed tidal-delta-associated ridges that have been modified under the present shelf hydraulic regime, has been named the Virginia Beach shoal retreat massif by Swift, et al. (1972).

Small-Scale Shelf Relief Elements--

1. Linear ridges. Superimposed on the larger relief elements is an undulating ridge and swale bathymetry composed of shoals with less than 9 meters of relief, with the long axis generally extending from 1 to 10 n. mi. and oriented such that it forms a small angle (< 35°) with the present shoreline. Linear ridges, separated by valleys called swales, are most prominent opposite the shorelines of Delaware and Maryland, the southern Delmarva Peninsula, the Virginia-North Carolina state line, and Oregon Inlet to Rodanthe, N.C.

2. Arcuate shoals. The arcuate shoals are most prominent when associated with capes such as within Chincoteague Shoals

opposite the south end of Assateague Island, Md. and Va. They are even more extensive immediately south of the study area, within Diamond Shoals opposite Cape Hatteras, N.C. Arcuate shoals are also located opposite the mouths of nearly all inlets along the coast of the Virginian Sea. The formation of the inlet shoals (i.e., ebb-tidal deltas) is related to the tidal-current-wave interaction, and they often have an important effect on the near-shore wave refraction patterns.

Probably the largest arcuate shoal in the study area is one associated with the entrance to Chesapeake Bay. Though highly bisected and cut by tidal channels, the distinct convex-seaward arcuate shape of this intermittent sand body, encompassing the mouth of the Bay, can be delineated from the detailed bathymetry. This huge sand body, suggestive of an ebb-tidal delta, may also be directly related to the origin of linear ridges adjacent to False Cape. Indeed, many of the linear ridges, especially those attached to shore, as well as many of the arcuate shoals, may owe their origin, in part, to the formation of now relict ebb-tidal deltas.

Data Presentation

The wave refraction calculations for this wide shallow shelf and adjacent shoreline area have been presented within several formats in a continuing series of publications, in order to encourage the widest possible usage.

1. <u>The wave ray diagrams</u> clearly illustrate the importance of these aforementioned east coast shelf-relief elements and shoreline wave energy distribution (Figs. 6a-c) much as Munk and Traylor (1947) found in their manual wave refraction diagrams drawn for the United States west coast.

A specific example of such shelf-shoreline interaction, quite prominent on much of the east coast shelf, is schematically presented in Figure 7. In addition to the development of alternate shoreline zones of wave ray convergence and divergence by the wave refraction over these abundant linear ridges, these studies further suggest that such wave refraction may be an important process whereby these linear ridges are developed and maintained (Goldsmith, 1972). The bending of the wave fronts over ridges tends to encourage sand movement both downwave and toward the long axes of ridges. This process would result in the observed shape and orientation of the linear ridges with their long axes oriented perpendicular to the dominant wave approach directions on much of the shelf (see Uchupi, 1968; Fig. 14).

2. <u>Shelf contour diagrams</u> (from Goldsmith et al., 1975) of wave height and maximum bottom wave orbital velocities have been prepared for the Virginian Sea shelf by contouring these values. The parameters were calculated along each of the wave rays for 122 specific wave conditions (Figs. 8a-c).

Note that both the wave heights and orbital velocities are higher over the relatively shallow Virginia Beach Massif (Fig. 3), and as a result are lower downwave from this feature, and seaward of the Virginia Beach area. Also note the tendency for the wave rays to converge, and hence, greater wave heights, at the inlets of the Virginia Eastern Shore barrier islands (Fig. 8b). This relationship exists for many of the wave ray diagrams in Goldsmith, et al. (1974).

3. Shoreline histograms of wave height and wave energy (from Goldsmith, et al., 1975) are computer-drawn from the values of height and energy calculated at the ends of each of the wave rays. Where two or more wave rays impinge upon the shore quite close together, the wave heights from these superimposed rays are added. Thus, for this and other reasons important differences do occur although there is generally a qualitative agreement between shoreline histograms of wave ray frequency and wave height and energy (Fig. 9).

Examples of these shoreline histograms at 1 nautical mile class intervals for 200 nautical miles (160 km) of coast, are presented in Figures 10a-c. The first two diagrams illustrate shoreline wave heights, and the third illustrates shoreline wave energy distribution. Thus, Figures 6b, 8, 10b and 10c all display wave information for waves from the east with a period of 10 seconds, but with a variety of formats.

Note the dramatic shoreline variations in wave ray convergences and divergences, in wave heights and wave energy, all for waves from the east. This is caused by extensive wave refraction over many shelf relief elements superimposed on the wide, shallow shelf (discussed in an earlier section and shown in Fig. 3).

Shoreline Response

Large variations along the shoreline in the computed wave parameters should be reflected in the shoreline processes, and these processes should be reflected in the shoreline response. The most obvious parameters that may be used to delineate the shoreline response are long-term historical shoreline changes and perhaps grain size of beach sediments.

Historical Shoreline Changes--

Shoreline changes for the area between Cape Hatteras and the Delaware-Maryland line are shown for approximately 80 to 105 year intervals (as indicated), depending on when the oldest and most recent surveys were made (Fig. 11). Several aspects of these data are of interest:

1. The largest amounts of erosion (i.e., shoreline recession) occur in the vicinity of inlets.

2. Even in areas away from inlets (e.g., south of Chesapeake Bay entrance) there is a large variability in shoreline erosion.

3. Other than at the inlets, the major erosion in this area occurs at Cape Hatteras and south of the Virginia-North Carolina state line.

4. The major accretion in this area occurs at the Maryland-Virginia state line and approximately 15 miles north of Cape Hatteras. There is little shoreline net change at about 36° N latitude.

Thus, the large variability in shoreline wave heights and wave energy appears to be reflected in the large variability in historical shoreline changes. With respect to 1. (above), the tendency for wave ray convergence at these inlets has already been mentioned. Of course, tidal processes are also involved. However, the relationship between inlets and the computed wave energy concentrations may be an indication of the origin of the inlets at these particular locations, with the size of the tidal prisms being a major factor in maintaining the inlets.

With respect to 3. (above) there appears to be a direct correlation between the shoreline recession at the Virginia-North Carolina state line (up to 5 meters/year) and the larger calculated wave heights (e.g., waves from the east with 10 and 14 second periods; Figs. 10a, 10b). Similarly, areas of accretion or small shoreline changes (in 4. above) compare well with low calculated wave heights (Figs. 10a and 10b).

It needs to be pointed out, however, that these are qualitative correlations, and that the correlations may be better for some wave conditions than for others. Present work at VIMS is being directed at quantifying and statistically representing these relationships for the 122 computed wave conditions. Spectral analysis techniques are being applied to shoreline spacing of wave heights. Preliminary analyses suggest strong spectral peaks at spacings of 5.3 and 12.0 n. mi. for the 200 n. mi. of coast for waves from the east (Goldsmith and Colonell, 1975).

Grain Size Distribution--

Mean grain size and standard deviation have been determined for the beach berm crests in four different investigations, at different times (Fig. 12). Despite the expected variability, some trends are apparent in this summary:

1. Whereas the northern area (Cape Henlopen to Chesapeake Bay entrance) shows a decrease in mean grain size to the south, the data for the southern area (i.e., the Outer Banks), indicates a general increase in mean grain size toward the south.
2. The coarsest beach sand is located north of Duck, North Carolina and at the south end of Assateague Island.

With respect to the former, it has been suggested that the increase in grain size to the south along the southerly Outer Banks is due to an increase in shoreline wave energy due to the abrupt narrowing of the shelf to the south (Shideler, 1973). This hypothesis seems to be substantiated by the computed shoreline wave heights for easterly 14-second waves (Fig. 10b), but not easterly 10-second waves (Fig. 10a). Does this mean that the 14-second wave is more important along the Outer Banks? Again, we need to expand our efforts along these lines by quantifying and further examining these relations. With respect to the very coarse zone north of Duck, North Carolina, reconnaissance surveys by the author suggest that this zone is due to an additional local source of sediment. The local sediment source, which is most probably a relict deposit, could be on the shelf and is being reworked and moved landward by waves, or could have originated when Currituck Sound had a direct opening through the Outer Banks barrier into the ocean.

STATE OF THE ART

Despite the wide usage of the wave refraction, and application to many coastal problems, theoretical advances in the approach since the work of Munk and Traylor has been surprisingly limited. In general, great confidence exists in the ability of the computed wave ray diagrams to reproduce wave behavior, even in areas of complex conditions (e.g., Fig. 5). Somewhat less confidence exists in the results of the wave computations involving wave height, such as wave energy and bottom orbital velocities. These data can, and should continue to be, used for understanding coastal processes, computation of design wave conditions, and other uses. This cautionary note is merely meant to heighten the awareness that there are still unsolved problems, some of which are discussed below.

Depth Fitting Procedures

All of these methods involve some application of a technique to smooth a surface fitted to the depth at the "local" grid points. Dobson (1967) fitted a quadratic surface to a grid of 12 adjacent depths in the form of a cross in order to determine the "local depth" (i.e., depth and locations between grid points). This is the scheme used in the VSWCM.

There is probably not another aspect of wave refraction computation, except for crossed-wave patterns, that produces so much controversy as that of local depth determination. Most of the current schemes employ such a grid of measured depths for this purpose. There seems to be as many schemes for handling this problem as there are programs. While each scheme has both advantages and disadvantages, there is none that is clearly superior to all others. This state of affairs is largely due to the fact that there does not seem to be a general agreement on what criteria should be used to evaluate the various schemes! Until such agreement exists, those schemes having the loudest and most persistent advocates will enjoy the highest regard.

Thus, in view of the limitations in the available depth information (discussed previously), it seems of little consequence to incorporate "better" depth-finding subroutines until we make vast improvements in the quality of our basic depth information (Fig. 4).

Crossed-Wave Patterns

The effects of shoaling and refraction can be estimated by linear wave theory. For example, the propagation of surface waves into shallow water is analyzed by consideration of the wave energy between two vertical planes which are orthogonal to the wave crests and which intersect with the surface to produce wave rays. Energy is assumed not to be transmitted along the wave crest; thus, it is not transmitted across wave rays. If it is also assumed that the wave period is constant and that there is no loss or gain of energy from reflection or percolation, then linear wave theory provides the well-known result,

$$\frac{H}{H_o} = K_r K_s K_f \tag{1}$$

Where H is modified wave height

" H_o is initial deep water wave height

" K_r is coefficient of refraction

" K_s is coefficient of shoaling

" K_f is coefficient of friction

The coefficient of refraction is given by

$$K_r = \frac{b_o}{b}^{\frac{1}{2}} \tag{2}$$

Where b_o is initial distance between adjacent rays

" b is distance between adjacent rays

It can be seen that in the calculation of the wave refraction coefficient (K_r) that as b goes to 0.0 when the wave rays cross, the resulting wave height will approach infinity; that is, according to linear wave theory. Wave observations and subsequent theoretical work prove that this is certainly not the case; i.e., wave heights do not become infinitely high. The proper interpretation of crossed wave rays (or fronts) in the refraction diagrams (i.e., caustics), such as those in many of the wave refraction diagrams, does not appear to be the problem it was once thought to be. Chao, in a thorough series of theoretical (Chao, 1970, 1971), wave tank (Chao and Pierson, 1970, 1972), and continental shelf (Chao, 1972, 1974) refraction studies of this caustic phenomena, has reached the following conclusion for such wave refraction studies (Chao, 1974, p. 32): "The rays, after escaping from the caustic regions, eventually follow the continued ray path and the wave conditions are determined by the b factor just as if no caustic had occurred except that there has been a phase shift, which is unobservable because of the randomness of waves in nature. These conditions eliminate the necessity of the evaluations of the waves near a caustic..." Although some wave height changes may occur in the waves that pass through a caustic region, theoretical and wave tank studies (Chao and Pierson, 1972) suggest that such changes seaward of the zone of breaking waves may be minimal and well within the bounds set by other limiting factors, such as depth information.

The qualitative correlation between the Saco Bay photograph and diagram (Fig. 5) suggests that the computational procedure is reasonably valid for this situation which is characterized by a complex shoreline and irregular bathymetry.

Wave Energy Dissipation due to Bottom Friction

The VSWCM incorporates the effects of bottom friction, which, in the wide shallow shelf of the Virginian Sea, acts to reduce wave energy and consequently, wave heights approximately 50 to 75 percent for the longer wave periods. Thus, these computations of bottom friction are quite important. The calculations of frictional loss were adopted from computer routines developed by Coleman and Wright (1971) based upon equations for calculating bottom friction developed by Putnam and Johnson (1949) and modified by Bretschneider and Reid (1954) and Bretschneider (1954).

Bretschneider and Reid (1954) presented a general theoretical solution for Putnam's equations for deriving wave energy loss due to bottom friction. In these equations a friction coefficient of 0.01 was used, but only with a carefully phrased preface alluding to the numerous assumptions that were made. These assumptions involve steady wave conditions, and hence, a stable bottom, because studies by Savage (1953) and others had demonstrated large variations in K_f with changes in bottom sand ripples. This results in up to 25% loss in wave height due to the presence of bottom sand ripples. Changes in bottom material along wave paths was also mentioned by Bretschneider and Reid (1954) as critical with respect to choosing a value for K_f.

In a succeeding report, Bretschneider (1954) reported on the results of a field investigation which was conducted, as a companion study to the theoretical work, in order to refine the equations for wave energy loss from bottom friction. The average of 10 values of K_f was 0.053 (Table 3, p. 9), and was derived from field measurements of wave height changes between two offshore oil platforms in the Gulf of Mexico. Because of the surprisingly high value of K_f, it was decided to carry the investigation further (Bretschneider, 1954, p. 10). A solution was theoretically derived to account for some of this energy loss through non-frictional processes; i.e., having a non-rigid, impermeable bottom, participate in the wave motion.

A thorough review was made by Jonsson (1966) of the methodologies for directly or indirectly measuring bottom friction under oscillatory flow. Jonsson (1966, p. 140) concluded that, "In nature the boundary layer is always rough and turbulent (thus, there is more friction than with laminar flow). The friction factor here will often exceed the value of 0.02 adopted by Bretschneider (1965). This is also confirmed by the observations of Iwagaki and Kakinuma (1965)". More recent studies have further supported this contention.

In summary then, both Bretschneider's theoretical and field studies fall far short of predicting a particular value for the frictional coefficient. Surprisingly, the value of .01 for K_f, which resulted largely from theoretical rather than field considerations (e.g., Bretschneider, 1954; Iwagaki and Kakinuma, 1965) has been generally adopted (see for example, CERC, 1973, p. 3-46) despite much subsequent work which indicates that a much higher value should be used for K_f.

In the VSWCM a value of $K_f = 0.02$ was used in order to adopt a conservative approach, since the higher the value of K_f, the greater the frictional reduction in wave height during wave progression through shallow water. However, the potential wave analyst should be alert to this new body of literature and evaluate the wave results accordingly.

Zone of Breaking Waves

Because of the complexity of the wave processes within, and landward of the zone of breaking waves, few attempts have been made to continue the wave refraction computations into this zone. Thus, nearly all of these refraction programs, including the VSWCM, end at the point of wave breaking. In reality, however, in areas of low nearshore gradients the waves generally break, reform, and break again, adding to the complexity of interpretation.

The major significance of this limitation is in the use of wave climate models in the computations of longshore drift, which is certainly a critical parameter for understanding the coastal processes of a particular area. There are, at present, several promising efforts in longshore drift computations that are applicable to adoption within presently existing wave refraction schemes, such as Komar (1975), Tanner (1974), Walton (1973 Galvin (1973), and Fox and Davis (1973).

CONCLUSIONS

Wave climate models have become an important tool for assisting in the understanding of coastal processes. This is because of the general recognition that the most important wave process on the continental shelf is the interaction between the ocean waves and the various shelf relief elements, resulting in the observed nonuniform wave energy distribution over the shelf and along the nearshore zone.

A regional approach to the study of this nonuniform wave energy distribution by the VSWCM has shown that the large variations in computed shoreline wave heights and wave energy are reflected in the large variations in the observed historical shoreline changes and, to a lesser extent, in the beach grain size variations.

Basic wave refraction patterns result in a wave energy concentration downwave from a topographic high (e.g., linear ridges) and a wave energy diminution downwave from a topographic low (e.g., shelf canyons). Also, of importance are areas of "confused seas", or crossed wave patterns (i.e., straight caustics), that occur over the downwave side of canyon rims for particular wave periods and approach directions, and other shelf areas.

The ability of wave refraction diagrams to accurately duplicate wave behavior, even under complex crossed wave patterns, has been largely verified. The results of computations of wave parameters based on wave heights should be interpreted in terms of the present state of the art with respect to the problems of bottom friction, crossed-wave patterns, and wave behavior beyond the zone of breaking waves.

ACKNOWLEDGMENTS

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SYMBOLS

AZ = incoming wave approach direction

b = distance between adjacent rays

b_o = initial distance between adjacent rays

C = modified water wave celerity

C_o = initial deep water wave celerity

H = modified wave height

H_o = initial deep water wave height

K_f = coefficient of friction

K_r = coefficient of refraction

K_s = coefficient of shoaling

L = modified wavelength

L_o = initial deep water wavelength

T = wave period

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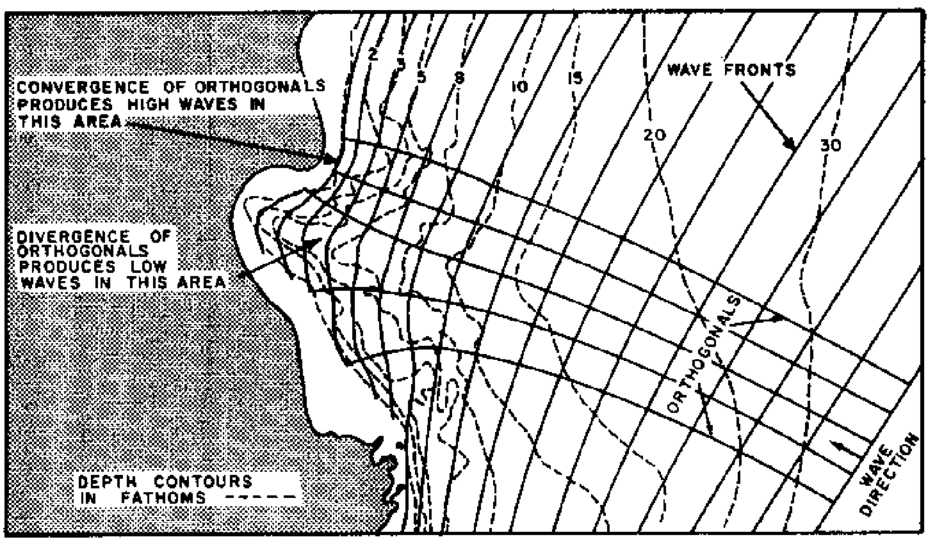
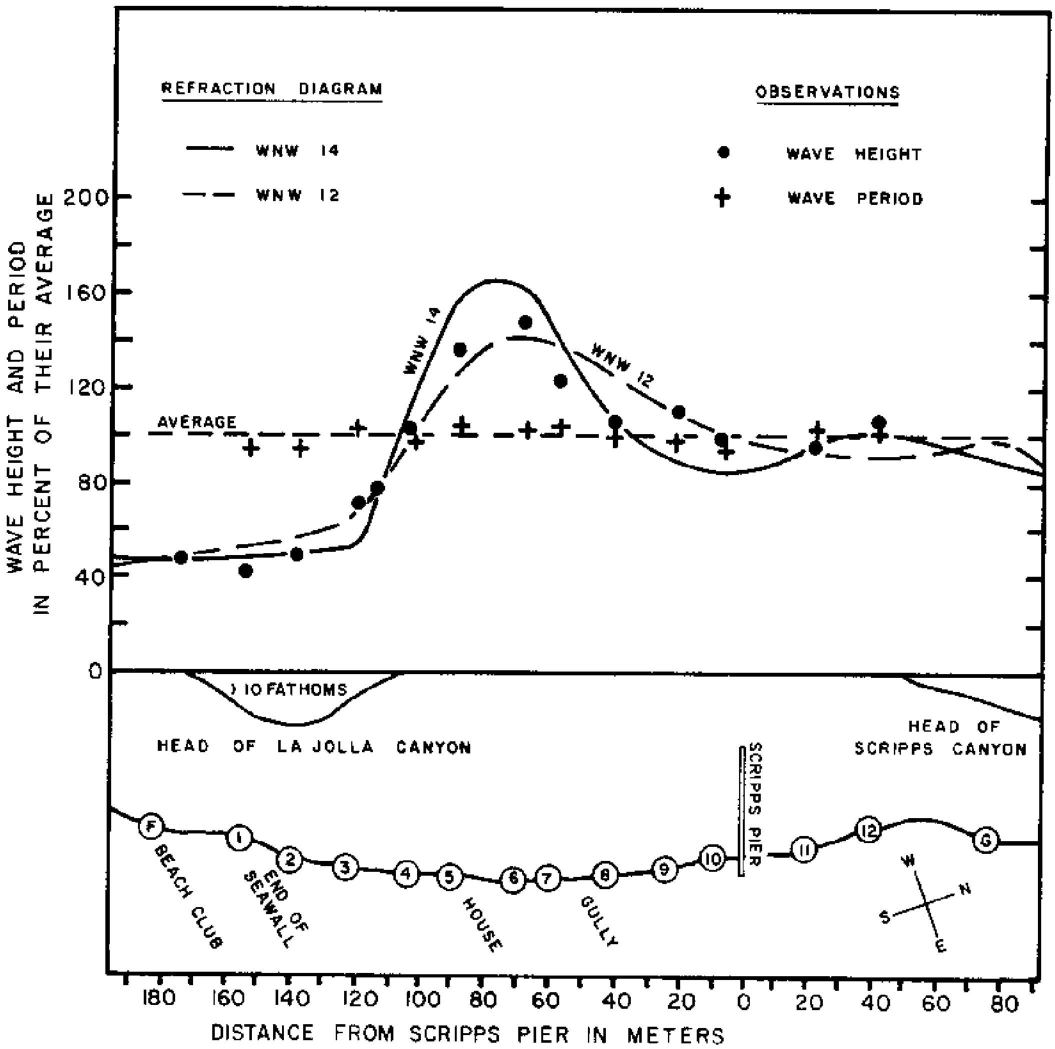
Figure 1. Schematic diagram illustrating the link between continental shelf waves and nearshore processes (from Goldsmith, et al., 1974, p. 8).



CONVERGENCE OF ORTHOGONALS PRODUCES HIGH WAVES IN THIS AREA
DIVERGENCE OF ORTHOGONALS PRODUCES LOW WAVES IN THIS AREA
DEPTH CONTOURS IN FATHOMS
WAVE FRONTS
ORTHOGONALS
WAVE DIRECTION
2
3
5
8
10
15
20
30

Figure 2. Correlation between measured wave heights and computed wave heights (as determined from manual-drawn refraction diagrams) for specific wave conditions. Note that low wave heights occurred in areas of wave ray divergence and larger wave heights in areas of wave ray convergence (modified from Munk and Traylor, 1947, Fig. 16).



REFRACTION DIAGRAM
WNW 14
WNW 12
OBSERVATIONS
WAVE HEIGHT
WAVE PERIOD
WAVE HEIGHT AND PERIOD
IN PERCENT OF THEIR AVERAGE
200
160
120
80
40
0
AVERAGE
WNW 14
WNW 12
) 10 FATHOMS
HEAD OF LA JOLLA CANYON
HEAD OF
SCRIPPS CANYON
SCRIPPS PIER
F
1
2
3
4
5
6
7
8
9
10
11
12
G
BEACH CLUB
END OF
SEAWALL
HOUSE
GULLY
W
N
S
E
180
160
140
120
100
80
60
40
20
0
20
40
60
80
DISTANCE FROM SCRIPPS PIER IN METERS

Figure 3. Bathymetry of the wide, shallow continental shelf of the Virginian Sea (Goldsmith, et al., 1973). The major shelf relief elements influencing the waves are indicated. The shelf edge canyons (Washington and Norfolk) head at approximately 70 meter depths.

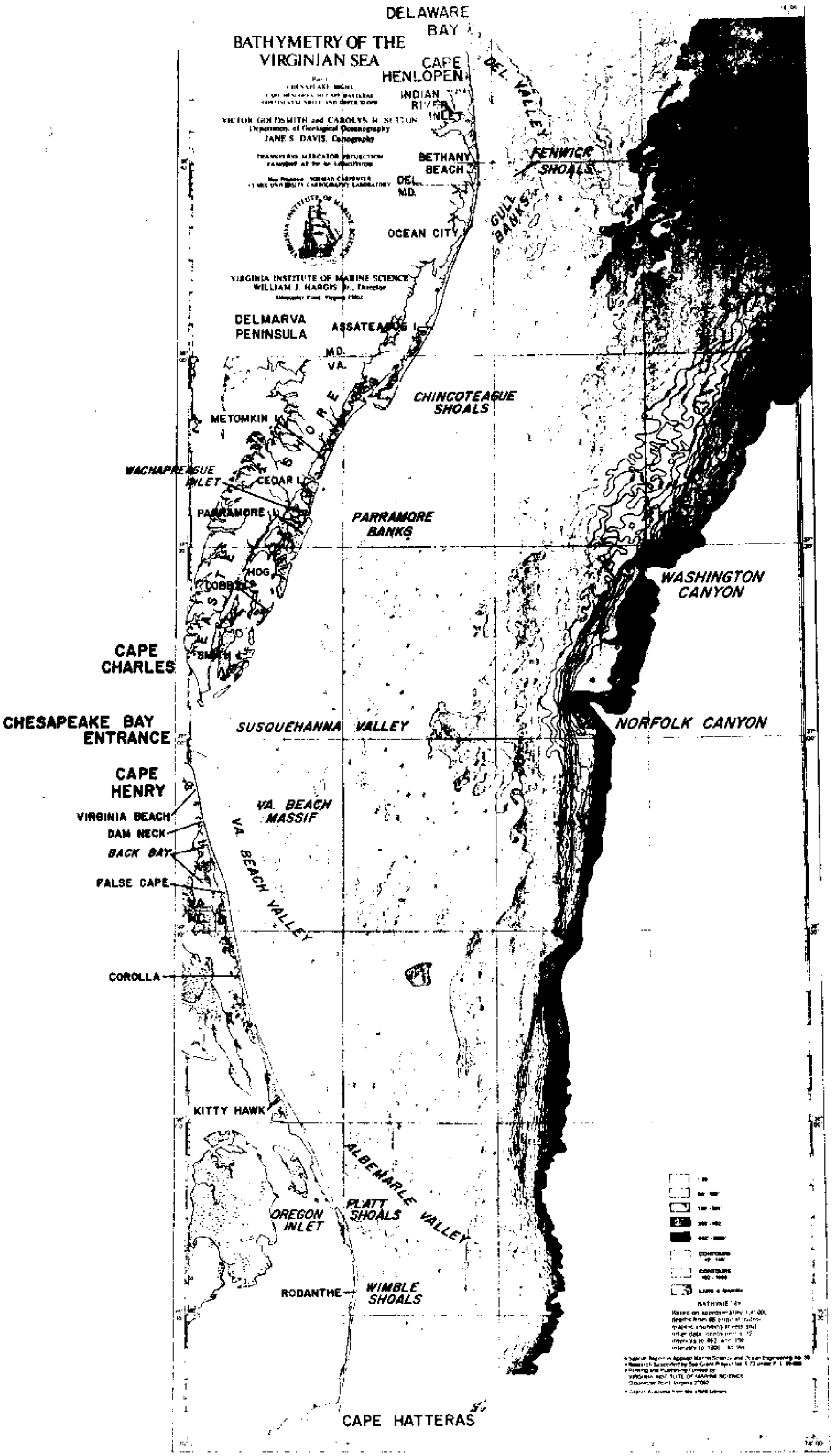
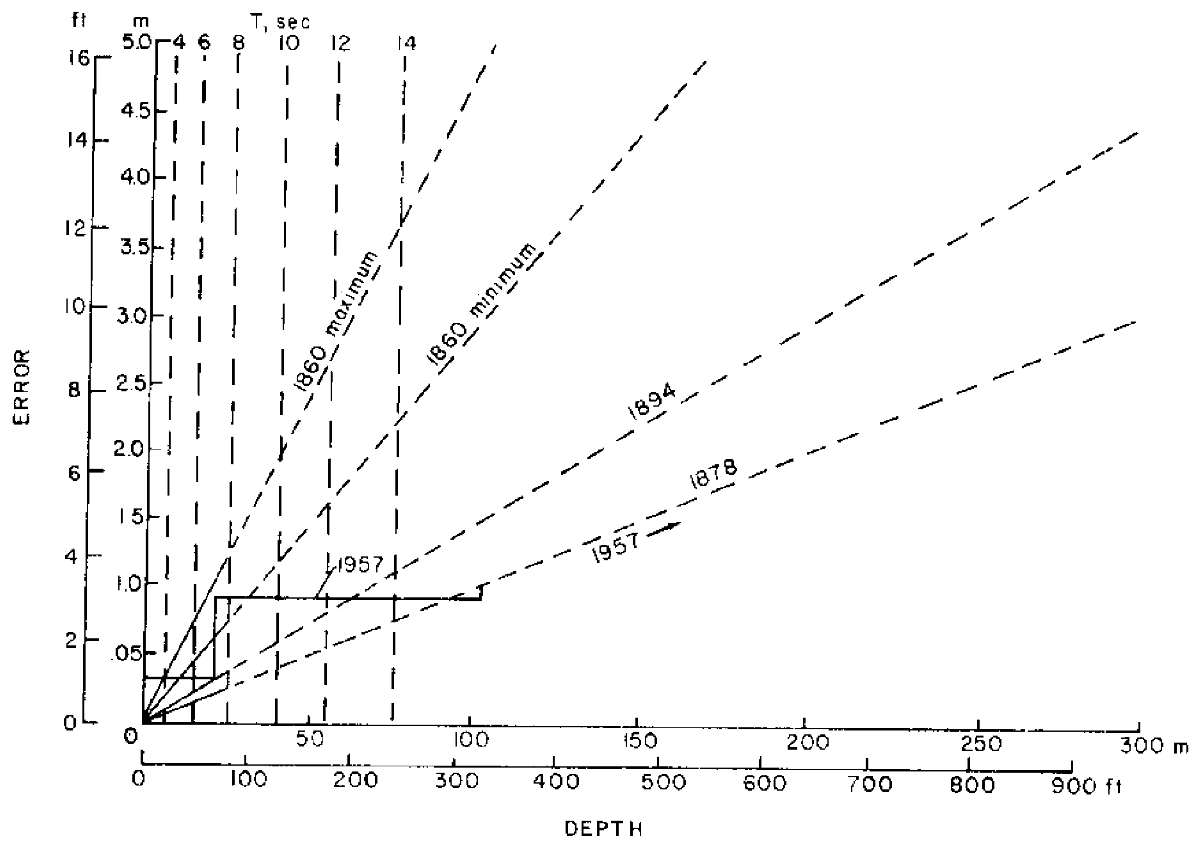
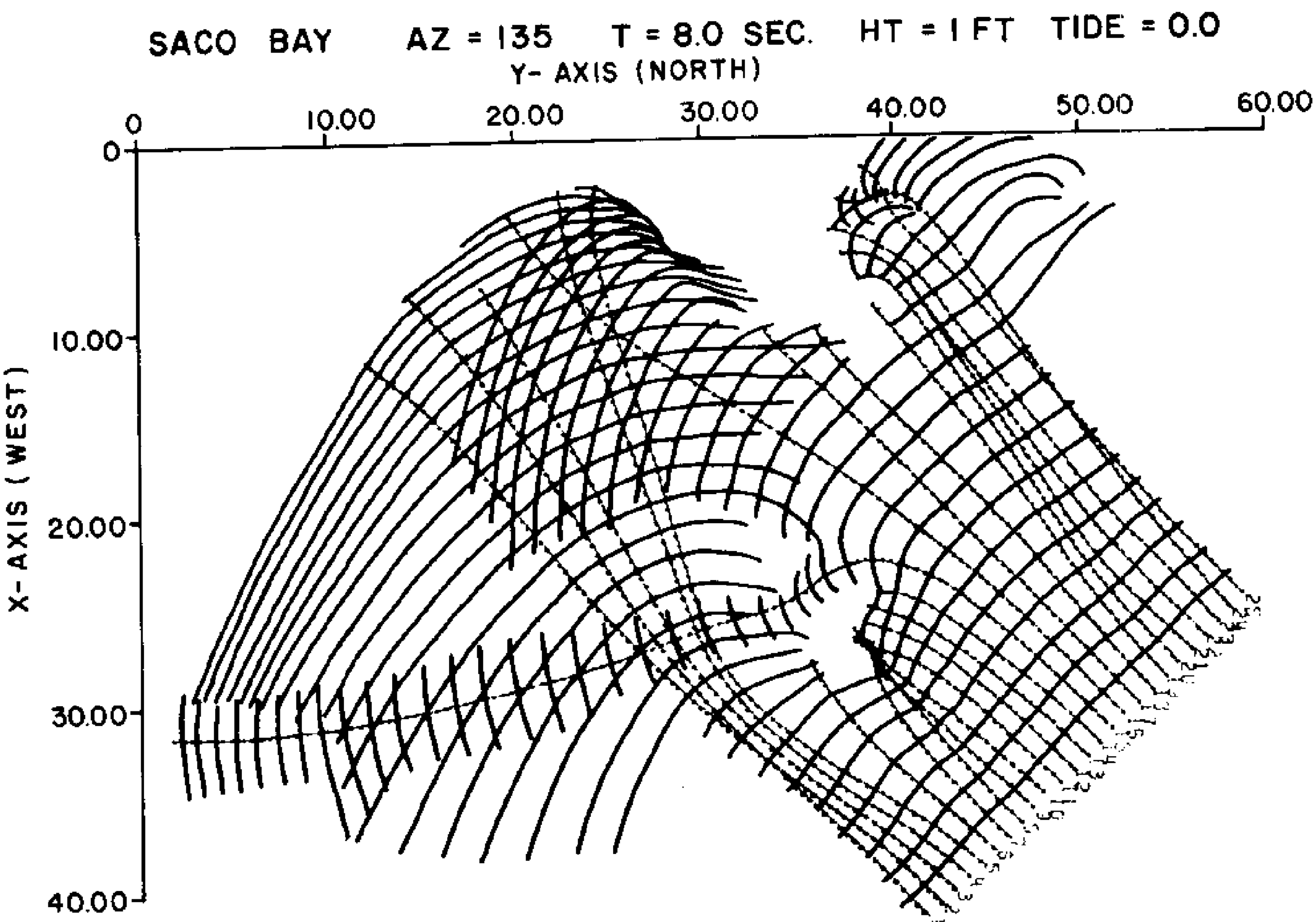

BATHYMETRY OF THE
VIRGINIAN SEA
VICTOR GOLDSMITH and CAROLYN H. SUTTON
Department of Geological Oceanography
JANE S. DAVIS, Cartography
VIRGINIA INSTITUTE OF MARINE SCIENCE
WILLIAM J. HARGIS Jr., Director
DELAWARE BAY
CAPE HENLOPEN
INDIAN RIVER INLET
DEL. VALLEY
BETHANY BEACH
FENWICK SHOALS
DEL.
MD.
GULL BANKS
OCEAN CITY
DELMARVA PENINSULA
ASSATEAGUE I.
MD.
VA.
CHINCOTEAGUE SHOALS
METOMKIN
WACHAPREAGUE INLET
CEDAR I.
PARRAMORE
PARRAMORE BANKS
HOG
COBB
SMITH
WASHINGTON CANYON
CAPE CHARLES
CHESAPEAKE BAY ENTRANCE
SUSQUEHANNA VALLEY
NORFOLK CANYON
CAPE HENRY
VIRGINIA BEACH
DAM NECK
BACK BAY
FALSE CAPE
VA.
NC.
VA. BEACH MASSIF
VA. BEACH VALLEY
COROLLA
KITTY HAWK
ALBEMARLE VALLEY
OREGON INLET
PLATT SHOALS
RODANTHE
WIMBLE SHOALS
CAPE HATTERAS

Figure 4. Sounding error criteria for the original bathymetric hydrographic sounding sheets used by National Ocean Survey NOAA (formerly C & GS), as compiled in Sallenger, et al., 1975). The depths equal to ¼ wavelength of the wave periods used in the VSWCM are superimposed on the diagram (see text).



ft
m
T, sec
4
6
8
10
12
14
16
14
12
10
8
6
4
2
0
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.05
1860 maximum
1860 minimum
1894
1878
1957
1957
ERROR
0
50
100
150
200
250
300 m
0
100
200
300
400
500
600
700
800
900 ft
DEPTH

Figure 5. Comparison of vertical aerial photograph of Saco Bay, Maine and wave refraction diagram computed for waves from the southeast with a period of 8 sec (from Farrell, et al., 1971.



SACO BAY AZ = 135 T = 8.0 SEC. HT = 1 FT TIDE = 0.0
Y- AXIS (NORTH)
0
10.00
20.00
30.00
40.00
50.00
60.00
X- AXIS (WEST)
0
10.00
20.00
30.00
40.00

Figure 6. Wave refraction diagrams computed in the VSWCM (Goldsmith, et al., 1974).

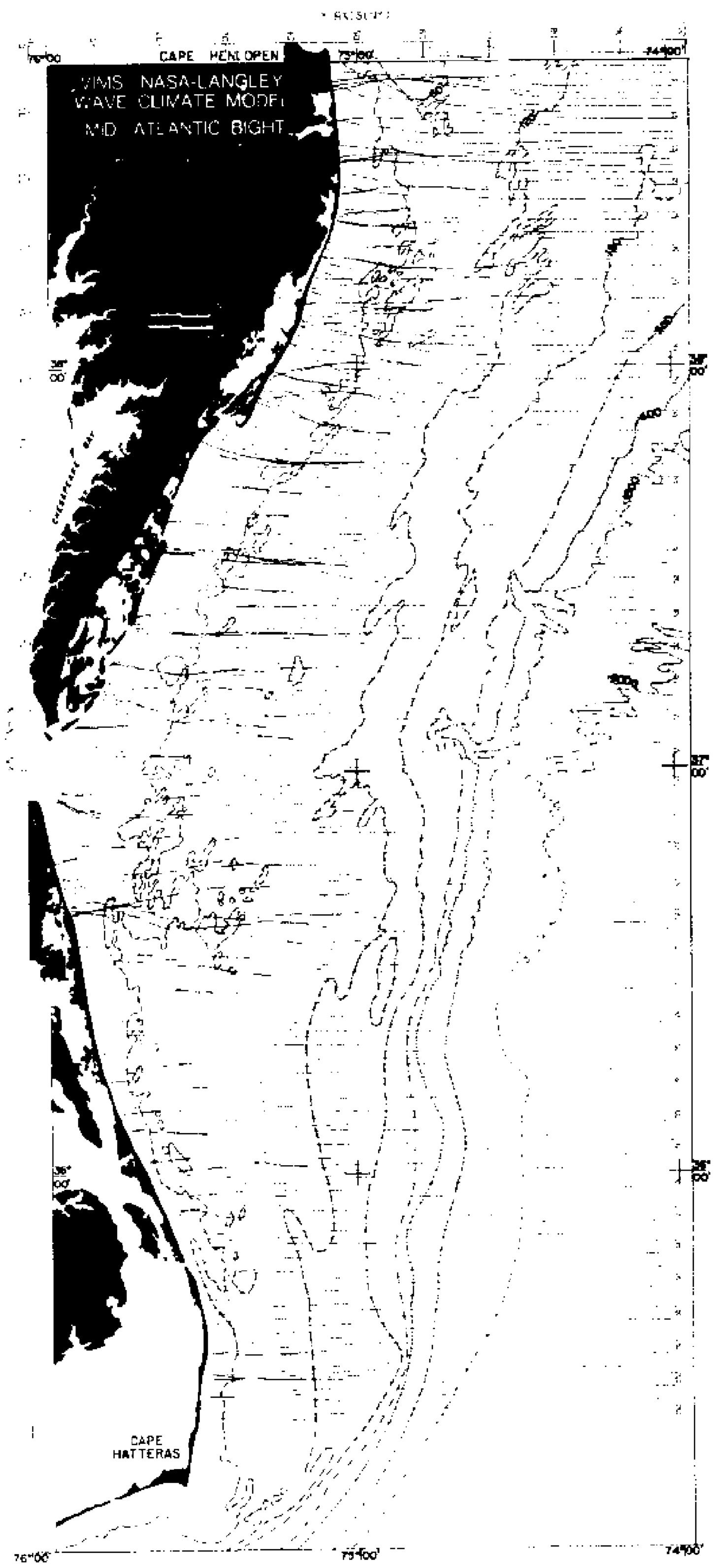
a. Waves from the northeast with a period of 10 sec

b. Waves from the east with a period of 10 sec

c. Waves from the southeast with a period of 10 sec

Note the dramatic shoreline changes in wave ray convergences and divergences for the different wave approach directions. These are just three of the 122 conditions computed in the VSWCM (Goldsmith, et al., 1974).

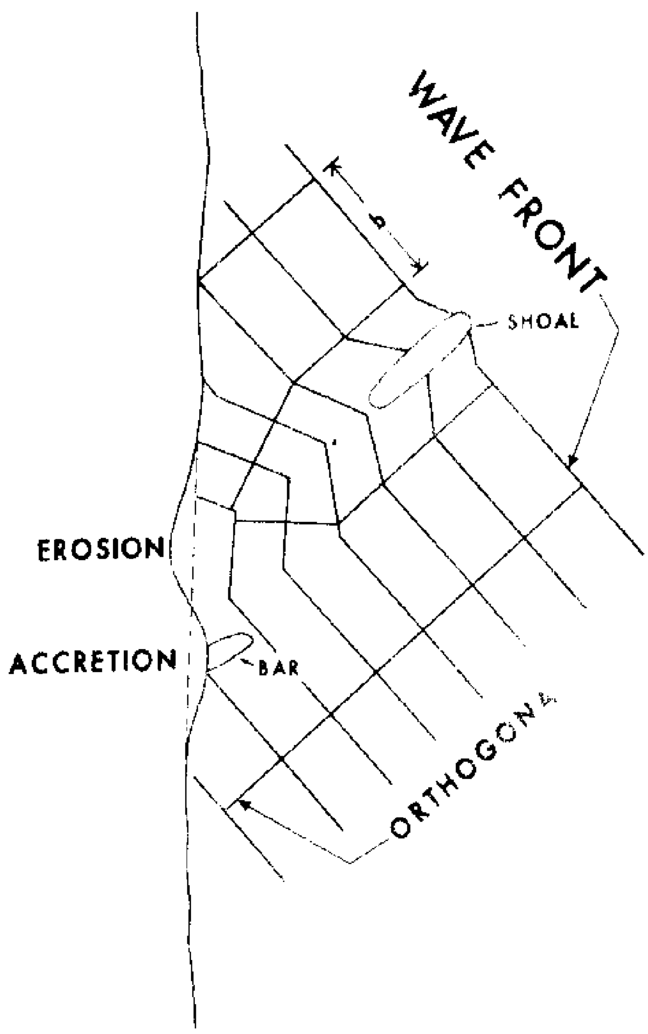
VIMS - NASA-LANGLEY
WAVE CLIMATE MODEL
MID - ATLANTIC BIGHT
CAPE HATTERAS
75°00'
74°00'
38° 00'
37° 00'
36° 00'



VIMS NASA-LANGLEY
WAVE CLIMATE MODEL
MID ATLANTIC BIGHT
CAPE HENLOPEN
CAPE HATTERAS
76°00'
75°00'
74°00'
38° 00'
37° 00'
36° 00'


VIMS - NASA-LANGLEY
WAVE CLIMATE MODEL
MID - ATLANTIC BIGHT
CAPE HENLOPEN
75°00'
74°00'
38°
00'
37°
00'
36°
00'
100
300
600
1000
2000

Figure 7. Schematic illustrating a mechanism proposed to explain growth and maintenance of linear ridges on shelf and its effect on shoreline wave energy distribution (Goldsmith, 1972, p. 37).



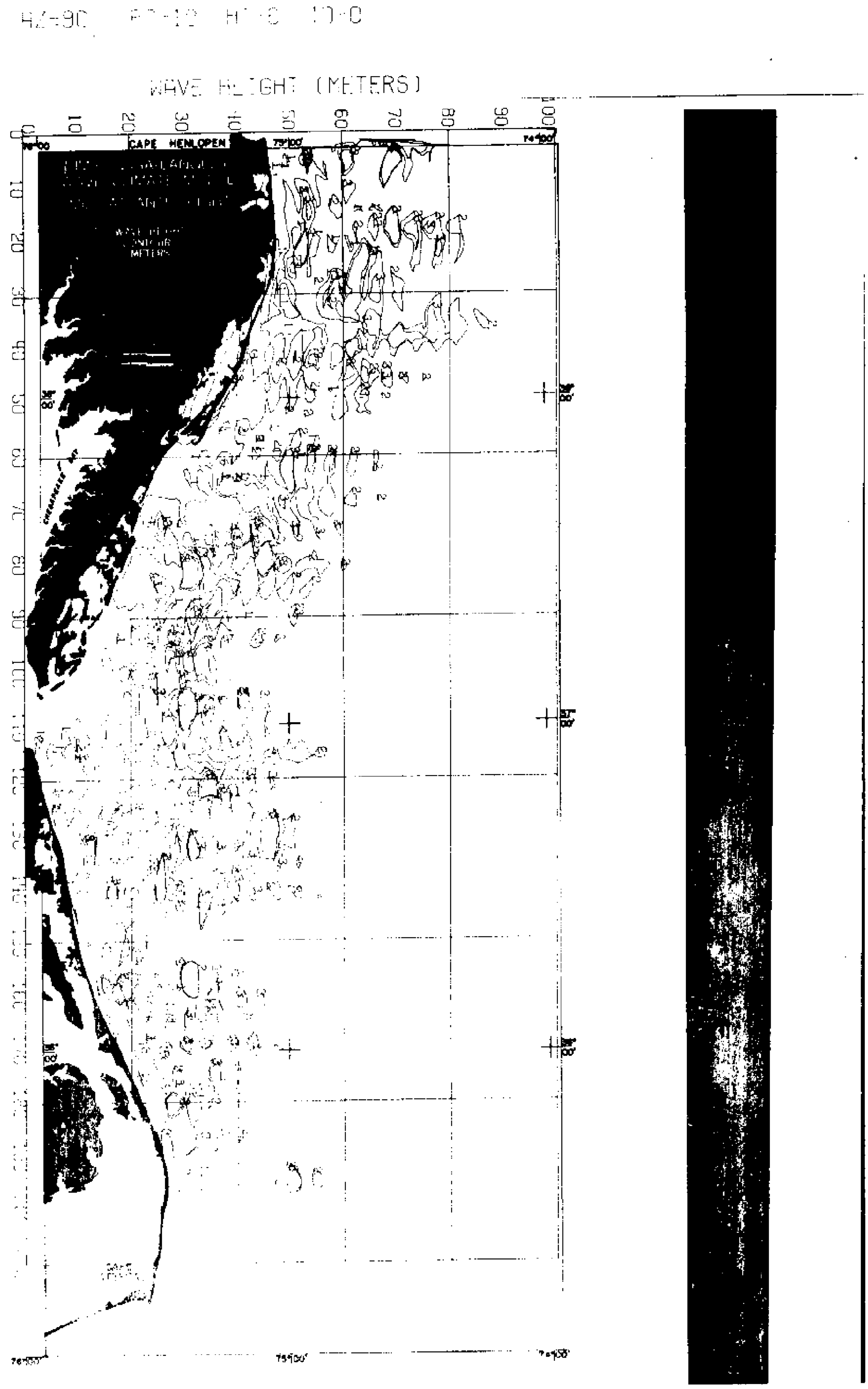
WAVE FRONT
SHOAL
EROSION
ACCRETION
BAR
ORTHOGONAL

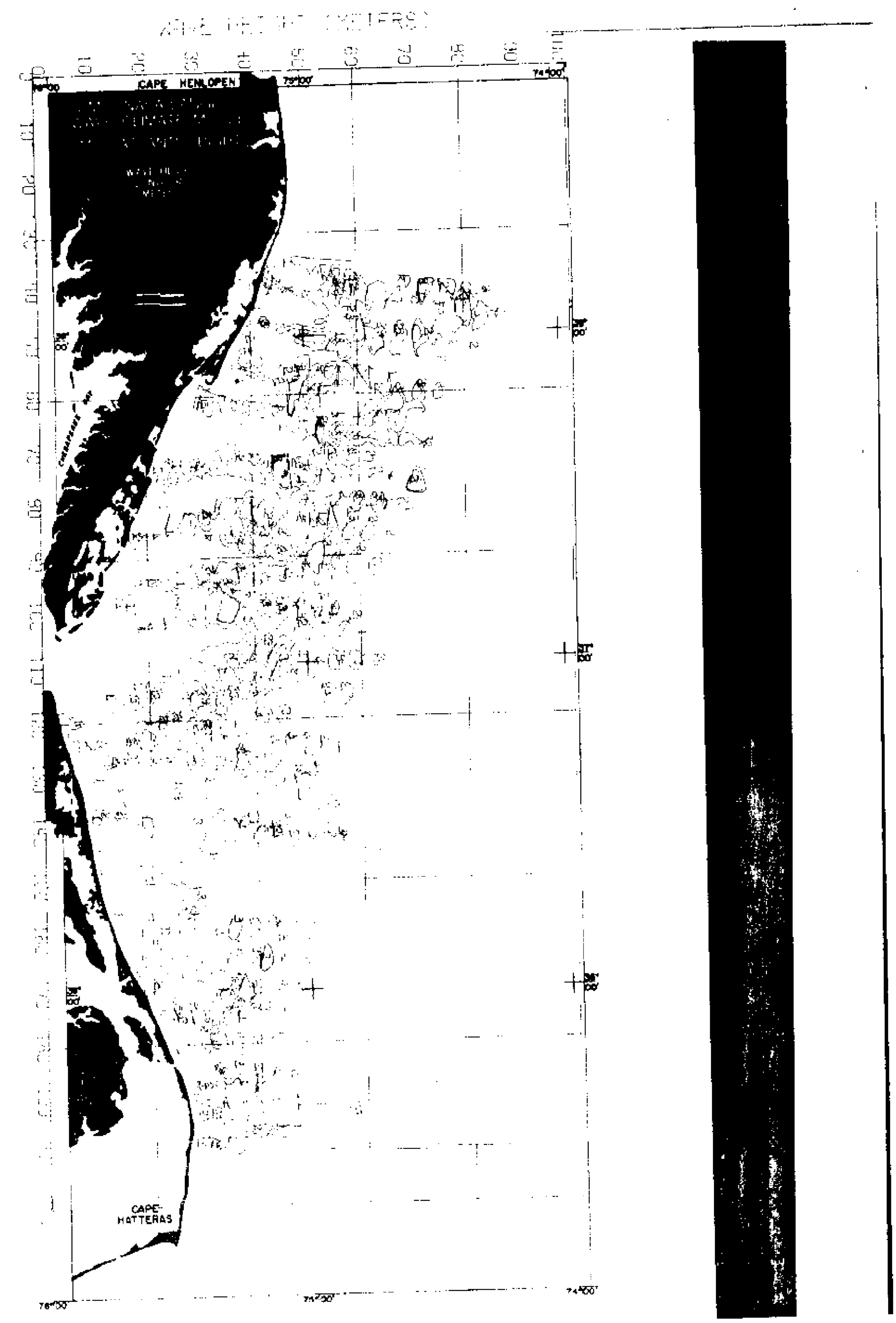
Figure 8. Continental shelf contour diagrams summarizing computations of wave parameters made in the VSWCM along wave rays (Goldsmith, et al., 1975).

a. Wave heights for waves from the east with a period of 10 sec.

b. Wave heights for waves from the east with a period of 14 sec.

c. Maximum bottom wave orbital velocities for waves from the east with a period of 10 sec.


WAVE HEIGHT (METERS)
0
10
20
30
40
50
60
70
80
90
100
CAPE HENLOPEN
75°00'
74°00'
38° 00'
37° 00'
36° 00'


CAPE HENLOPEN
75°00'
74°00'
CAPE HATTERAS

PD=10 HT=6

ORBITAL VEL (CM/SEC)

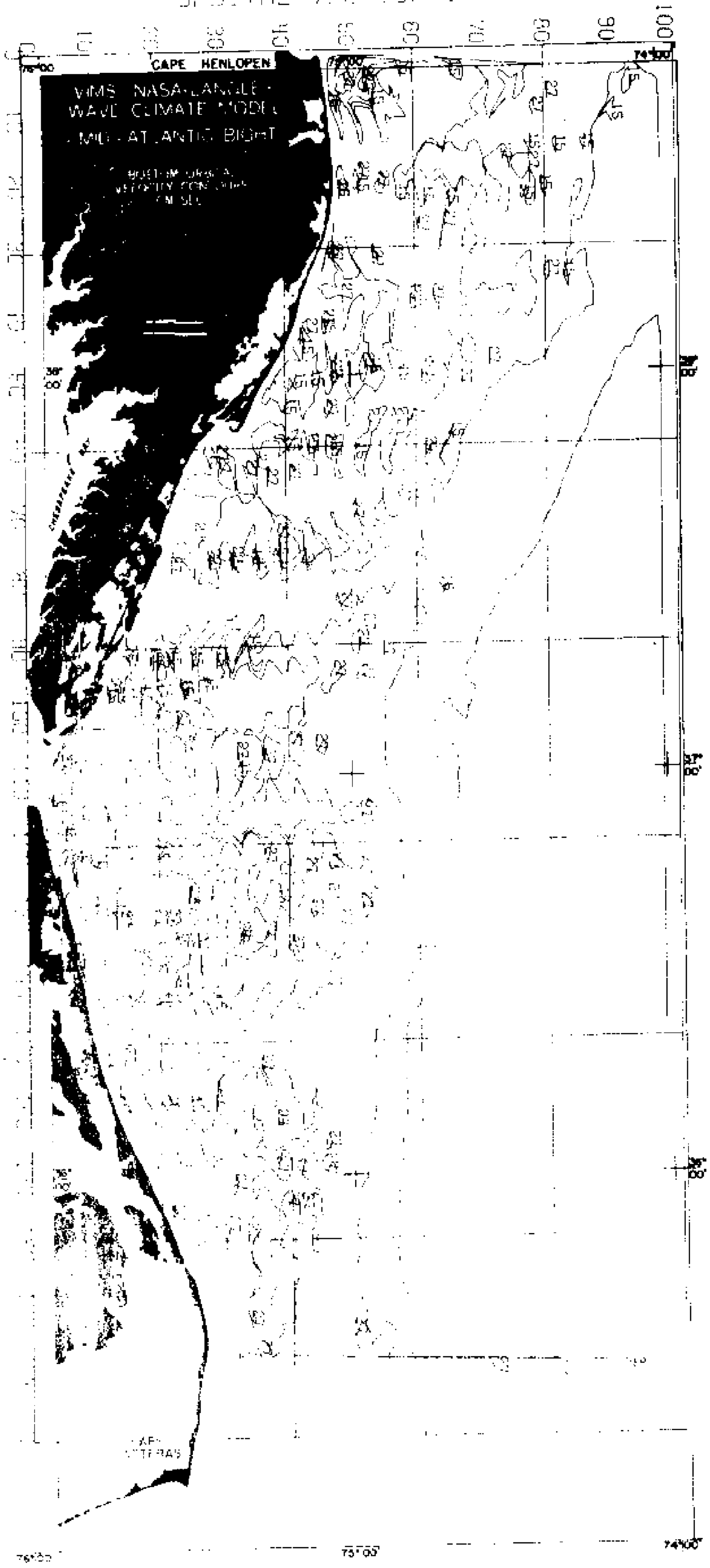


Figure 9. Shoreline wave ray histogram for waves from the east eith a period of 10 sec. Compare with Figures 10a and 10c.

AZIMUTH : 90.0 PERIOD : 10. TIDE : 0.0

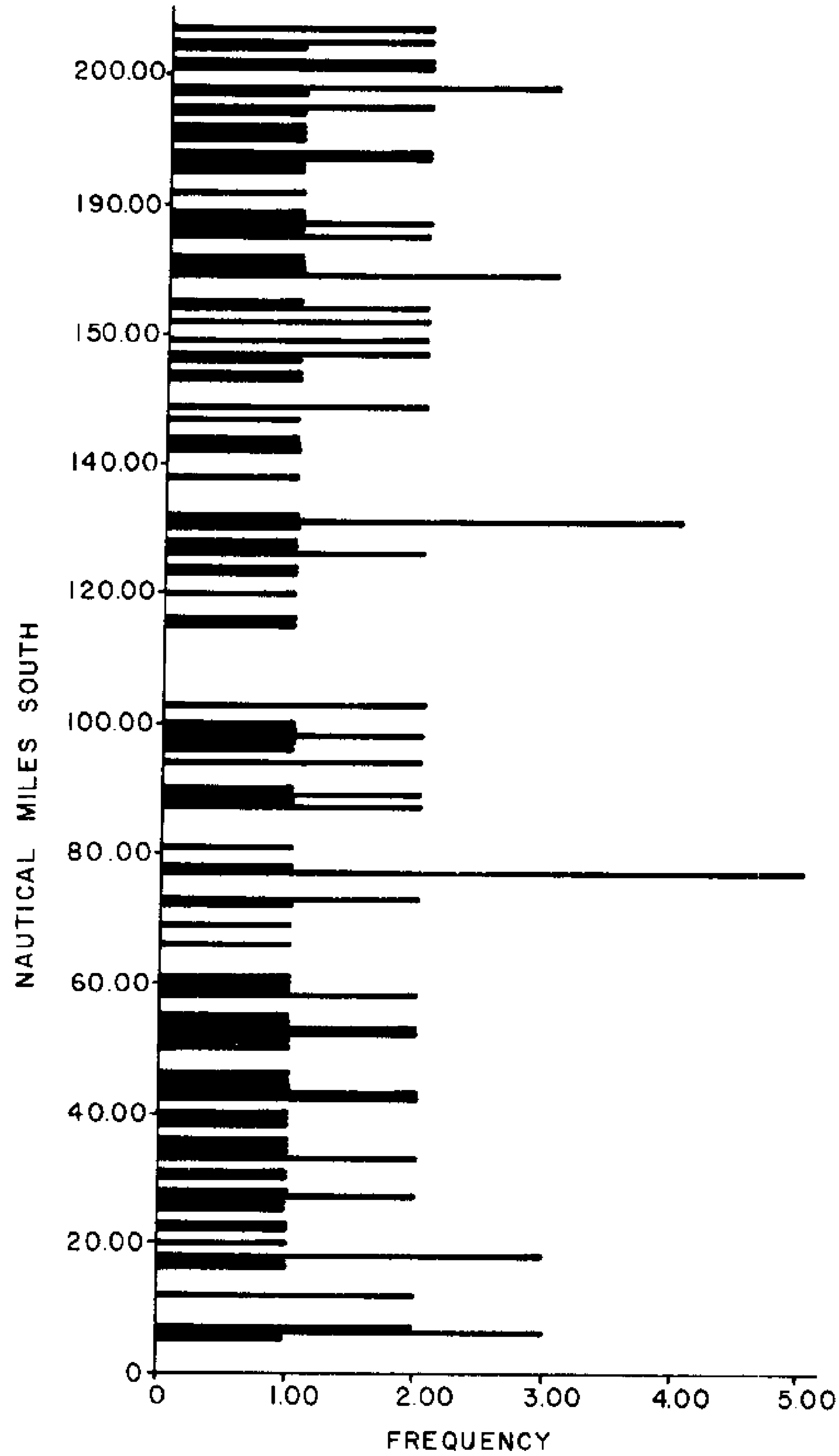


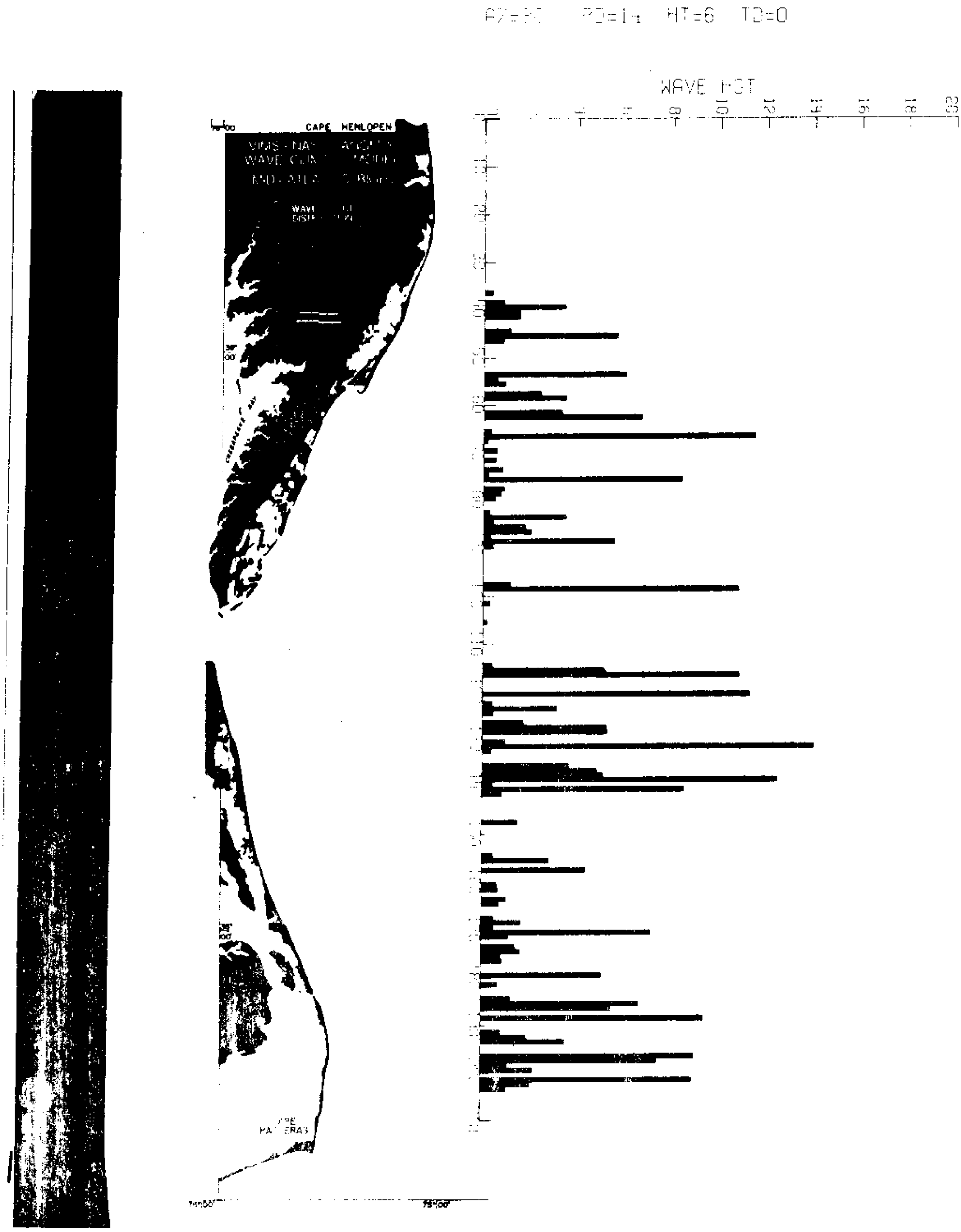
Figure 10. Shoreline histograms summarizing computations of wave parameters made in the VSWCM at the shoreline ends of the wave rays (Goldsmith, et al., 1975).

a. Wave heights for waves from the east with a period of 10 sec.

b. Wave heights for waves from the east with a period of 14 sec.

c. Wave energy for waves from the east with a period of 10 sec.


TD=0
CAPE HENLOPEN
CAPE HATTERAS
12
14
16
18
20


HT=6
TD=0
WAVE HGT
CAPE HENLOPEN
WAVE

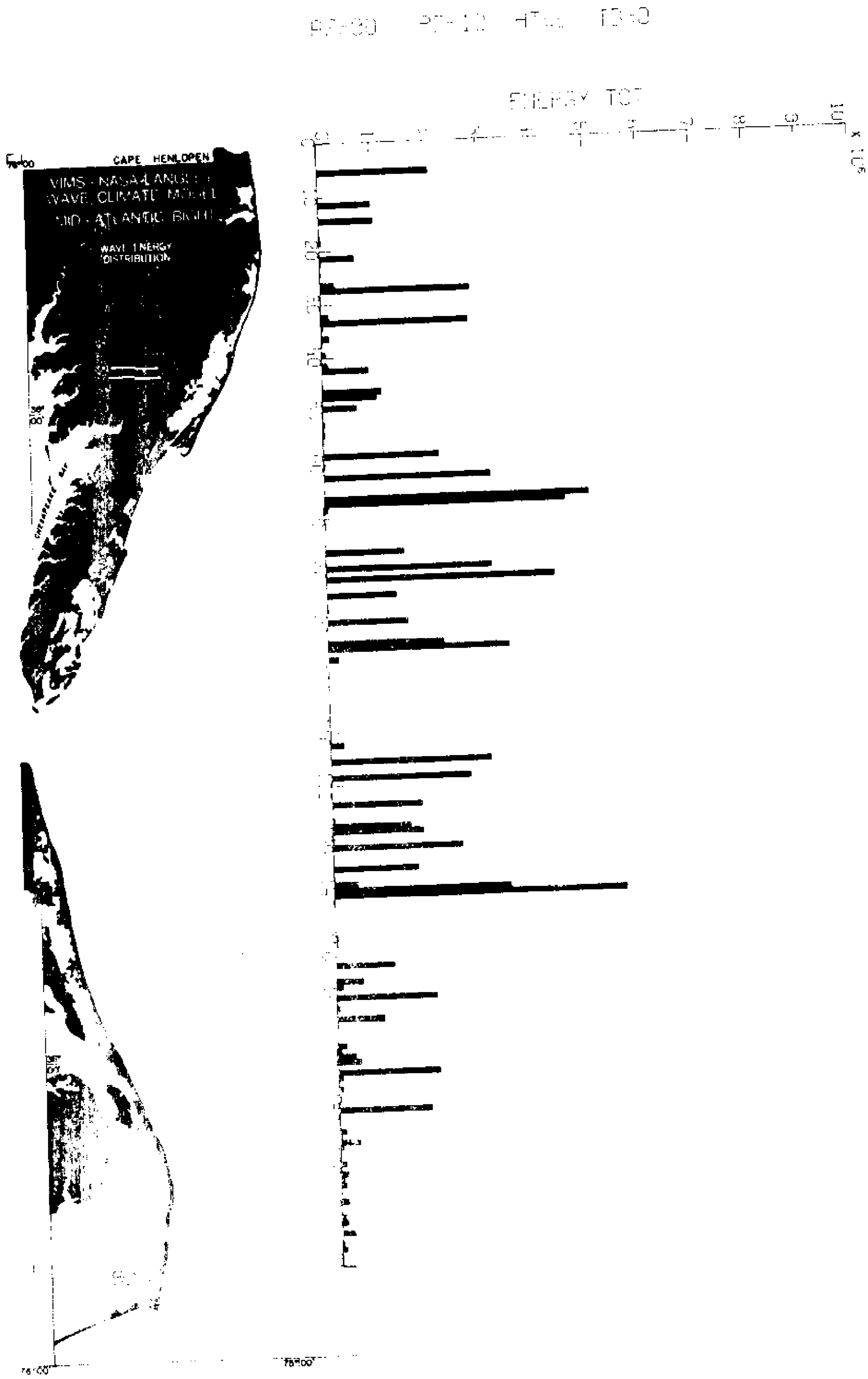

CAPE HENLOPEN
VIMS - NASA-LANGLEY
WAVE CLIMATE MODEL
MID - ATLANTIC BIGHT
WAVE ENERGY
DISTRIBUTION
ENERGY TOT
x 10⁵
76°00'

Figure 11. Historical shoreline changes for intervals of 48 to 105 years (as indicated) for the shoreline of the Virginian Sea between the Delaware-Maryland state line and Cape Hatteras, North Carolina. Compare with Figures 8 and 10 (see text). Data for Eastern Shore of Virginia (Maryland-Virginia line to Chesapeake Bay) from Byrne (1973).

SHORELINE
EROSION AND ACCRETION
(~100 yrs)

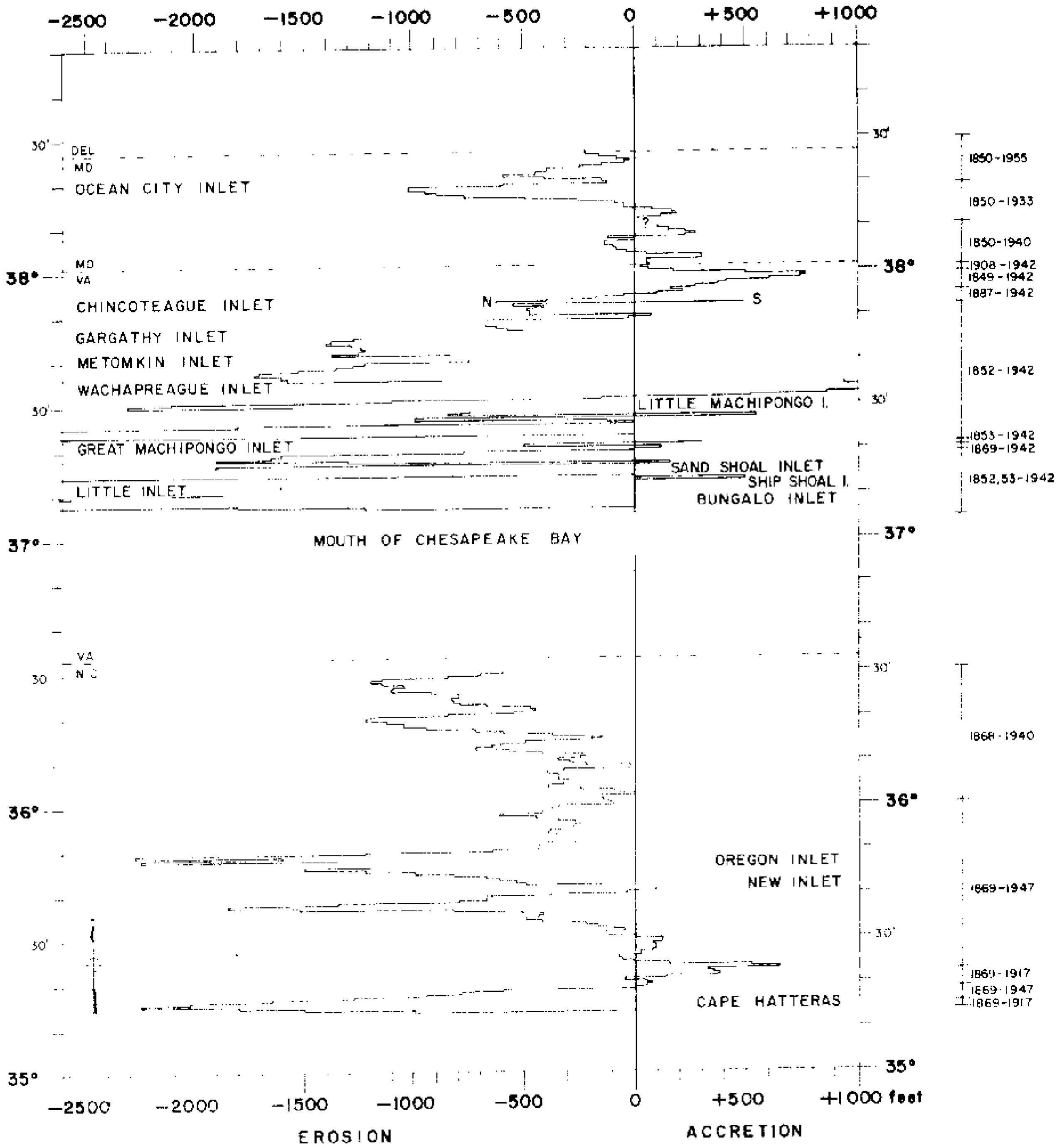
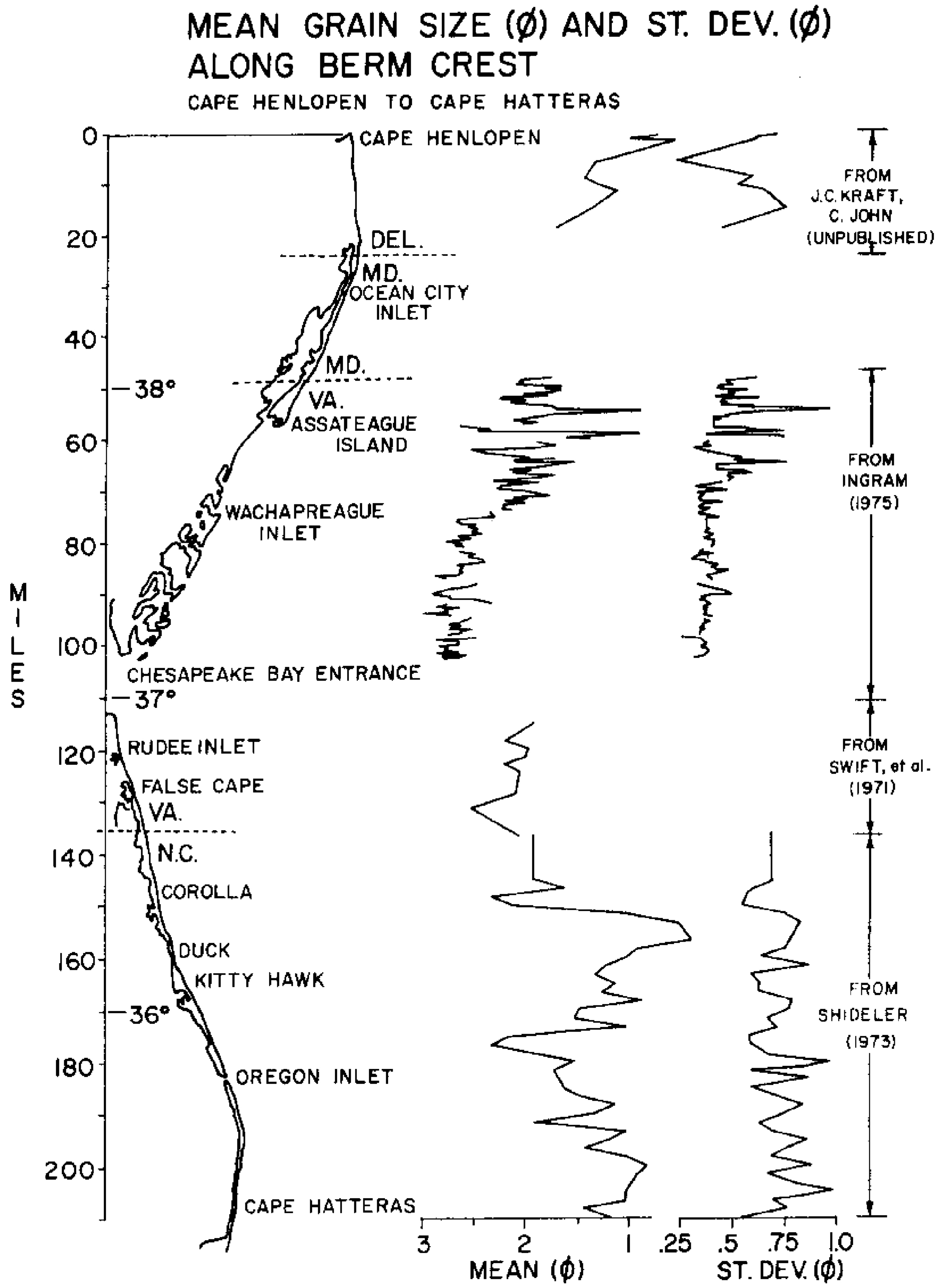


Figure 12. Mean grain size and standard deviation along the berm crests between Cape Henlopen, Delaware and Cape Hatteras, North Carolina. Compare with Figures 8 and 10 (see text).


MEAN GRAIN SIZE (Ø) AND ST. DEV. (Ø)
ALONG BERM CREST
CAPE HENLOPEN TO CAPE HATTERAS
CAPE HENLOPEN
DEL.
MD.
OCEAN CITY INLET
MD.
VA.
ASSATEAGUE ISLAND
WACHAPREAGUE INLET
CHESAPEAKE BAY ENTRANCE
RUDEE INLET
FALSE CAPE
VA.
N.C.
COROLLA
DUCK
KITTY HAWK
OREGON INLET
CAPE HATTERAS
38°
37°
36°
MILES
0
20
40
60
80
100
120
140
160
180
200
3
2
1
MEAN (Ø)
.25
.5
.75
1.0
ST. DEV. (Ø)
FROM J.C. KRAFT, C. JOHN (UNPUBLISHED)
FROM INGRAM (1975)
FROM SWIFT, et al. (1971)
FROM SHIDELER (1973)