LAMONT-DOHERTY GEOLOGICAL OBSERVATORY OF
COLUMBIA UNIVERSITY
PALISADES, NEW YORK 10964

PATTERNS OF RELATIVE RELIEF, SLOPE, AND TOPOGRAPHIC TEXTURE IN THE NORTH ATLANTIC OCEAN

by

Troy L. Holcombe and Bruce C. Heezen

Technical Report No. 8
CU-8-70 Naval Ships Systems Command N00024-67-1186

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Foreword:

The research reported in this document is part of a long term continuing investigation of the geology of the deep sea floor conducted by Professor Bruce C. Heezen, his students and associates in the submarine geology program of the Lamont-Doherty Geological Observatory. The specific quantitative investigation described was conducted in 1965 and 1966. The report was largely written in 1967 but its printing has been delayed by administrative difficulties. Consequently the maps and conclusions reflect knowledge as of 1965 and do not incorporate subsequent advances including those portrayed on Heezen and Tharp's 1968 revision of their Physiographic Diagram of the North Atlantic Published by the Geological Society of America.

Troy L. Holcombe
Bruce C. Heezen

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Abstract

Charts have been constructed which quantitatively define the distribution patterns of relative relief, slope, and topographic texture in the North Atlantic Ocean. Precision fathograms collected over a 12-year period at Lamont-Doherty Geological Observatory of Columbia University were reread at 1-minute intervals of ship's time, and these data, totaling about 300 thousand soundings, were digitized for computer processing. Six quantitative parameters, two for relative relief, two for slope, and two for topographic texture, were selected to describe and characterize the topography. These parameters were computed from the data and plotted as charts. Profiles of the raw parameters were plotted for illustrative purposes and for comparative studies. Roughness patterns were extrapolated by employing the North Atlantic physiographic provinces chart of Heezen, et al. (1959).

Once the quantitative characteristics of each physiographic province and sub-province were distinguishable, the slope data were then sub-divided into samples on the basis of physiographic similarity. Frequency distribution of slopes, and statistical parameters measuring central value and dispersion were then calculated.

The analyses of relative relief and mean bottom slope provide a basis of subdividing the North Atlantic into smooth provinces and rough provinces. Smooth provinces, where processes of sedimentation have been the dominant geomorphic agent, were defined as having relief generally less than 50 echo time units (tau) and mean bottom slope generally less than 1:50. Rough provinces, where tectonism and volcanism have been predominant in shaping the topography, were defined as having relief generally greater than 50 tau and mean bottom slope generally greater than 1:50.

The abyssal plains, obviously, constitute the areas of lowest relief and slope in the North Atlantic. Generally low though locally moderate relief, gentle slopes (except on the continental slope), and many areas of small-scale texture characterize the continental margin provinces. A wide range of roughness, from gently undulating, low relief topography to local belts of extremely rugged topography, occur on the North Atlantic oceanic rises. The highest relief and steepest slopes in the North Atlantic characterize the crest of the

Mid-Atlantic Ridge throughout its extent as well as the outer flanks of the ridge and the abyssal hills between latitudes 20^o and 30^oN. In contrast: The relief and slopes of the ridge flanks north of latitude 30^o and south of latitude 20^o are gently undulating to rough, varying with the degree of burial by sedimentation.

Slopes for much Mid-Atlantic Ridge topography fall into three categories: 1) gentle slopes, generally less than 5 degrees with a strong mode at zero degrees, reflecting flat-floored sedimentary basins and gently undulating sediment-subdued topography, 2) intermediate range slopes, generally 5-15 degrees, which characterize the hillside slopes of the primary basement relief, and 3) the steep slopes, generally greater than 12-15 degrees, which describe the steep-faced tectonic scarps.

The hillside slopes of the basement relief are remarkably symmetrical and of fairly uniform steepness. They are thought to reflect the angle of repose of extrusive lavas associated with the extensional tectonics of the Mid-Oceanic Ridge crest. Most of the tectonic activity involved in shaping the present ocean bottom is thought to be secondary to the volcanism, acting on the already rugged basement relief. No direct relationship is observed between the steepness of the hillside slopes of the primary relief and either the size of the relief or the rate of sea-floor extension.

I. INTRODUCTION

Within the last decade much has been learned regarding the physiographic character of the world's oceans. Long-term studies have resulted in physiographic diagrams of the North Atlantic (Heezen et al., 1959), South Atlantic (Heezen and Tharp, 1962), Indian (Heezen and Tharp, 1964), and northeastern Pacific (Menard, 1964) Oceans. Accompanying the original North Atlantic physiographic diagram was a descriptive study and semi-quantitative classification of North Atlantic topography, and a physiographic province chart which subdivided the North Atlantic into its presently accepted physiographic categories.

More recently, as a result of these and other studies, it has become increasingly apparent that measuring the dimensions of sea-floor topography in a systematic, quantitative, and rigorous manner would provide further data from which definitive descriptive and comparative studies of sea-floor topography could be carried out, both regionally and world-wide.

To this end, Krause and Menard (1965) carried out a quantitative study of fifteen sections of ocean-floor profile, each representing 60 nautical miles of traverse, between Hawaii and California. They measured the heights and widths of individual hills, plotted the frequency distribution of hill heights, bottom depths, and hill widths, and devised a classification scheme for abyssal hills based on height and the ratio between height and width. Smith, et al. (1965) constructed charts showing the schematic distribution of relief in parts of the eastern Pacific Ocean. Agapova (1965) measured slopes from an east-west section of profile along latitude 38°N. west of the Azores, grouped these on the basis of physiographic similarity, and obtained from each group statistical measurements of central value and dispersion.

This study utilizes what is already known about the distribution of North Atlantic Physiographic provinces in the preparation of a series of charts (CHARTS 1-6) which schematically illustrate selected functions of relative relief, slope, and topographic texture.

The data employed in compiling these charts was obtained by digitizing high resolution fathograms and, measuring relief, slope, and texture through the use of digital computers. Methods of data reduction and chart preparation are described in section II of this report.

Statistical indices from slope data have been computed which characterize each physiographic province in the North Atlantic.

From the charts and statistical data, it has been possible to briefly and quantitatively describe North Atlantic topography and to call attention to a number of interesting relationships and characteristics observed in the data which have a bearing on the geologic history and geomorphology of the Atlantic. These observations, contained in sections III and IV, demonstrate that bathymetric data treated as it is in this report may be useful in studying many aspects of oceanography, acoustics, bottom sedimentation, and crustal tectonics. The area of this study is the North Atlantic Ocean between latitudes 10°N and 40°N (figure 1).

Acknowledgements

This work has been supported by the U. S. Navy under contracts NObsr 89401 with the U. S. Navy Bureau of Ships and N-00024-67-C-1186 with the Naval Ship Systems Command. Support under contract NObsr 89401 was directed through contract No. 601322 for Bell Telephone Laboratories, Incorporated, on behalf of Western Electric Company, Incorporated. The echo-sounding data was collected by R/V VEMA (cruises 6 through 21), R/V ROBERT D. CONRAD (cruises 6 through 9), R/V ANTON BRUUN (cruise 9), and WYANDOT, with the support of the U. S. Navy Bureau of Ships, the National Science Foundation, and the Office of Naval Research. This publication is for technical information only and does not represent recommendations or conclusions of the sponsoring agency. Reproduction of this document in whole or in part is permitted for any purpose of the United States Government.

The plates and some other material in this report appeared in an earlier unpublished report by the writers entitled, Geographic Distribution of Bottom Roughness in the Atlantic, 12p. 1965.

Much was learned in the early phases of programming from the pioneering efforts in machine processing of sounding data at the Lamont-Doherty Observatory by M. Talwani and D. Hayes. Also helpful in the programming phases were the contributions of A. Tata and G. Paterson. C. Moore adapted the Talwani-Hayes system of reducing topographic data to the IBM 7094 computer and the SC/4020 plotter. C. Bertelsen contributed greatly to the data processing work by efficiently organizing computer runs and handling the indexing IBM cards and tapes. D. Johnson drafted the charts and figures and prepared the computer-drawn profiles for publication. E. Escowitz reduced the navigation data to digitized form. Others of the regular and summer staff of Lamont's submarine geology department worked long and tirelessly reading and recording PDR data, plotting data points on the charts, and assisting in the other numerous details associated with the project.

II. PREPARATION OF CHARTS

Quantitative Characteristics of Echo-Sounding Data

Since 1953, when the Precision Depth Recorder (PDR) first operated successfully, detailed studies of sea floor topography have been possible (Luskin, et al., 1954). The PDR and other similar instruments produce fathograms readable to an echo-time accuracy of 1/400 second or better at any ocean depth (Luskin, et al., 1954; Knott and Hersey, 1956; Luskin and Israel, 1956). This unit of echo-time (1/400 second) has become the standard unit for PDR record reading and is herein referred to as 1 tau (t).

All sea floor relief calculations in this report are in units of tau. Corrections of echo-times for the velocity of sound in water have not been effected for two principal reasons: 1) Although the corrections are typically +40 to +80 units at typical oceanic depths (Matthews, 1939), the effect of such corrections on the relative dimensions of the terrain is not significant here. Relief figures obtained from echo-time units would typically be 2-5 percent less than those obtained from the same soundings corrected for sound velocity. Slope figures would be higher, as a result of velocity correction, by 0-0.5 degrees for echo-time slopes of 5 degrees or less and 0.5 - 1.0 degrees for echo-time slopes of 5-20 degrees. 2) By using echo-time units instead of corrected depths, the data obtained may be more easily compared with that obtained in the field. Fathograms are easily readable in echo-time units, whereas correction for sound velocity requires a certain amount of computation. It is safer and less confusing to compare data from different sources if it is in echo-time units unless the source of the sound velocity data and the methods of correction are known in detail.

Pinke (1935), a participant in the SNELLIUS Expedition, was one of the first to analyze the effect of bottom slope on depth determinations. Schuler (1952) and Krause (1962) have calculated the effect of hypothetical geometric models on the shape of an echo trace. Krause's report also evaluates the quantitative significance of such minor factors in depth determinations as refraction in the water column and distance the ship travels between the points of sending and receiving. Hoffman (1957) and Luskin, _et al._, (1957) have discussed the significance of hyperbolic echo traces and how they may be used to aid in determining depth, maximum effective beam width, and ship's speed. Elmendorf and Heezen (1957) have demonstrated how to reconstruct graphically a closer approximation of true depth and slope. It is not necessary here to repeat the facts and figures presented in these reports, but a few words are in order regarding the amount and nature of fathogram distortion resulting from a sloping bottom.

It is estimated that, from the data point spacing employed in this report, slopes of 5 degrees or less extend over roughly 70-80 percent of the area of the Mid-Atlantic Ridge and over 95 to 100 percent of most other provinces in the North Atlantic. At typical ocean depths the vertical and horizontal components of geometric distortion due to a bottom slope of 5 degrees would be about 10 fathoms and 0.2 nautical mile (N.M.), respectively; with increasing slope the distortion increases exponentially, being about 120 fathoms and 0.7 N.M., respectively, for a bottom slope of 20 degrees. In rough areas hyperbolic echoes and echoes returning from several bottom surfaces simultaneously complicate the measurement of depth and bottom geometry. Also, conical-shaped features randomly distributed throughout the "shadow" of the effective cone of sound result in an obvious distorting effect on relief, wavelength, and slope measurements. The most fundamental distorting factor in bottom slope determination is the uncertainty in evaluating the angular difference between ship's course and direction of topographic strike. Relief is the least affected parameter in rough areas, with wavelength and slope being affected to a somewhat greater degree.

Initial Reduction of PDR Data

For this study PDR records were read at a constant time interval of one minute ship's time (tracks shown in figure 1), resulting in a total accumulation of approximately 300,000 individual soundings.

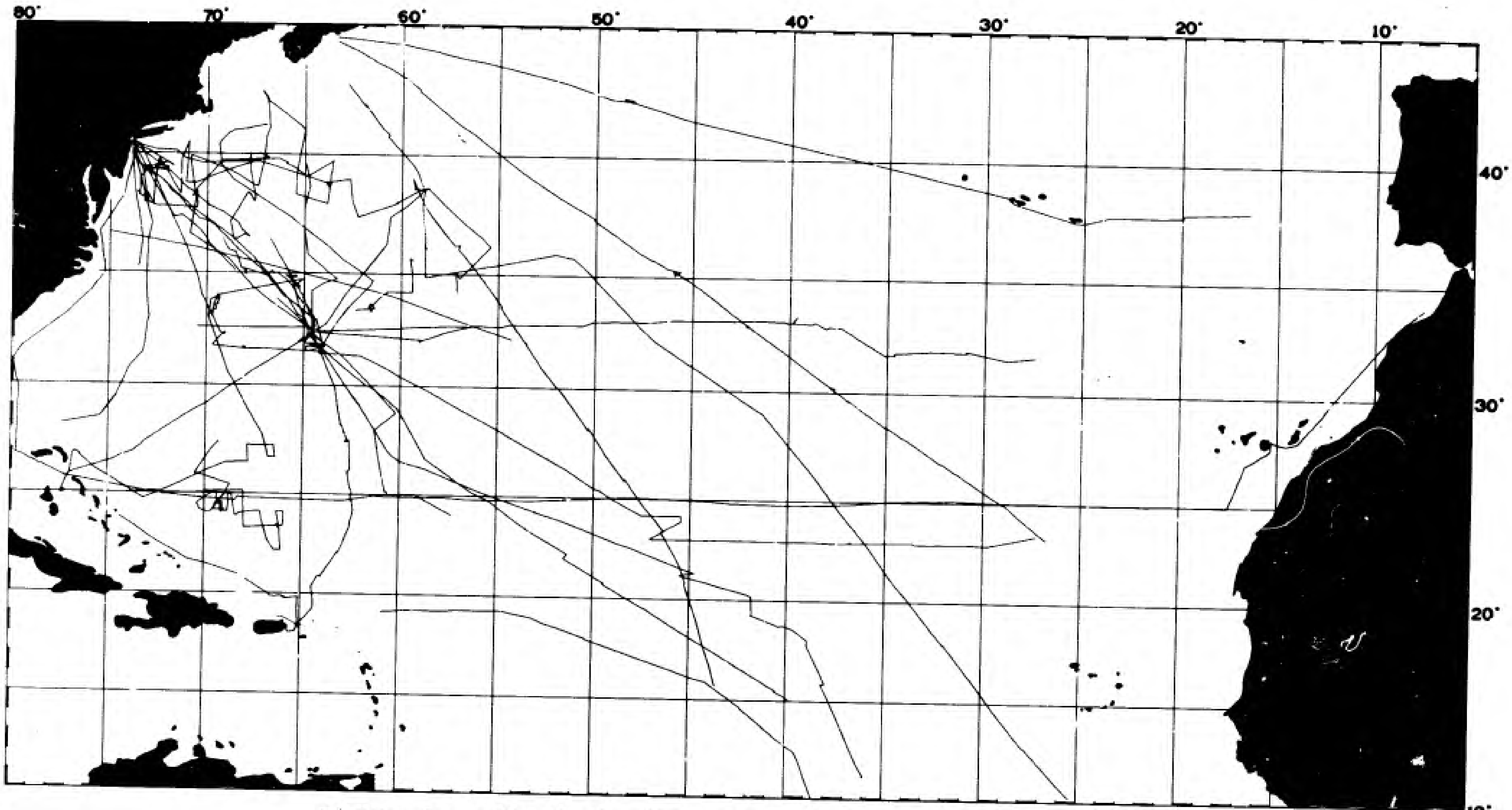


Figure 1. - Chart showing track coverage for PDR records read at one-minute intervals of ship's time.

At normal cruising speeds of 8-10 knots the interval between successive soundings would be 0.13-0.17 N.M. Except in certain areas of continental shelf, continental rise, and locally in other provinces, where irregularities less than 0.3 N.M. in wavelength are seen in precision fathograms, this interval is small enough relative to the wavelength of the relief to allow reading at regular intervals without seriously departing from the shape seen in the PDR records. Readings were taken to the nearest tau. Linear interpolation was applied in areas of hyperbolic reflections (figure 2). Normally the records were not read during time intervals when the ships were on station.

The sounding data read for this study were supplemented by Lamont's library of sounding data routinely collected and reduced. The standard procedure for this data is to read a sounding for every successive peak, valley, and marked change in slope.

Navigation was read from the navigation charts by obtaining latitude and longitude at each time corresponding to a speed change and/or course change, thus dividing the tracks into a series of intervals over which the ship moved continuously in one direction at a constant speed.

Both time vs. sounding and navigation data were punched into cards and processed with the NAVTOP program, written by Manik Talwani and Dennis Hayes at Lamont, which 1) reads navigation data and calculates course, distance, latitude, and longitude, 2) reads

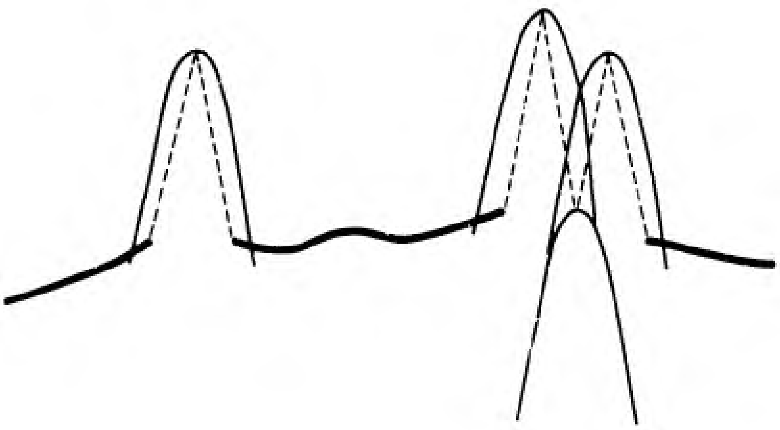


Figure 2.- Hypothetical representation of PDR record trace showing method of reading hyperbolic reflections. Dashed line illustrates straight-line interpolation.

time vs. sounding data and interpolates from the navigation, using time as the dependent variable, the latitude, longitude, and cumulative track distance for each sounding, 3) calculates each sounding in corrected fathoms and corrected meters, and 4) draws a preliminary topographic profile for use in editing.

Approximately two-thirds of this processing was achieved on IBM 7094 computers, where preliminary profiles were obtained on an SC/4020 plotter; sounding data were accumulated on magnetic tape for further processing. The remainder of the data were run on an IBM 1620 computer. Punched-card output was obtained and preliminary profiles were drawn on a 30 in. CALCOMP drum plotter.

<u>Determining Slope, Relative Relief, and Topographic Texture</u>

Slopes are calculated from difference in depth vs. horizontal distance between adjacent soundings. For obtaining chart parameters only absolute slope values were employed. For statistical analyses, however, it was convenient to calculate positive or negative values, with X coordinate value increasing in the direction of ship's travel. Each slope calculated obviously represents a mean value over the horizontal distance between soundings. With the one-minute reading interval employed herein, the reading of echo-time to the nearest tau imposes a limit of resolution to slope measurements. This limit is not significant in most areas of the Atlantic where the topography is sufficiently rough, but does become an important factor on the very gentle abyssal plain and continental rise slopes. In the areas of very gentle sloping terrain it is desirable to measure slopes by averaging several adjacent increments of slope or by making individual slope measurements over a larger interval of horizontal distance.

In order to obtain parameters for charts encompassing the entire Atlantic, slopes must be summarized to obtain numbers representative of successive short intervals along the ship's track. The length of track segment chosen must include sufficient samples to characterize the roughness of the bottom but still be short enough to insure that each number plotted is sufficiently sensitive to geographic location. For example, with 0.2 N.M. spacing of soundings, a single slope value of 0 degrees obtained in the rough topography of the Mid-Atlantic Ridge does not characterize the roughness and is not mappable at other than a very large chart scale. However, 100 adjacent slope values of 0 degrees obtained in rough topography would indicate a flattening of sufficient scale relative to the scale of bottom roughness (and chart scale) to be significant with respect to overall bottom shape and to be mappable.

Data points for the chart of mean bottom slope (chart 2) were obtained by calculating arithmetic means from successive groups of 30 adjacent separate slope measurements. At normal ship speeds this

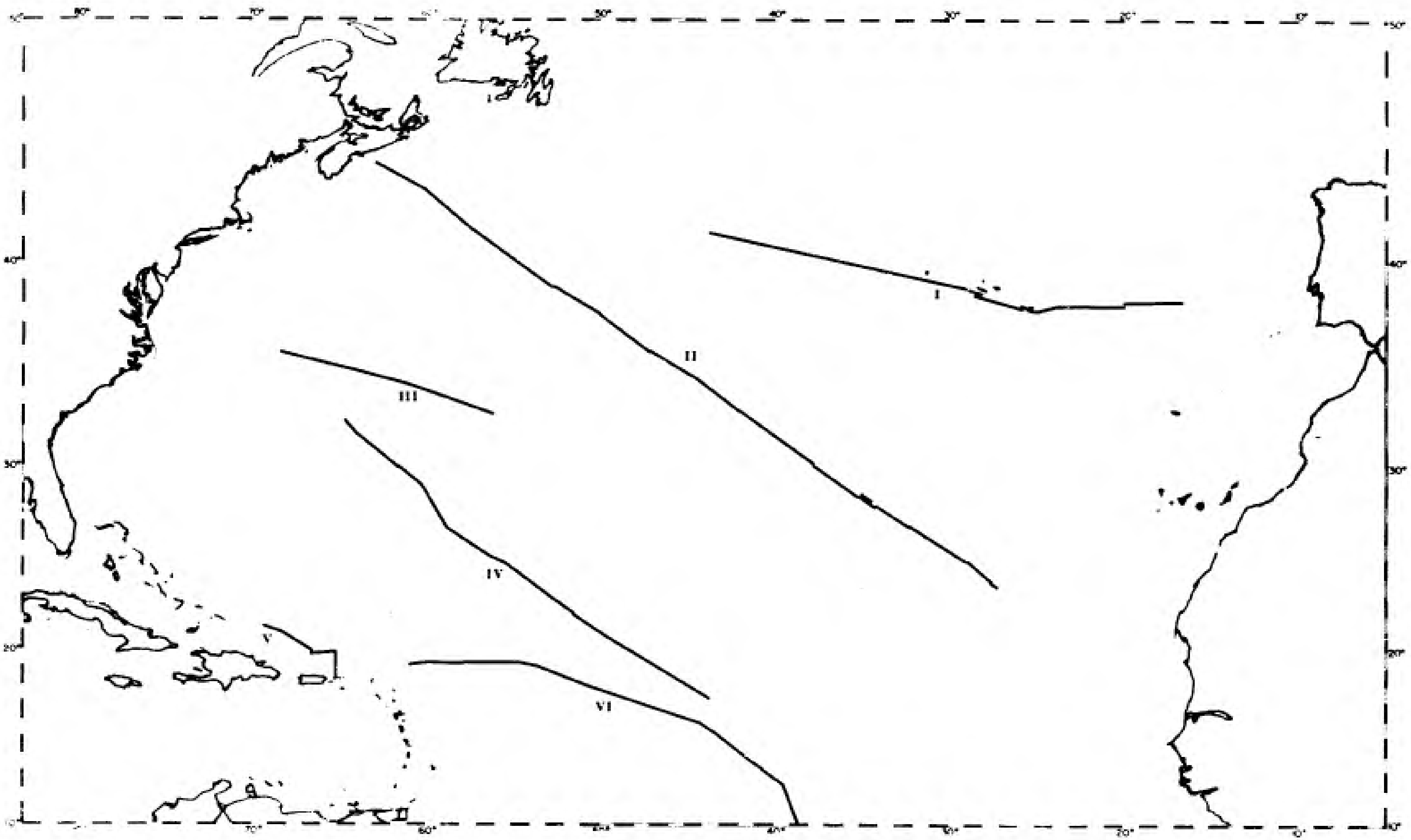


Figure 3. - Index chart of the North Atlantic showing track locations for plates I - VI.

provides a mean for about 5 N. M. of track. Where overcrowding of points occurred on the preliminary chart, alternate points were plotted. The units employed for both this chart and the chart of 90th percentile are cotangents, which correspond to the convention of referring to gradients of 1:10 (cotangent=10), 1:200 (cotangent=200), and so on.

Data points for the chart of 90th percentile of slopes (chart 3) were obtained by sorting each successive group of 30 soundings and extracting the third ranked value. This parameter tends to illustrate, in areas where steep-sided hills alternate with flat-floored valleys or plain, the slope magnitude characteristic of the hillsides. In contrast, the mean, in areas where the flat component is large, gives a value which is much smaller in magnitude than the typical hillside slopes. In areas of plain and smooth continental rise, the 90th percentile loses significance because of the limit of resolution already described. In areas where the cotangent readings were 100 or greater, the arithmetic mean values, which would be approximate 90th percentile values, were substituted.

It cannot be overemphasized that the slope parameters are not true indices of bottom inclination, being derived from direct measurement of apparent PDR record slopes. On a traverse in any direction over randomly oriented topography, one might expect to obtain, from statistical parameters describing large blocks of sounding data, numbers which are about 0.7 as large as those which would be obtained from true slope measurements. In the North Atlantic, however, randomly oriented topography is the exception rather than the rule, and most of the transoceanic tracks employed in this study cross the major topographic trends, fracture zones excepted, ostensibly at right angles, thus leading one to expect that parameters obtained from tracks crossing the ridge might average closer correspondence to the true slope than 0.7, perhaps as high as 0.9.

Directly measuring relief involves defining successive peaks and valleys in the sounding data. To do this by computer it was convenient to test soundings in groups of 3 successive depths, overlapping by 2/3 each time. A smaller depth flanked by two greater depths defines a peak, and a greater depth flanked by two smaller depths defines a valley. When two of the three depths tested are equal, definition would proceed as illustrated in figure 4. Fundamental relative relief, or amplitude (chart 5), constituting the smallest relief resolved by the fathograms and reading methods, is then defined as shown in figure 5. A second calculation (figure 6), provides a crude but accurate measure of the larger scale relative relief (chart 1).

The methods of defining relative relief provided valid measurements throughout the North Atlantic in all types of topography. Measuring

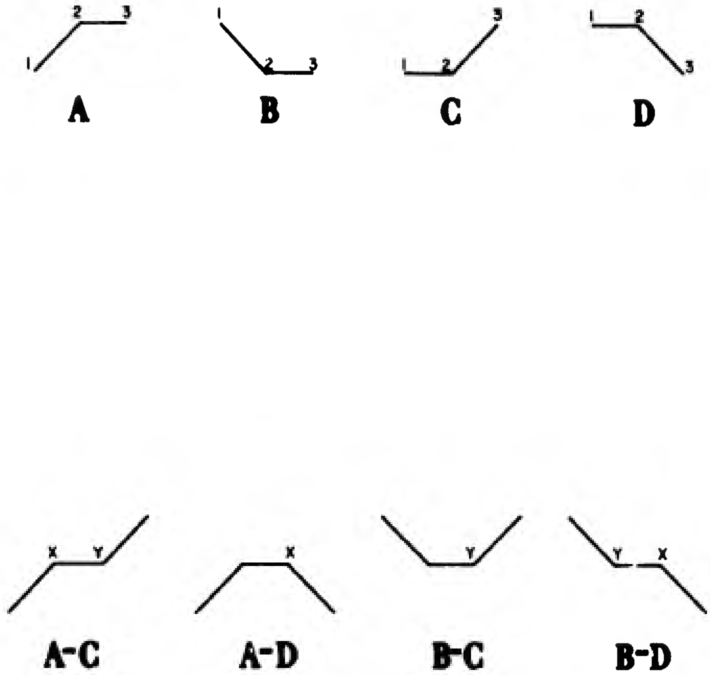


Figure 4.- Method of defining peaks and valleys where two adjacent soundings are equal in depth.

(1) The numbers 1,2, and 3 represent a group of 3 adjacent soundings. In A, "1" has the greatest depth, with "2" and "3" being of equal depth, and so on. A,B,C, and D represent possible combinations of depth when two or three soundings are equal.

(2) Four combinations of A,B,C, and D are possible, as illustrated by A-C, A-D, B-C, and B-D. "X" and "Y" show where peaks and valleys would be defined, respectively.

on the basis of reversal in slope obtains measurement of amplitudes inherently related to spacing of peaks and ridges. This method also results in a convenient basis for correcting out regional slope effects. A clear-cut size difference between regional and fundamental amplitudes is resolved in rough areas where such a distinction clearly exists.

The size of the smallest relief resolvable with the PDR records employed in this study varies with the water depth and with the quality of the records obtained. The consistency of results obtained from many crossings of the Mid-Atlantic Ridge and Bermuda Rise suggest that depth probably plays a greater role in relief resolution than record quality. In the deepest areas of the North Atlantic, resolution is generally quite poor when compared with, for example, a crossing of the ridge crest. Regional relief would obviously be the parameter least affected by differences in record quality.

Fundamental wavelengths (chart 4) and regional wavelengths (chart 6) are calculated as shown in figures 5 and 6, respectively. Fundamental wavelengths are meaningless in areas of abyssal plain and smooth continental rise because of the absence or sporadic spacing of peaks and valleys. These are the areas designated "plain and long regional slope."

Data point spacing for both wavelength and relief varies with the distance between successive peaks. For the "fundamental" para-

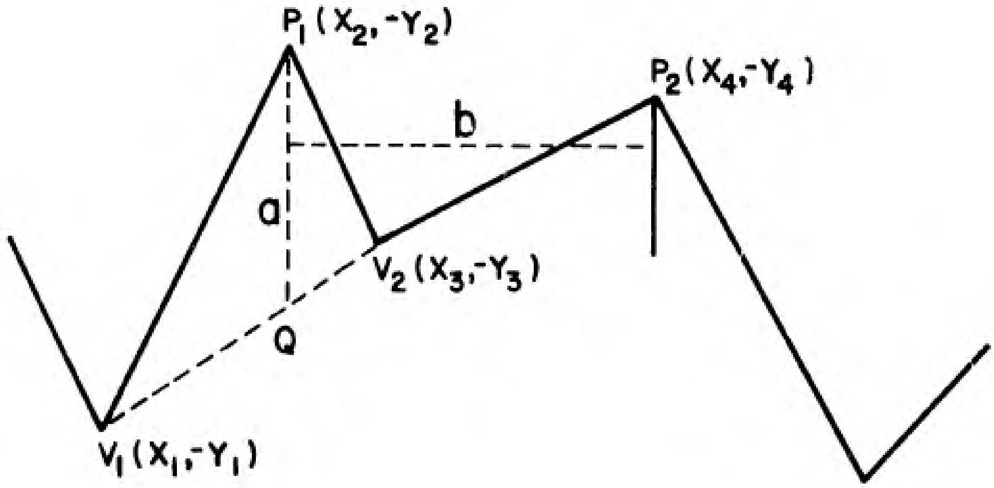


Figure 5.- Method of defining fundamental amplitudes and wavelengths.

P1 and P2 represent peaks, and V1 and V2 represent valleys. Amplitude and wavelength are represented by a and b, respectively.

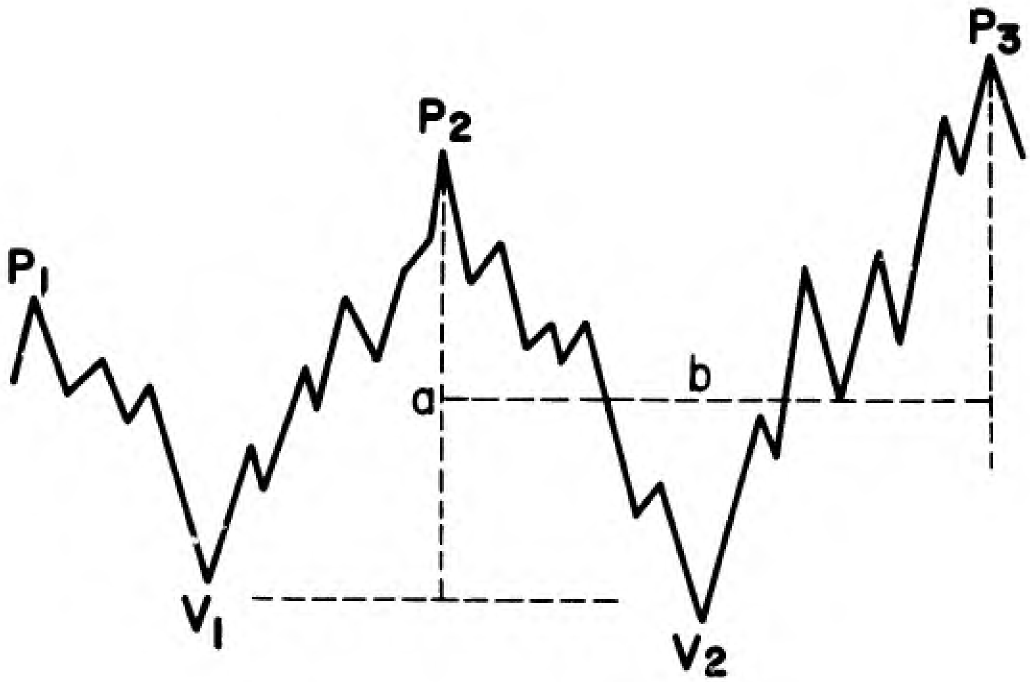


Figure 6.- Method of defining regional amplitudes and wavelengths.

P1 and P2, etc., represent peaks which stand higher than adjacent peaks. V1, V2, etc., represent deepest valleys between every pair of dominant peaks. Amplitude and wavelength are represented by a and b, respectively.

meters, points were too closely spaced to allow plotting at the chart scale employed. Representative numbers were obtained by determining a range of magnitude based on all the peaks and valleys of for example 5 to 20 N. M. of track, depending on the rate of change along the track. Values anomalously high and anomalously low were excluded in favor of those occurring with greater frequency. This selection was quite easy to achieve in many areas where a certain natural amplitude and wavelength size predominates. However, in some areas a wide distribution of amplitude and wavelength sizes was present, no predominant relief size being evident. The latter case was resolved by simply increasing the upper and lower limits of size ranges. The final result is size range overlapping in charts 4 and 5.

Data points for regional relief and wavelength are in most areas spaced sufficiently to allow plotting of every data point calculated. The wavelength numbers vary sufficiently to make overlapping magnitude ranges a necessity. Regional relief is sufficiently distinct from one area to another to allow sharper discrimination of provinces, without overlapping.

Construction of Charts and Profiles

Charts 1-6 use the outline map of North Atlantic physiographic provinces as a common base. This is essentially the map published by Heezen *et al.*, (1959), with slight modifications resulting from additional data obtained since the original province map was constructed. A new province, the Krylov Rise, a N-S elongate area between latitude 15-25°N and longitude 28-32°W, consists of sediment-subdued relief at a general level of 50-200 fathoms above the surrounding ocean floor. About 600 N.M. long and 10-200 N.M. wide, this province takes its name from a seamount at 17°30'N, 30°00'W, discovered in 1959 on a cruise of the Russian Ship R/V MIKHAEL LOMONOSOV (Academy of Sciences, U.S.S.R., 1963). The lower, middle, and upper steps of the Mid-Atlantic Ridge are not discriminated, having been grouped here under the term "Flank of the Mid-Atlantic Ridge." Likewise the "Crest of the Mid-Atlantic Ridge" has not been differentiated into rift valley, rift mountains, and high fractured plateau. Subsequent data from surveys by R/V DISCOVERY, R/V CHAIN, R/V ATLANTIS, R/V VEMA, and other oceanographic research vessels has shown that the abyssal plains on the eastern North Atlantic ocean basin floor, in particular the Cape Verde Abyssal Plain and the Madeira Abyssal Plain, are more limited in areal extent than originally drawn. Where the Kelvin Seamount Group transects the northeastern extremity of the Bermuda Rise, data from R/V VEMA cruises 16 and 19 have shown that the Sohm Abyssal Plain is of greater extent than was earlier expected. Here the plain sediments appear to lap around several of the seamounts as if filling moats.

Track control is shown on each chart by narrow white bands containing symbols coded by color and by shape to display relative magnitudes. Primary differences are shown by contrasting colors, with finer distinctions being portrayed by symbols. Using the data coded along the tracks, boundaries have been extended with the aid of additional topographic profiles, the North Atlantic physiographic diagram, and the physiographic province boundaries. Provinces are shown by colors corresponding to the appropriate symbols. The validity of each boundary line drawn varies with the character of the topography and the degree with which that character changes. For example, while the outer limits of the abyssal plains are usually characterized by a distinct and abrupt change from flat plain to hills, many of the boundaries occurring within a province, for example within the flank of the Mid-Atlantic Ridge, represent transitional changes which would be evident in statistical data. Additional data coverage would no doubt alter the details of the boundaries shown, but the general pattern would not be changed. Future surveys with instruments providing higher resolution of navigation and depth would result in more accurate quantitative values but the distribution pattern would not be altered except for specifics. The pattern of boundary lines within the Mid-Atlantic Ridge is schematic.

Plates I-VI illustrate the basic parameters obtained prior to the application of smoothing and coding functions associated with construction of the charts. Location of each plate is shown by its plate number in figure 3. The topography is plotted at 100:1 vertical exaggeration. Slope, amplitude, and wavelength profiles are aligned so that their horizontal scale matches that of the topography. Amplitude and wavelength are scaled vertically so that they correspond to the vertical and horizontal scales of the topography, respectively. Slope was assigned an appropriate vertical scale.

III. ROUGHNESS CHARACTERISTICS OF THE PHYSIOGRAPHIC PROVINCES

Continental Shelf

On the continental shelf of North America between Nova Scotia and Florida, the smoothness of the terrain is evident: Regional and fundamental relief is low (0-10 tau, chart 1; 0-5, chart 5) and slopes are gentle ($<$1:1000, chart 2; $<$1:100, chart 3). Off the Canadian coast where Pleistocene glaciation has contributed more directly to the present character of the topography, higher regional relief (10-50, chart 1; figure 7) and slopes (1:1000-1:50, chart 2; 1:15-1:100, chart 3; figure 8) occur. The corresponding contrast in fundamental relief is less pronounced (figure 7). No marked contrast exists for either wavelength category ($<$1.5n, chart 4; $<$10n, chart 6; n=nautical miles).

Low relief (0-10 tau, chart 1) and gentle slopes characterize the continental shelf off West Africa and the Iberian Peninsula.

The fine textured ($<$1.5n, chart 3) choppy topography of the western portion of the Blake Plateau possesses regional relief (10-50, chart 1) and mean slopes (1:50-1:1000, chart 2) which are higher than those on the eastern part where these categories (relief 0-15, chart 1; mean slopes $<$ 1:1000, chart 2) reflect a bottom character similar to that of the continental shelf.

Figure 7.- Continental shelf - statistical frequency distribution of relief.

Cumulative frequency distribution of regional and fundamental relief, comparing tracks off New York (solid lines) with those off Nova Scotia (dashed lines). Curves C and D represent regional relief; curves A and B represent fundamental relief.

Relief in 1/400 second echo time units (TAU).

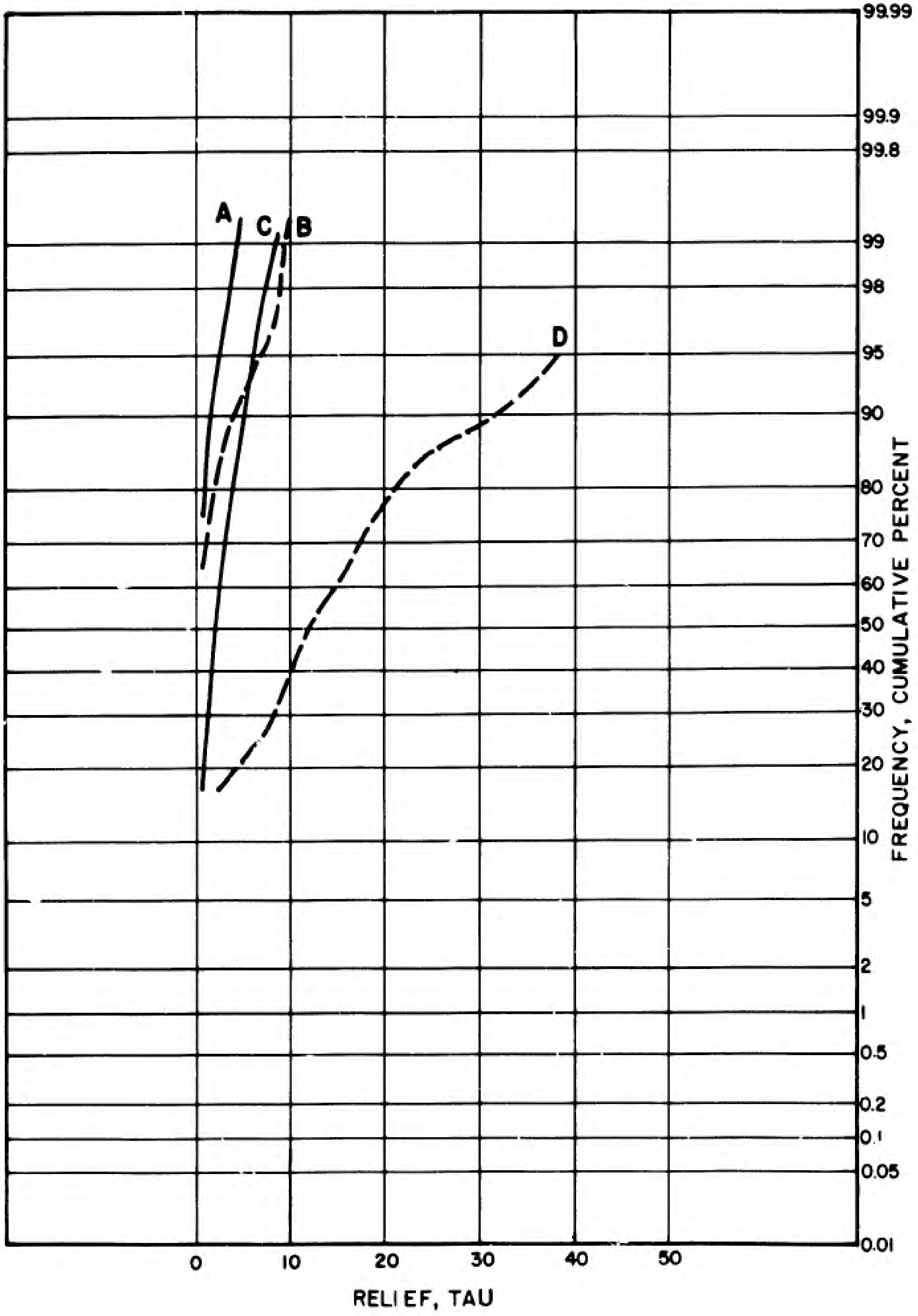
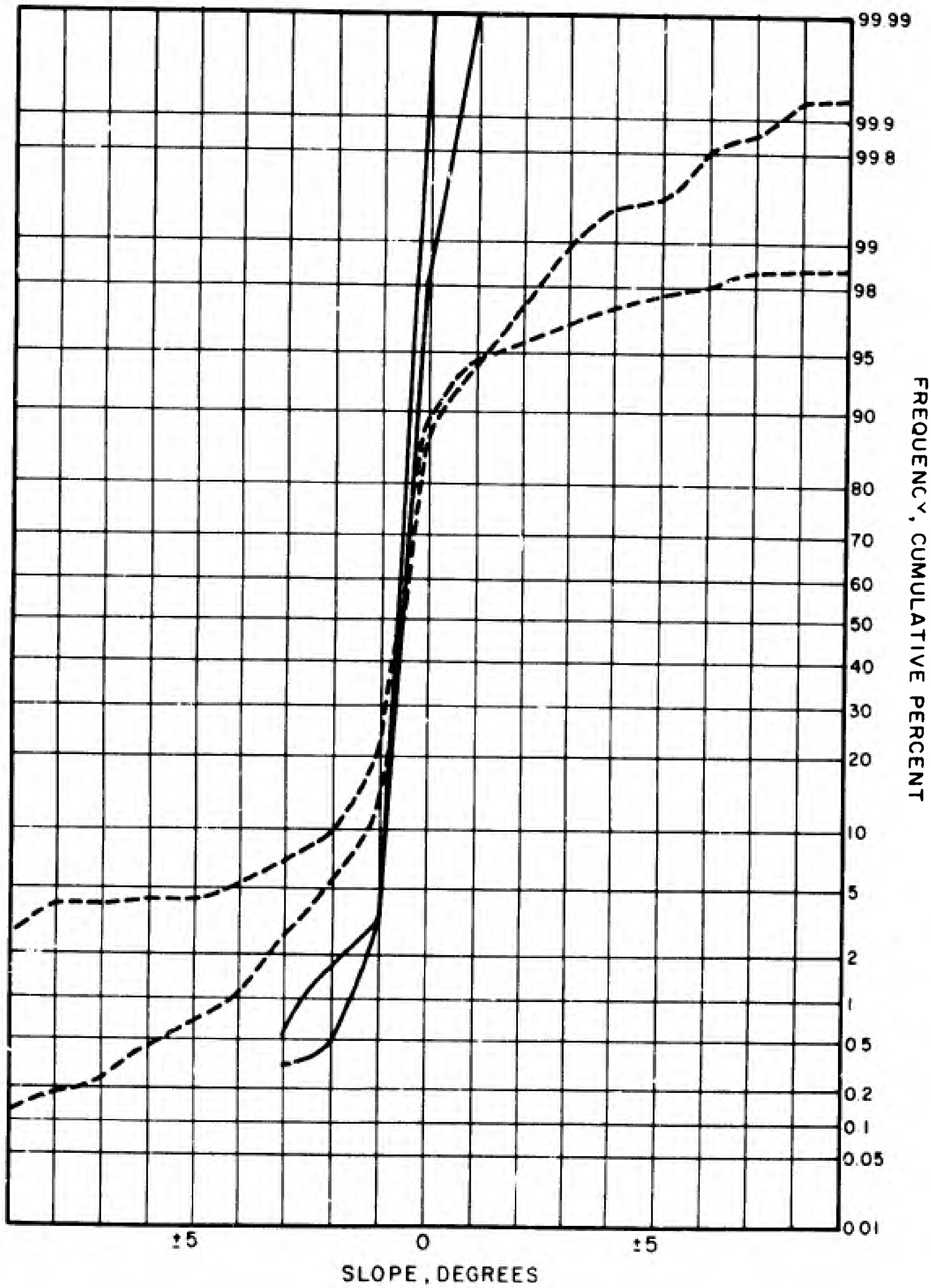

A
C
B
D
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
0
10
20
30
40
50
RELIEF, TAU

Figure 8.- Continental shelf - statistical frequency distribution of slopes.

Cumulative frequency distribution comparing the shelf off New York (solid lines) with that off Nova Scotia (dashed lines). Both categories show a high though contrasting percentage of slope values less than 0.5 degrees (96 and 93 percent for the shelf off New York, 69 and 74 percent for the shelf off Nova Scotia). The curves from data taken off Nova Scotia show a significant component of slope values greater than 1.5 degrees.



99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
±5
0
±5
SLOPE, DEGREES

Continental Slope

Regional relief of the continental slope generally falls in the 50-200 range (chart 1) along both eastern and western margins of the North Atlantic, with local exceptions above and below these limits. Fundamental relief varies along strike, but it is predominantly 0-10 (chart 5).

Slopes are steep (1:10-1:50, chart 2; 1:5-1:15, chart 3), reflecting the high regional slope even where relative relief is negligible. Tracks which parallel the strike of the continental slope generally yield relief measurements which are either higher or lower than the usual range seen in crossings normal to the strike, depending on the presence or absence, respectively, of submarine canyons (figure 9).

Continental Rise

Over most of the continental rise off North America, relief lies predominantly in the 0-10 tau range (chart 1, figure 10). Higher relief (10-50, and 50-200, chart 1) occurs in the 50-100 N.M. wide Lower Continental Rise Hills belt bordering the northwestern boundary of the Hatteras Abyssal Plain, locally near the base of the continental slope, and in the seamounts of the Kelvin chain.

Mean and 90th percentile slopes on the continental rise off North America, on the Blake-Bahama Outer Ridge, and on the

Figure 9.- Continental slope - statistical frequency distribution of relief.

Cumulative frequency distribution of regional and fundamental relief, comparing two tracks which parallel the strike of the continental slope, one off New York (solid lines) and one off Nova Scotia (dashed lines). Curves C and D represent regional relief; curves A and B represent fundamental relief.

The track off New York traverses a section of shelf where few submarine canyons are present. The one off Nova Scotia traverses a slope well dissected with canyons. Relief is in units of 1/400 second echo time (TAU).

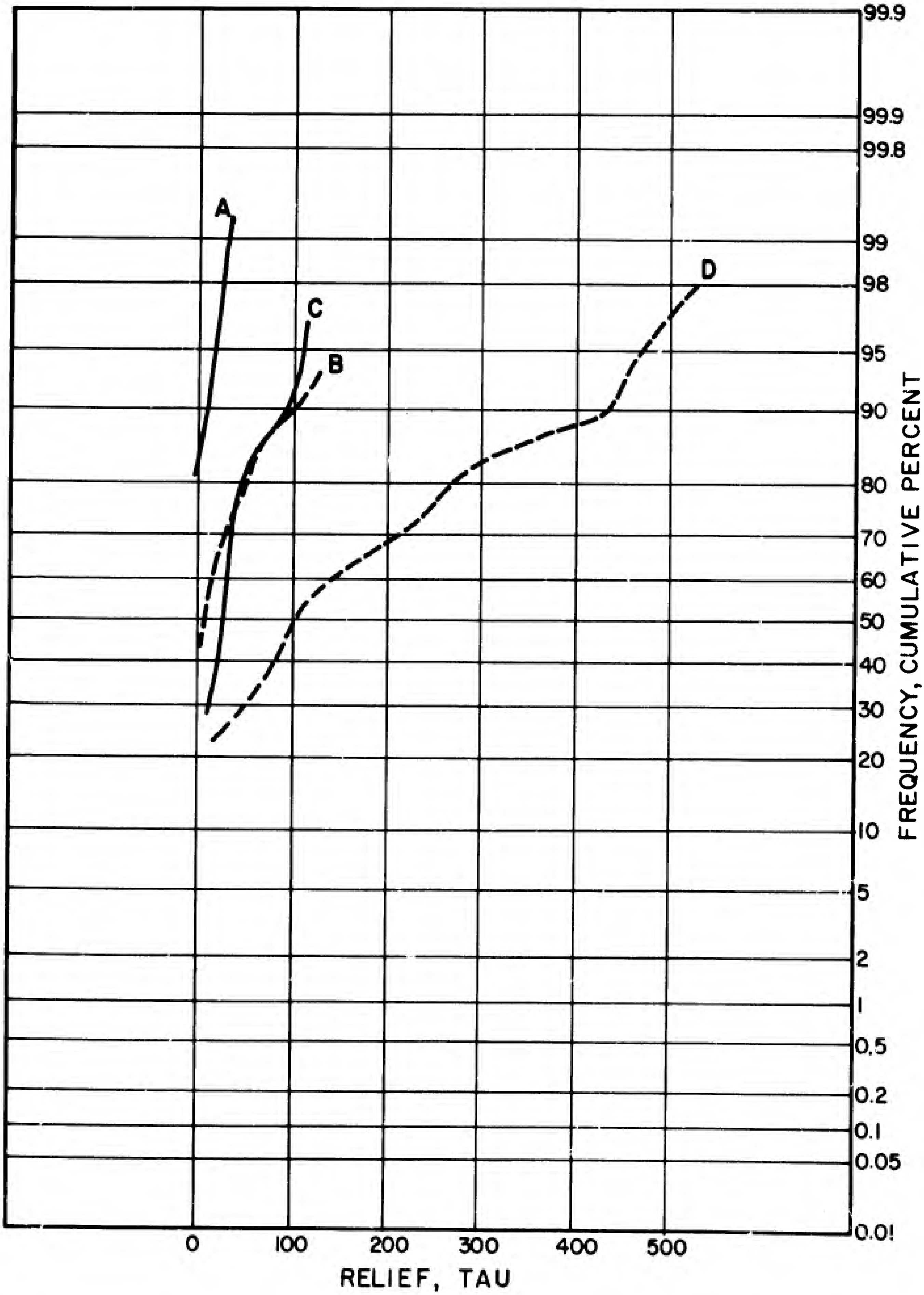

99.9
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.0!
FREQUENCY, CUMULATIVE PERCENT
A
B
C
D
0
100
200
300
400
500
RELIEF, TAU

Figure 10. - Continental rise - statistical frequency distribution of relief.

Cumulative frequency distribution of regional and fundamental relief, comparing three tracks off New York (solid lines) with two off Nova Scotia (dashed lines). Curves C and D represent regional relief; curves A and B represent fundamental relief.

No major differences between tracks off New York and those off Canada are evident, in contrast to the continental shelf.

Relief in 1/400 second echo time units (TAU).

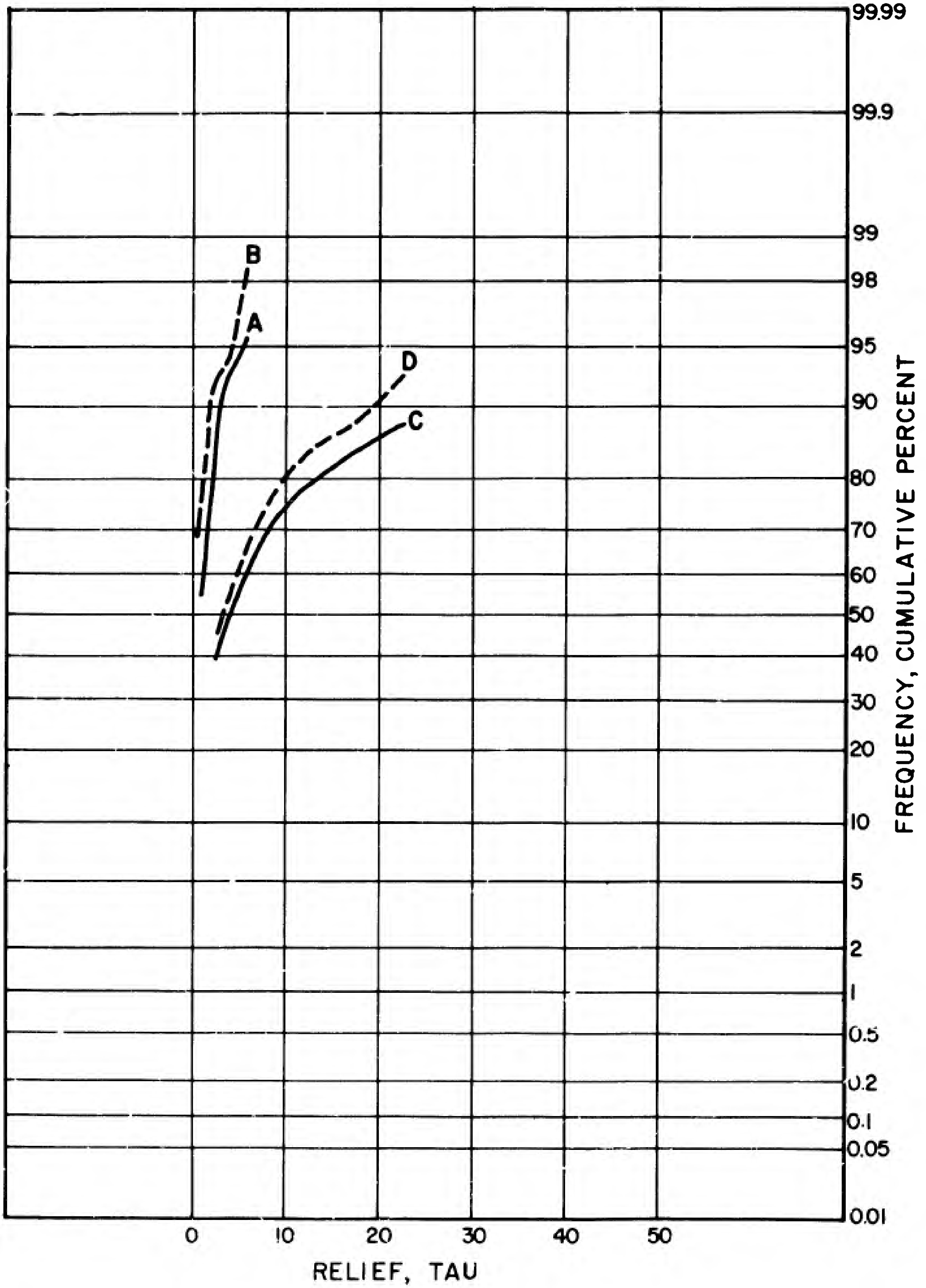
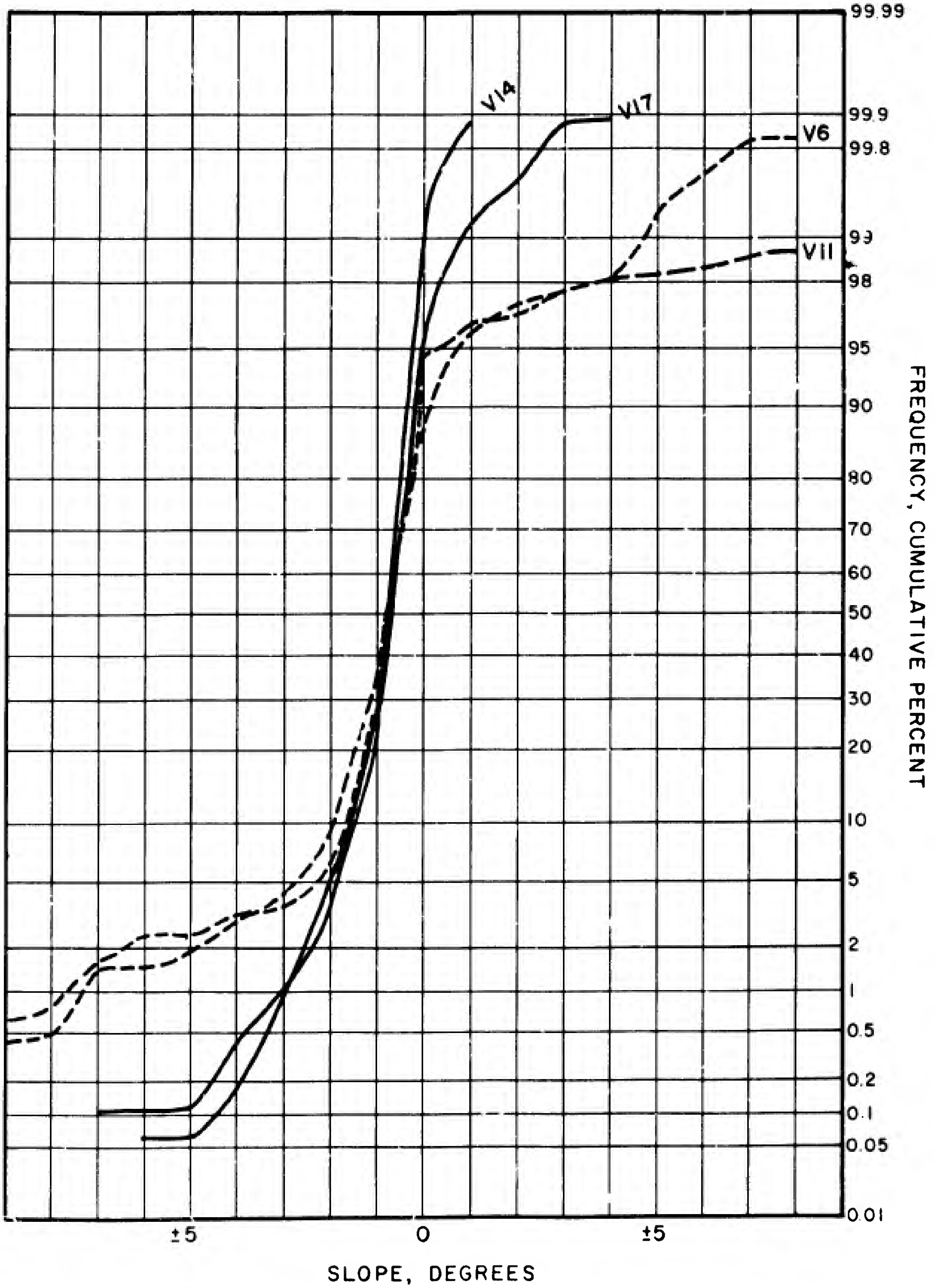

99.99
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
B
A
D
C
0
10
20
30
40
50
RELIEF, TAU

Figure 11. - Continental rise - statistical frequency distribution of slopes

Cumulative frequency distribution of slopes for two tracks off New York (dashed lines) and two tracks off Nova Scotia and Newfoundland (solid lines). Strong asymmetry is not seen in spite of the long regional slope of the continental rise, because most of the slope values are sufficiently near zero to fall within the interval (-0.5 to +0.5) plotted at zero.


V14
V17
V6
V11
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
±5
0
±5
SLOPE, DEGREES

Antilles Outer Ridge, are predominantly in the 1:50-1:1000 range (chart 2) and in the 1:15-1:100 range (chart 3, figure 11) respectively. A decrease in slopes toward the outer flanks of the continental rise off North America is evident (chart 3). The 90th percentile slope range of >1:100 includes the outer margins of the rise as well as the abyssal plains.

Generally, relief on the continental rise of the eastern North Atlantic margin tends to be higher than that of the western margin, particularly adjacent to seamounts and island groups. A relief of 10-50 (chart 1) characterizes the upper portion of the continental rise as well as large areas adjacent to the extreme relief of the Cape Verde and Canary Island groups and the seamounts off northwestern Spain and directly west of Gibraltar.

Relief patterns parallel the NW-SE orientation of the Blake-Bahama Outer Ridge, with two 50-200 (chart 1) zones on the eastern and western flanks lying between 0-10 and 10-50 zones occurring along the crest and lower flanks. The Antilles Outer Ridge is characterized by 10-50 and 50-200 regional relief. Steeper slopes corresponding to higher relief occur in the Lower Continental Rise Hills and locally on the Blake-Bahama Outer Ridge, but not in the 50-100 N.M. wide belt of higher relief between New York and Bermuda, where dimensions of the bottom topography increase without an increase in roughness;

longer wavelengths (1-3n) coincide with this belt than are normal for the continental rise as a whole (<1.5n, chart 5, figure 12).

Fundamental relief of the continental rise off North America grades from 0-10 near the base of the continental slope to 0-1 on the margins near the abyssal plains (chart 5, figure 10). Between New York and Bermuda, on the Blake-Bahama Outer Ridge, and on the Antilles Outer Ridge, fundamental relief is predominantly 0-10.

Abyssal Plains

On the abyssal plains relief is virtually absent (0-10, chart 1; 0-1, chart 5), except for isolated summits which extend above the general level of the floors. Slope parameters reflect the regional gradients of the plains (>1:1000, chart 2;>1:100, chart 3).

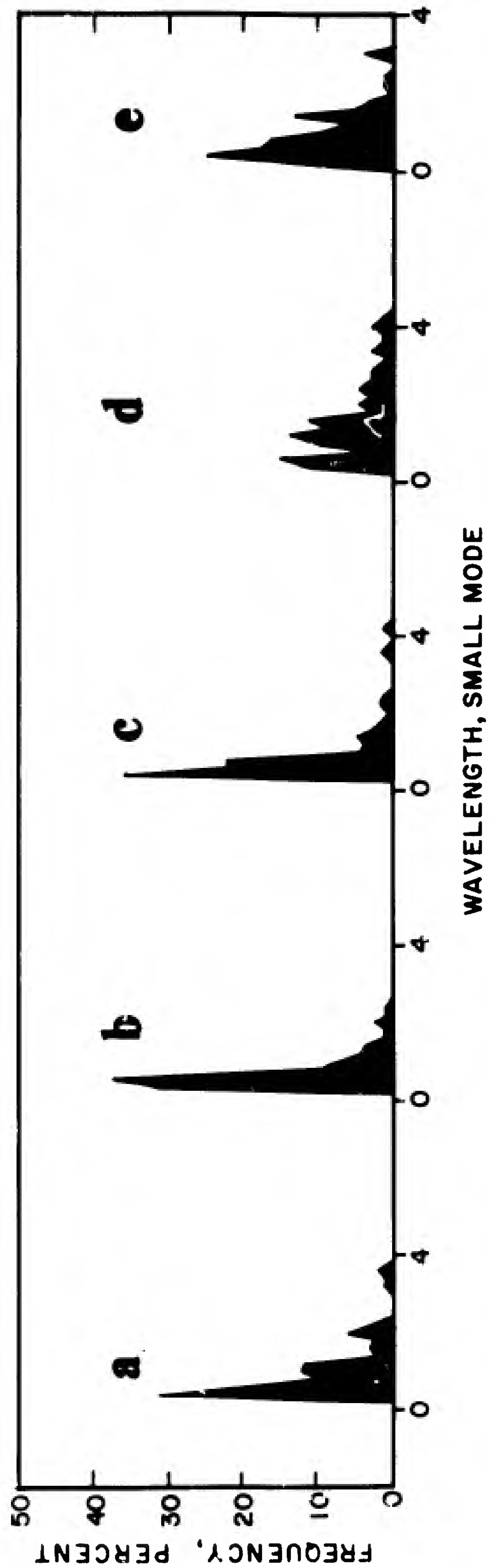
Occurrence of peaks dotting the plain floors is higher in the eastern portion of the Nares Abyssal Plain and in the southern panhandle of the Sohm Abyssal Plain than elsewhere on the abyssal plains of the western North Atlantic.

Oceanic Rises

The Bermuda Rise is divisible into four subprovinces on the basis of roughness patterns seen in charts 1, 2, and 3. A 50-200 N.M. wide belt on the western and northern perimeter, adjoining the Hatteras and Sohm abyssal plains, respectively, consists of sediment-subdued

Figure 12. - Continental rise - statistical frequency distribution of topographic texture.

Statistical frequency distribution of small mode wavelengths (parameter 4) for four tracks off New York (a, b, c, d) and one track off Newfoundland (e). Wavelengths in nautical miles. Tracks a, b, and c show a striking uniformity in small wavelength frequency distribution. The mode for these curves lies at 0.4-0.6 nautical miles and represents the bulk of all measurements. Track d traverses a seamount and crosses the Hudson Submarine Canyon southeast of New York. Track e illustrates that, off Newfoundland, the fine-textured irregularities are more variable in their dimensions. It should be noted that over much of the continental rise, particularly on the lower portions, wavelength and relief is too small to be resolved at PDR scale and thus cannot be measured. Therefore, even though the fine "bumpy" texture does not extend throughout the continental rise, and particularly not the lower gentle portion near the abyssal plains, the relative extent of smooth versus "bumpy" continental rise is not reflected the frequency distribution curves.



a
b
c
d
e
0
4
WAVELENGTH, SMALL MODE
FREQUENCY, PERCENT
0
10
20
30
40
50

Figure 13. - Oceanic rise - statistical frequency distribution of relief on the Bermuda Rise.

Cumulative frequency distribution of large mode relief (parameter 1) comparing northwestern Bermuda rise (A), Bermuda apron (B), central Bermuda rise (C), and Bermuda scarp zone (D). Curve (A) is a composite of 5 track segments; (B) is composite of 3 track segments; (C) is a composite of 6 track segments; and (D) is a composite of 2 track segments. As in some other provinces of the Atlantic, large-scale relief differs from province to province with respect to the spread of values obtained rather than to mutually exclusive size differences.

Relief in 1/400 second echo time units (TAU).

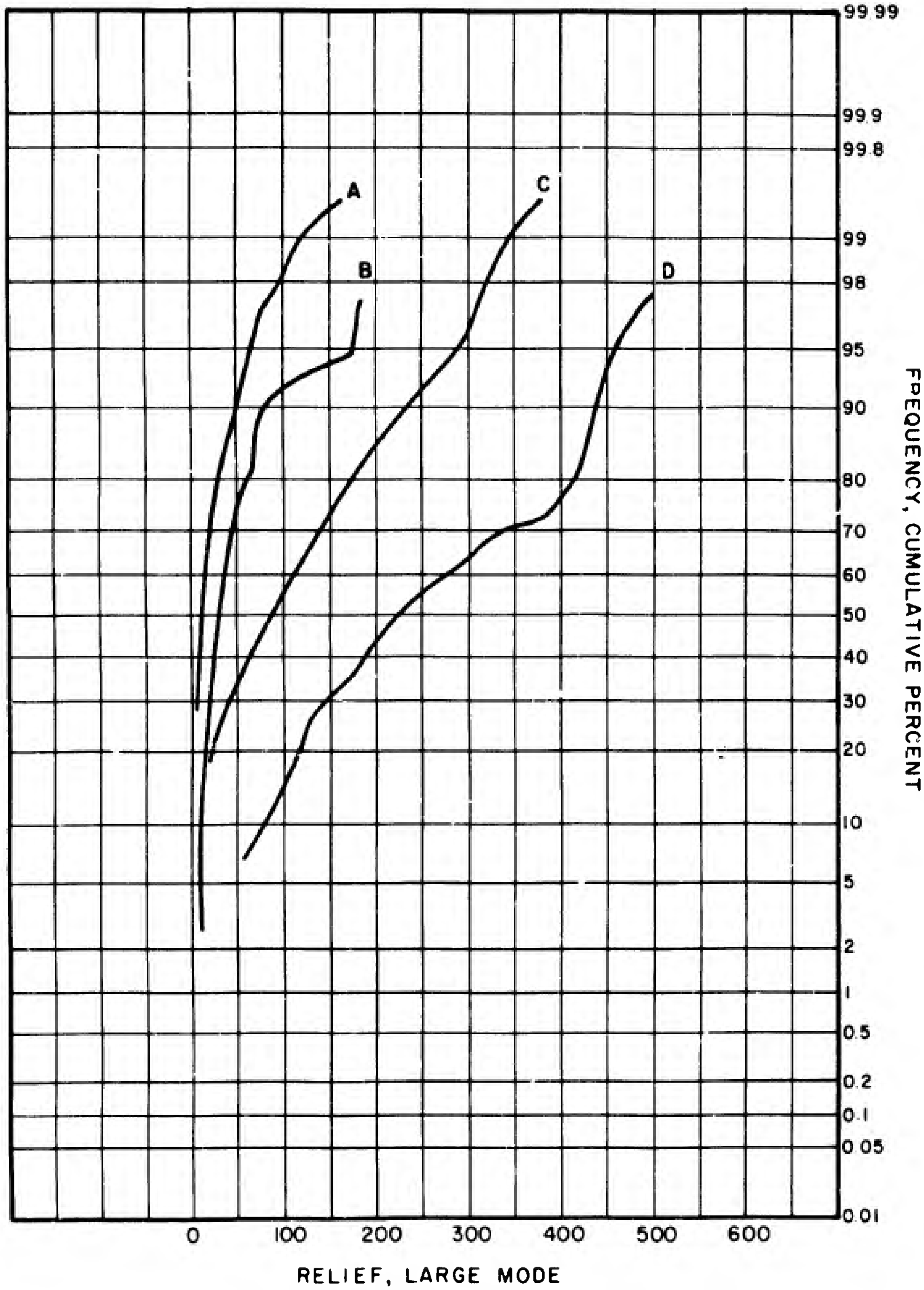
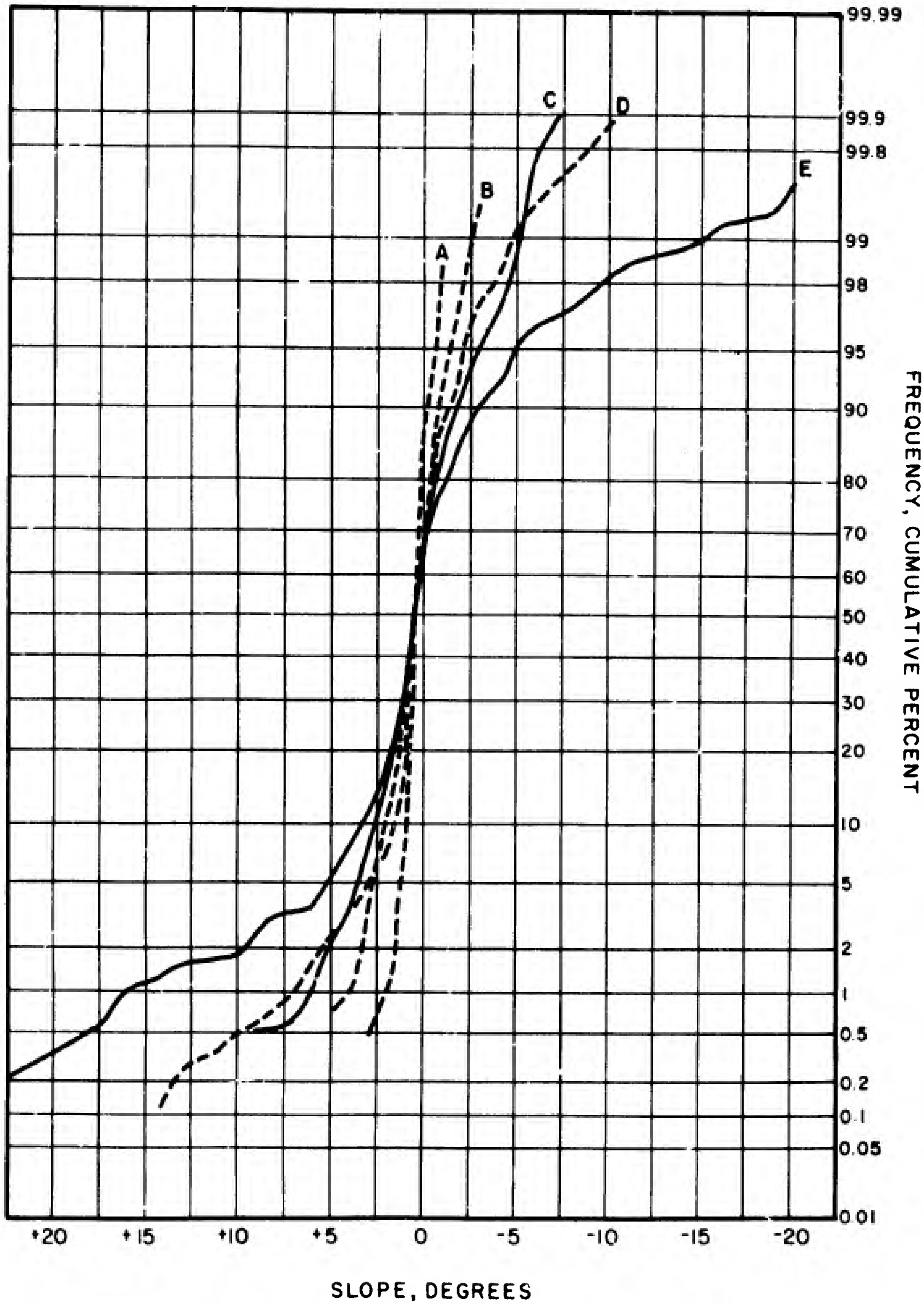

A
B
C
D
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
0
100
200
300
400
500
600
RELIEF, LARGE MODE

Figure 14. - Oceanic rise - statistical frequency distribution of slopes on the Bermuda Rise.

Cumulative frequency distribution of slopes for three track segments from northwestern Bermuda rise (dashed lines) and two track segments from central Bermuda rise (solid lines).


A
B
C
D
E
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
+20
+15
+10
+5
0
-5
-10
-15
-20
SLOPE, DEGREES

terrain (see Heezen, et al., 1966) of low regional relief (10-50, chart 1) and gentle slopes (1:50 - 1:1000, chart 2; 1:15 - 1:100, chart 3). Similar relief and slopes (10-50, chart 1; 1:50 - 1:1000, chart 2, 1:15 - 1:100, chart 3) characterize the sediment apron surrounding the Bermuda Pedestal. A NE-SW trending belt of rugged terrain (regional relief 400-700, chart 1; mean bottom slopes < 1:10, chart 2; slope 90th percentile < 1:5, chart 3), the Bermuda Scarp Zone, occurs along the southeastern perimeter of the Bermuda Rise, adjoining the Nares Abyssal Plain, the Sohm Abyssal Plain, and the abyssal hills. Elsewhere on the rise, terrain of moderate relief (50-200, chart 1) and slope (1:10 - 1:50, chart 2; 1:5 - 1:15, chart 3) is characteristic. The relief locally exceeds 200 in areas of the southern portion of the rise. Differences in relief of the topographic sub-provinces of the Bermuda Rise are further illustrated in figure 13. Statistical cumulative frequency curves of slope data (figure 14) compare the northern and western perimeter of the Bermuda Rise with the central portion.

A pattern different from that seen in relief and slopes is evident in the topographic texture of the Bermuda Rise. North and east of Bermuda and along portions of the Bermuda Scarp Zone, wavelengths of both categories are as high as in any area of the North Atlantic (2.5 - 6.0n, chart 4; 10-30n, chart 6). South and west of Bermuda, wavelengths are moderate (1-3n, chart 4; 5-20n, chart 6), relative to the North Atlantic as a whole. Lower fundamental wavelength values occur along the subdued terrain of the northern perimeter of the rise (<1.5n, chart 4).

Fundamental relief patterns do not possess well-defined boundaries. There is a general increase from 0-5 in the north and west to 10-100 in the southeast (chart 5).

The Krylov Rise possesses moderate relief similar in size to that of the central interior of the Bermuda Rise (50-200, chart 1). Slopes of both categories are correspondingly similar (1:10-1:50, chart 2; 1:5-1:15, chart 3).

Seamounts of the Corner Rise stand out in contrast to an area of otherwise low to moderate relief (10-50 and 50-200, chart 1). Mean slopes and 90th percentile slope values likewise contrast markedly (from 1:50-1:1000 to <1:10, chart 2; from 1:15-1:100 to <1:5, chart 3).

Mid-Oceanic Ridge and Abyssal Hills

Of all physiographic provinces the Mid-Oceanic Ridge and the abyssal hills provinces possess the widest range of relief, slope, and topographic texture, ranging from gently undulating, low terrain to extremely rugged mountain ranges. Relief and slope parameters vary in a pattern that is symmetrical with respect to the ridge crest. The abyssal hills constitute an integral part of this symmetry.

A general latitudinal variation is evident in the regional relief

Figure 15. - Latitudinal distribution of regional relief in the North Atlantic.

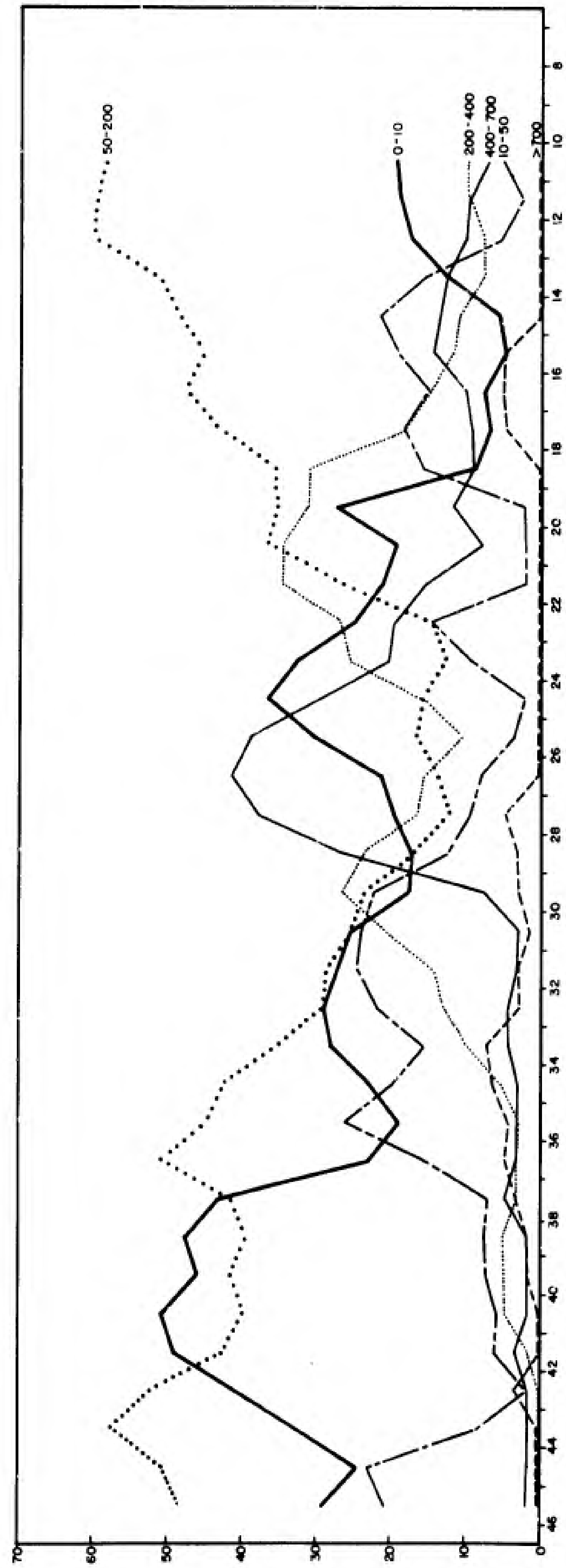
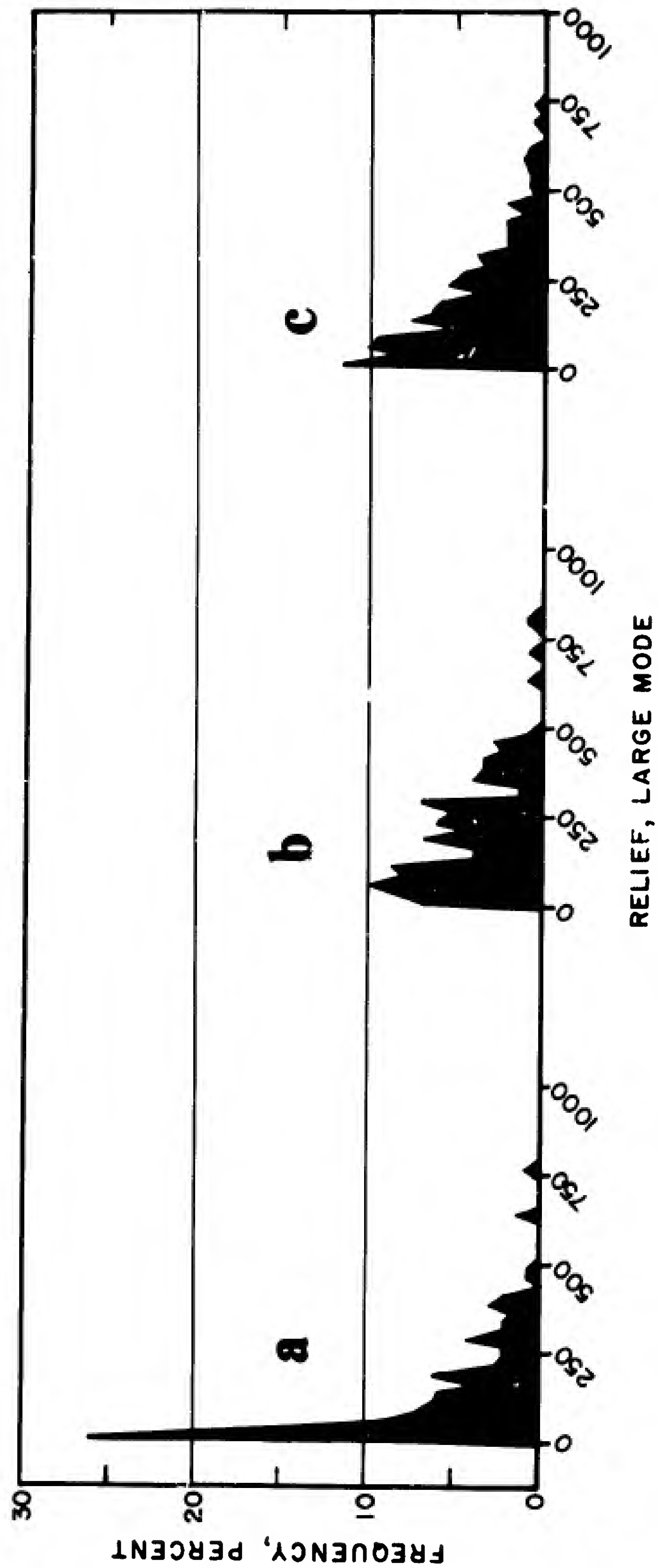

50-200
0-10
200-400
400-700
10-50
>700
LATITUDE NORTH
PERCENT OF AREA
0
10
20
30
40
50
60
70
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46

Figure 16. - Mid-Oceanic Ridge and abyssal hills--Latitudinal variation in statistical distribution of regional relief.

Curve A is a statistical frequency curve for all regional relief data obtained from the ridge crossing at latitude 40°N. Curve B is for all regional relief data obtained from the ridge crossing which cuts the northern extremities of both the Krylov Rise and the Corner Rise, ranging from latitudes 27-36°N. Curve C is for all data obtained from the ridge crossing at latitudes 10-18°N. All three are similar in their overall distribution except in the lower ranges ($< 100t_e$) where curve A shows a signigicantly higher percentage than the other two, curve C showing a higher percentage than curve B.


a
b
c
0
250
500
750
1000
0
10
20
30
FREQUENCY, PERCENT
RELIEF, LARGE MODE

(figures 15 and 16). North of latitude 30°N, relief on the ridge flanks is generally moderate (50-200, chart 1; 0-10, chart 5), with many local exceptions both higher and lower than the general average. South of latitude 30°N relief is higher and more nearly uniform in size over large areas. The Mid-Atlantic Ridge between latitudes 20°N and 30°N constitutes the zone of highest general relief in the North Atlantic Ocean. Here relief predominantly higher than 200 occurs in two roughly triangular shaped belts which are symmetrically disposed with respect to the ridge crest. Taken together with the ridge crest this belt constitutes a region, extending about 1800 N.M. from east to west and 1200 N.M. from north to south and having an area of about 1.5 million square statute miles (about half that of the continental United States). Relief on the crest in this belt is predominantly 400-700. On the inner flanks of the ridge, relief is in the 200-400 range with frequent local occurrence of summits greater than 400 in size. On the outer flanks of the ridge and in the abyssal hills -- the outer corners of the triangles -- lie belts of higher relief (400-700, chart 1), possessing remarkable uniformity of roughness. Relief is again moderate south of latitude 20°N (50-200 and 200-400, chart 1) on the ridge flanks.

In contrast to the north-south variations in relief on the ridge flanks and in the abyssal hills, the crest of the Mid-Atlantic Ridge possesses high relief (400-700, chart 1) throughout the North Atlantic Ocean, except in local belts near where it is interrupted by the transverse trending topography associated with fracture zones.

Slopes defining the crest of the Mid-Atlantic Ridge stand in marked contrast to the ridge flanks and the abyssal hills along most of the ridge's extent in the North Atlantic (figures 17, 18, 19, 20, 21, and 22). Slopes are consistently high along a 50-200 mile wide belt constituting the ridge crest ($<$1:10, chart 2; $<$1:5, chart 3), where relief is high and wavelengths are low. North of latitude 30-35°N slopes, like relief, are relatively subdued (1:10-1:100, chart 2; 1:5-1:100, chart 3) on the ridge flanks, particularly on the western flank.

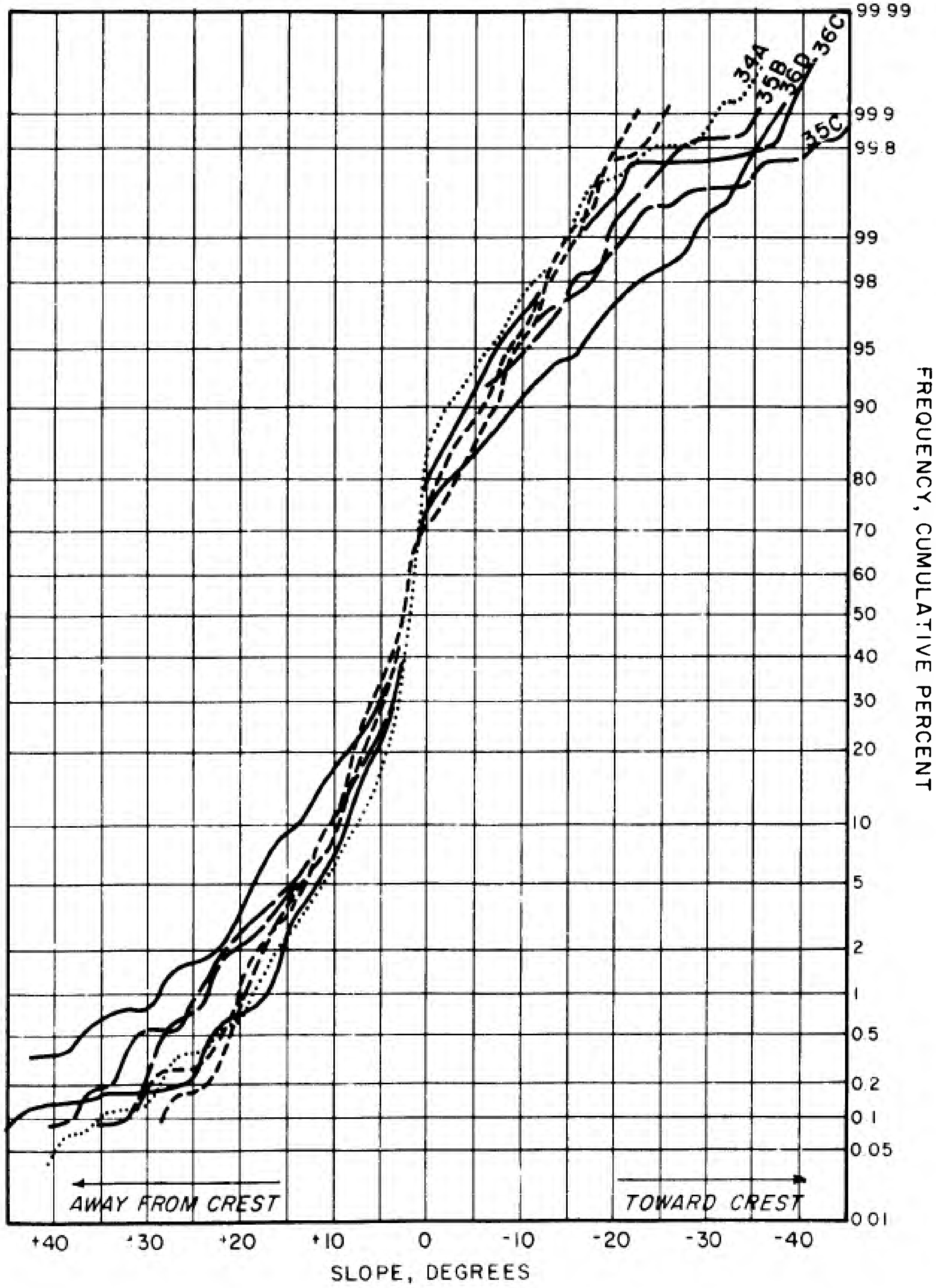
South of latitude 35°N, mean and 90th percentile slopes on the flanks of the Mid-Atlantic Ridge and in the abyssal hills lie mostly in the 1:10-1:50 (chart 2) and 1:5-1:15 (chart 3) ranges, respectively. Slopes in the steeper ranges define the boundaries between the outer flanks of the ridge and the abyssal hills between latitudes 20°N and 30°N, where relief and wavelengths are correspondingly high, as markedly as they do those of the ridge crest.

Wavelengths define the limits of the ridge crest, being low to moderate ($<$3.0n, chart 4; $<$20n, chart 6) over most of the ridge and the abyssal hills. Longer fundamental and regional wavelengths (2.5-6.0n, chart 4; 10-30n, chart 6) define the belts of high relief and slopes on the outer flanks of the ridge and in the abyssal hills between latitudes 20°N and 30°N.

Fundamental relief displays a pattern similar to that of regional relief, though less detailed. A fundamental relief range of 0-10 characterizes most of the ridge flanks and abyssal hills north of latitude 30°N. Along the ridge crest over the roughest portion of the ridge flank, between latitudes 20°N and 30°N, the 25-200 range best fits the fundamental relief. The remainder of the Mid-Atlantic Ridge south of latitude 30°N is characterized by fundamental relief in the 5-20 and 10-100 ranges.

Figure 17. - Mid-Oceanic Ridge and abyssal hills--Cumulative frequency distribution of slopes for seven track segments from the ridge flanks in which the ship was steaming toward the ridge crest.

Curve identification denotes corresponding curve in figures 34, 35, and 36. The strong effect of the flat-bottom component and the broader range of slopes in the negative direction (toward the crest) is noted.



34A
35B
36D
36C
35C
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
AWAY FROM CREST
TOWARD CREST
+40
+30
+20
+10
0
-10
-20
-30
-40
SLOPE, DEGREES
FREQUENCY, CUMULATIVE PERCENT

Figure 18. - Mid-Oceanic Ridge and abyssal hills--Cumulative frequency distribution of slopes for seven track segments from the ridge flanks in which the ship was steaming away from the ridge crest.

Curve identification denotes corresponding curve in figures 34, 35, 36. The strong effect of the flat-bottom component and the broader range of slopes for most curves in the positive direction (away from the crest) is noted.

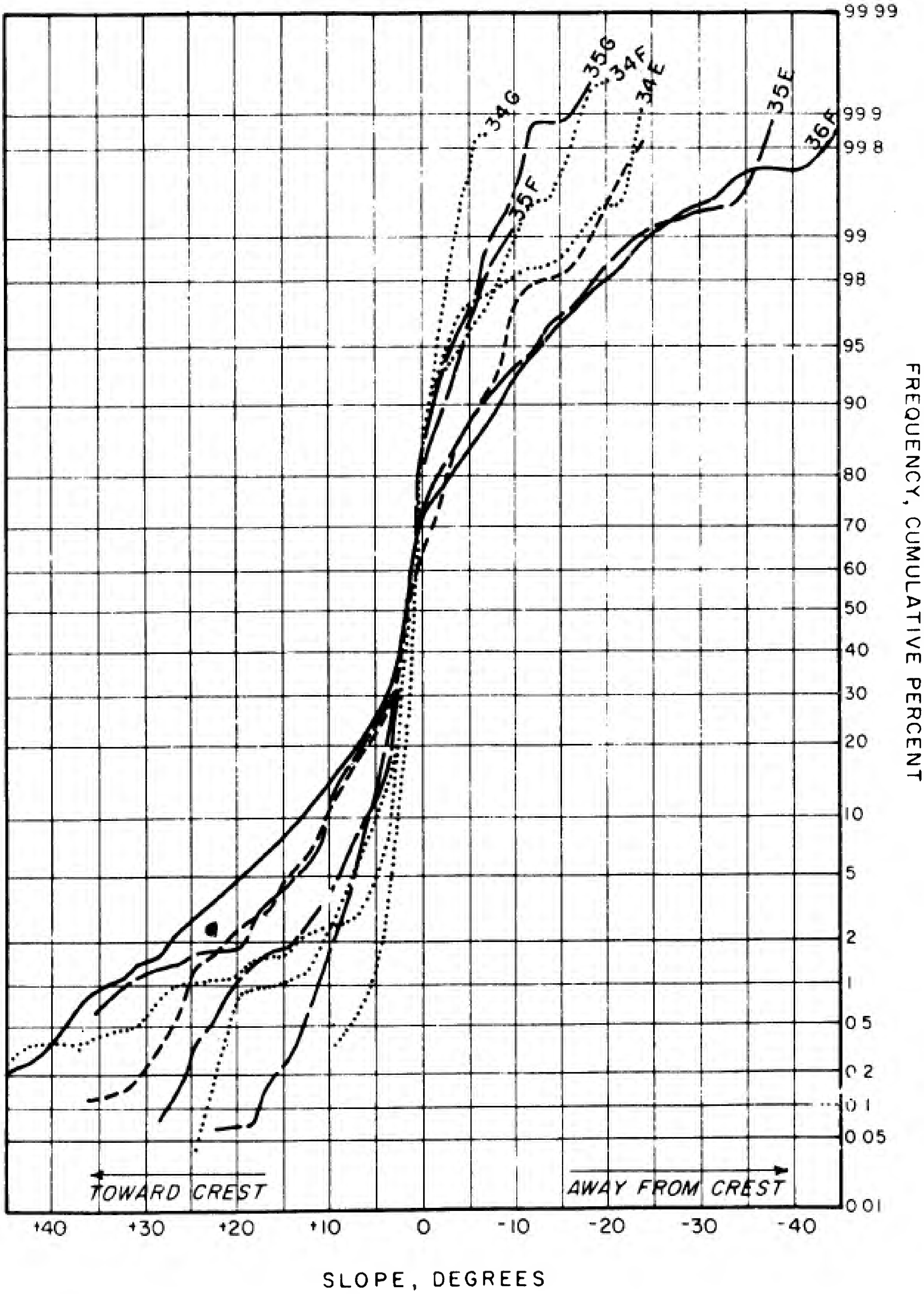

34G
35G
34F
34E
35E
36F
35F
99 99
99 9
99 8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0 5
0 2
0 1
0 05
0 01
FREQUENCY, CUMULATIVE PERCENT
TOWARD CREST
AWAY FROM CREST
+40
+30
+20
+10
0
-10
-20
-30
-40
SLOPE, DEGREES

Figure 19.- Mid-Oceanic Ridge and abyssal hills-- Cumulative frequency distribution of slopes for four track segments from the ridge crest.

Curve identification denotes corresponding curve in figures 34, 35, and 36. These curves illustrate absence of strong zero slope component.

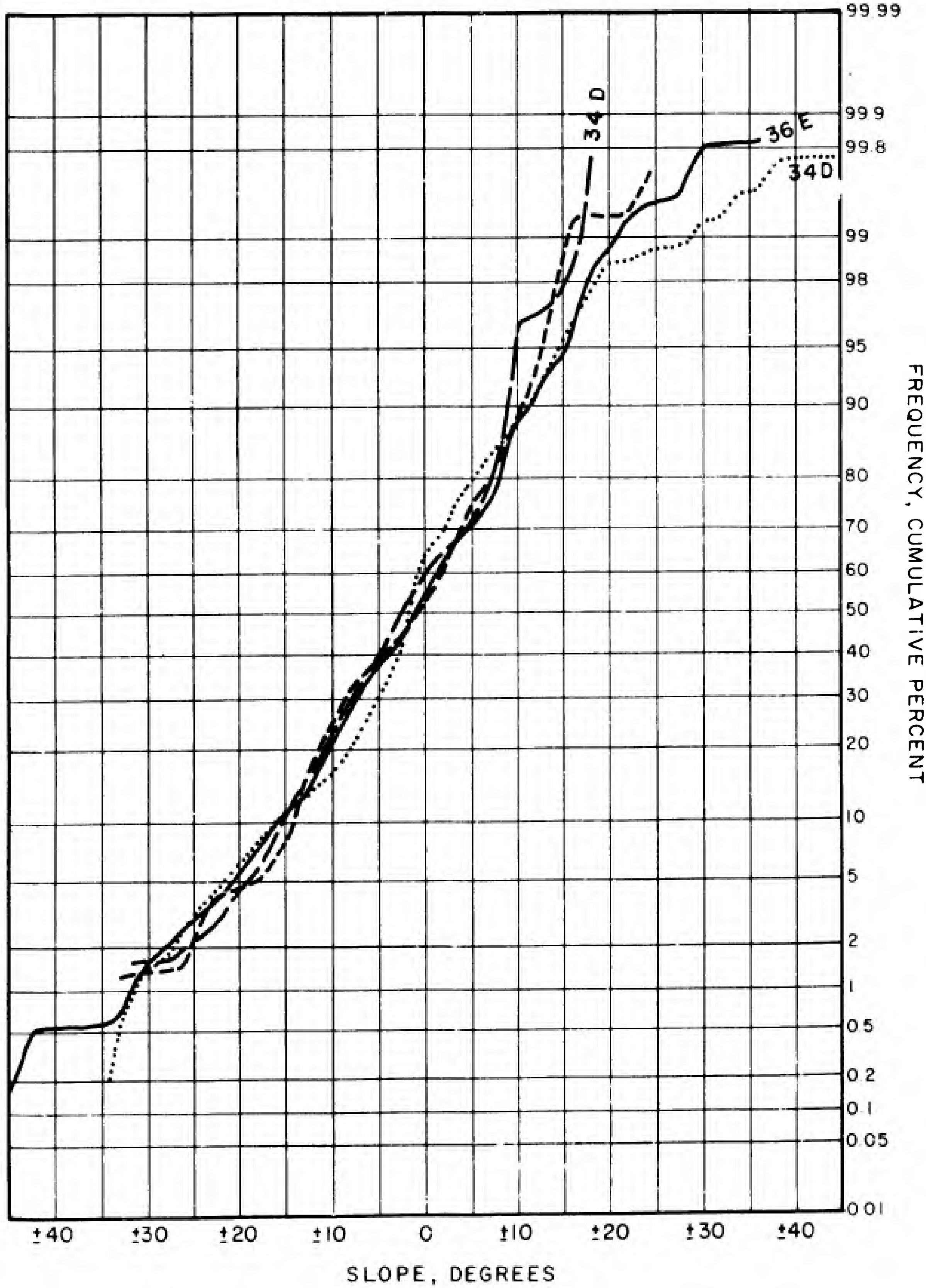

34 D
36 E
34 D
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
±40
±30
±20
±10
0
±10
±20
±30
±40
SLOPE, DEGREES

Figure 20. - Mid-Oceanic Ridge and abyssal hills--statistical frequency distribution of slopes, illustrating the changing character of the topography across the ridge at about latitude 40°n.

The track has been divided into seven segments, within which the topography is relatively uniform and different from adjacent segments. The basis for these divisions is seen in the graphic output of raw slope data in Plate I. Curve A summarizes data from the eastern flank of the Mid-Atlantic Ridge, shown in mileage interval 0-340 in Plate I. Curves B and C summarize data from the Azores Plateau, miles 340-500 and 500-620, respectively. Curve D represents the crest of the Mid-Atlantic Ridge, miles 620-680. Curves E and F represent sections of the western flank of the Mid-Atlantic Ridge, mileage 680-810 and 810-100 (Plate I, section 2), respectively. Curve G, mileage 100-275 (Plate I, section 2), summarizes the abyssal hills. The greater roughness of the ridge crest and the Azores plateau is evident. In all curves the zero slope component is prominent. The west flank is less rough generally than the east flank. On the west flank the zero slope component is higher on the upper flank than in the abyssal hills.

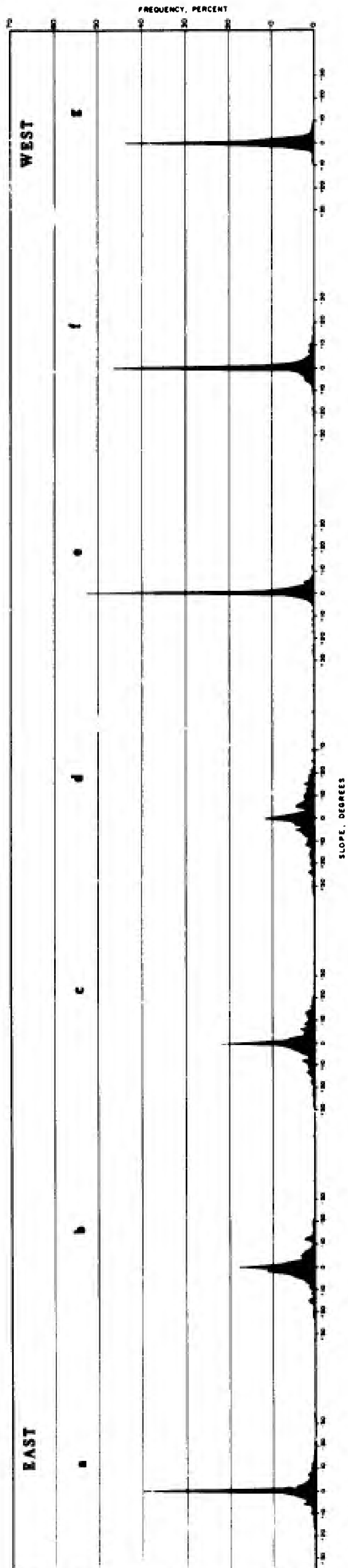

FREQUENCY, PERCENT
SLOPE, DEGREES
WEST
EAST

Figure 21. - Mid-Oceanic Ridge and abyssal hills--statistical frequency distribution of slopes, illustrating the changing character of the topography across the ridge for a diagonal crossing, latitudes 24° - 37°N.

This track crosses the Mid-Atlantic Ridge in a NW-SE direction. Curve A is from the high-relief topography on the outer eastern flanks of the ridge at latitude 24° - 28°N, mileage 200-500 on plate II. Curves B and C reflect the upper eastern flanks of the ridge, with an inclusive mileage of 500-895, plate II. Curve D illustrates the ridge crest, mileage 895-945, and curves E and F show the western flanks of the ridge at a higher latitude than the eastern flanks, mileages 945-110 (plate II, section 2) and 120-225 (plate II, section 2). Curve G is taken from the abyssal hills province, mileage 375-575 (plate II, section 2), at about latitude 35° - 37°N, adjacent to the Corner Rise. Again the ridge crest stands out due to lack of zero slope component. On the eastern flank the zero component increases toward the inner ridge flanks. On the western flank, at higher latitude, the percentage of zero slopes is higher on the outer flanks and in the abyssal hills. The overall spread of slope values is similar for all curves except curve F and curve G, which possesses a notably narrow range.

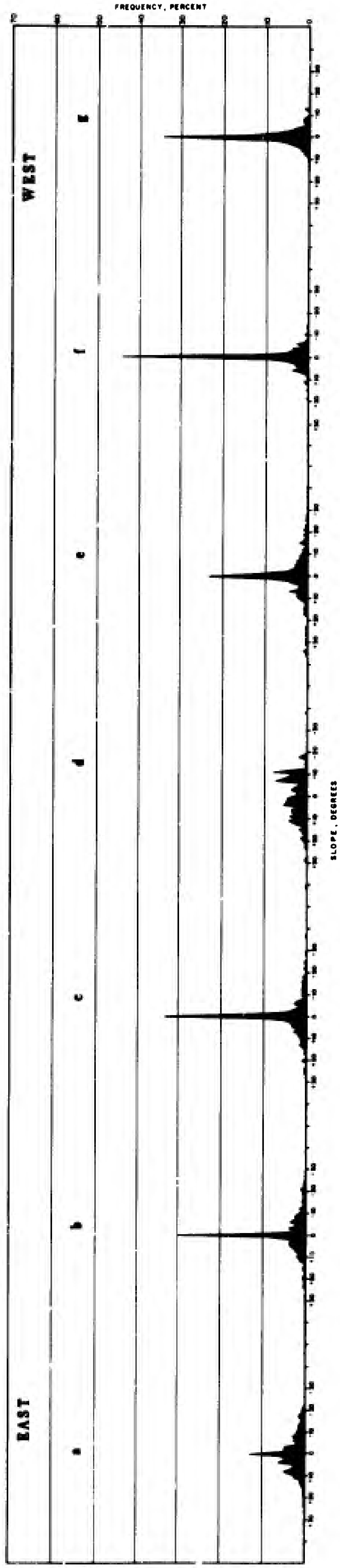
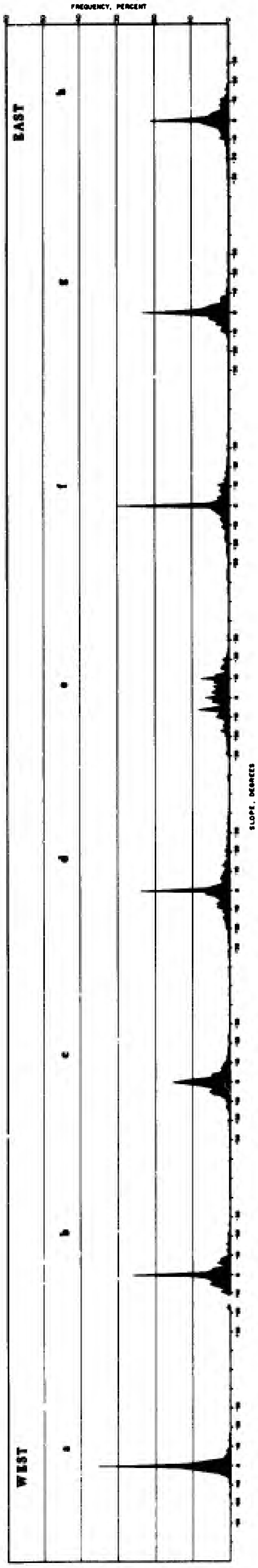

FREQUENCY, PERCENT
SLOPE, DEGREES
WEST
EAST
a
b
c
d
e
f
g

Figure 22. - Mid-Oceanic Ridge and abyssal hills--statistical frequency distribution of slopes, illustrating the changing character of the topography for the ridge crossing at latitude 10° - 18°N.

Cumulative mileage on plate VI is as follows: curve a, 0-210; curve b, 210-320; curve c, 320-650; curve d, 650-825; curve e, 825-895; curve f, 895-120 (plate VI-2); curve g, 120-340 (plate VI-2); and curve h, 340-650 (plate VI-2). Percentage of zero slopes decreases from curve a to curve c and then increases with ascent of the ridge flank, curve d. The flat-bottomed component is notable absent in curve e, representing the ridge crest, as it is in the previous figure. The flat-bottomed component decreases on the eastern flank as one proceeds away from the crest. However, curves g and h have a narrower overall range than curves d, e, and f. This illustrates the linear orientation of topography parallel to the strike of the ridge; curves g and h represent a section of track in which the orientation is sub-parallel to the ridge crest.


FREQUENCY, PERCENT
SLOPE, DEGREES
EAST
WEST
a
b
c
d
e
f
g
h

IV. SOME ASPECTS OF NORTH ATLANTIC GEOMORPHOLOGY

Smooth Provinces and Rough Provinces--A Twofold Classification

A twofold classification of topography can be applied in the North Atlantic Ocean, based on quantitative bottom roughness, and geomorphic processes.

Relief greater than 50 tau and mean bottom slopes steeper than 1:50 characterize the Mid-Atlantic Ridge, the abyssal hills, the Krylov Rise, and most of the Bermuda Rise, comprising about 60 percent of the North Atlantic Ocean floor between latitudes 10^{o} and 40^{o} north. Relief less than 50 tau and mean bottom slopes gentler than 1:50 characterize the continental margin provinces, the abyssal plains, and parts of the Bermuda Rise. By using the 50 (relief, chart 1) and 1:50 (slope, chart 2) boundary lines we have geographically separated provinces which are generally "smooth" from those which are generally "rough." The exceptions, namely, the continental slope and seamounts within the smooth provinces, and, flat-floored basins within the rough provinces, do not obscure this classification.

That processes of sedimentation and erosion have been predominant in sculpturing topography in the smooth provinces has been well documented. Wedges of sedimentary rock several kilometers thick underlie the continental shelf and continental rise off North America (see Drake, et al., 1959). The flatness of the abyssal plains through burial of rough topography by turbidity current deposition is well known (Heezen, et al., 1951). Erosion by turbidity currents has no doubt been active in the formation of submarine canyons (for discussion see Kuenen, 1950). Deposition of silts and lutites by contour currents has been a factor in shaping the continental rise and the perimeters of the Bermuda Rise (Heezen, et al., 1966a; Heezen, et al., 1966b).

Volcanism and tectonism have been the primary processes resulting in the present topographic form of the rough provinces. Volcanic outpourings have given rise to conical shaped seamounts and knolls, and have contributed to the formation of ridge and valley topography. Tectonism is evident in the regular succession of ridges and valleys of the Mid-Atlantic Ridge, in the seismic activity along the rift valley, and in the displacement of topographic (Heezen and Tharp, 1962; Heezen, et al., 1964) and magnetic (Vacquier, et al., 1961; Mason and Raff, 1961; Raff and Mason, 1961) patterns along fracture zones in the Atlantic and elsewhere. What sediments are present generally occur pocketed in valleys or draped over basement relief (Ewing, et al., 1964).

The boundaries between "smooth" and "rough" provinces are abrupt where the outer edges of the abyssal plains abut the abyssal hills. Along the western and northern edges of the Bermuda Rise, however, the area included in the quantitatively smooth category extends eastward from the abyssal plain boundary and grades into the rough category.

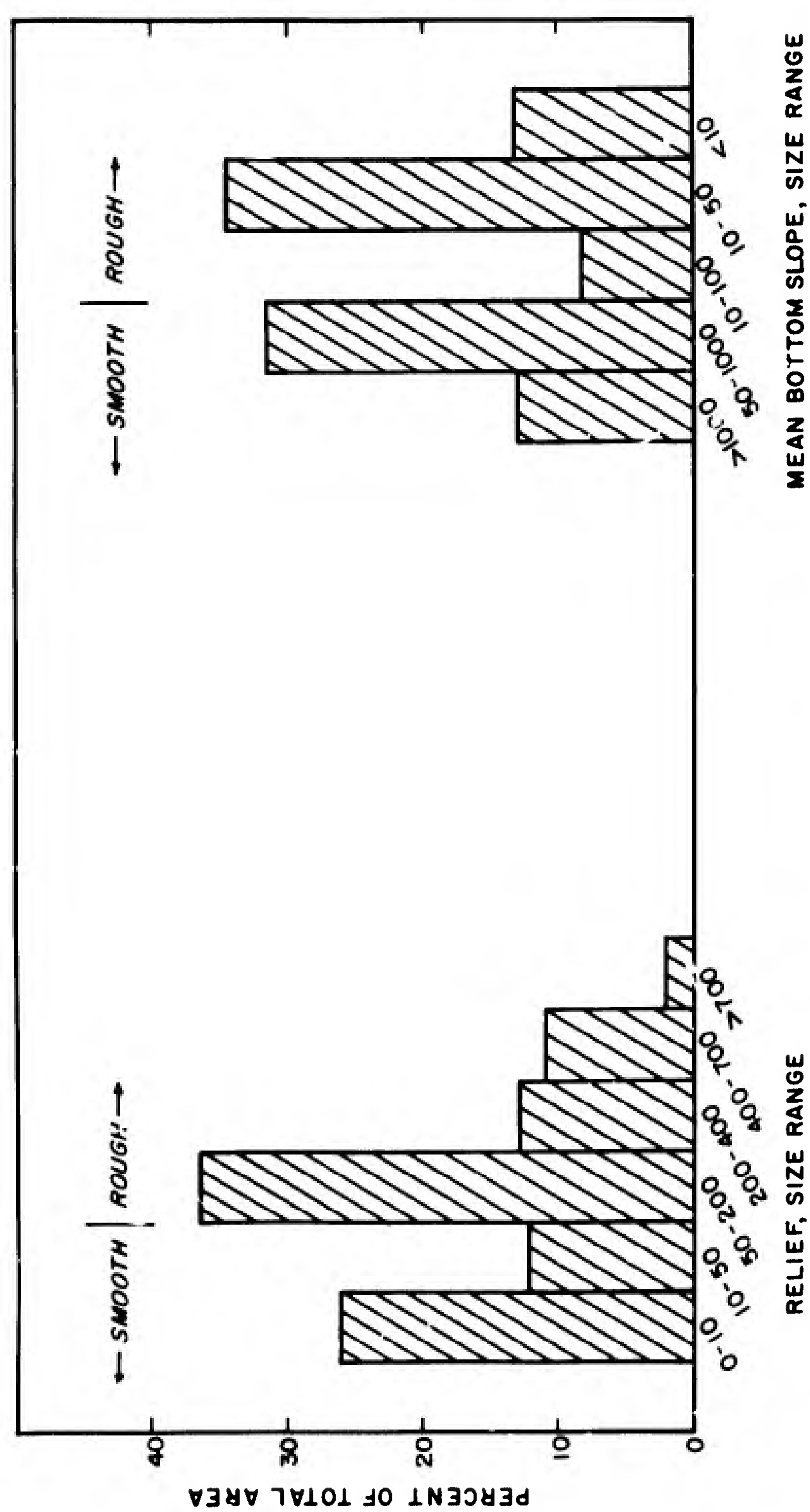
By calculating the relative areas of the different ranges of relief and slope shown in charts 1 and 2 and constructing frequency curves we obtain a statistical look at the areal extent of relief and slope sizes (figure 23). A bimodal distribution is evident in both these curves.

Continental Rise Topography and Contour Currents

We have noted (figure 12) that off New York a striking uniformity in the frequency distribution of fundamental wavelengths exists. Direct examination of topographic profiles and PDR records reveals intervals of fine-textured hyperbolae having a remarkably regular spacing suggesting linear topographic features oriented at high angles to the ship's tracks. Much of the smoother continental rise in this region is characterized by what appears as "mush" on PDR records, suggesting topographic irregularities too small to be resolved at PDR scale.

The areal extent of hyperbolae and "mushy" bottom between Nova Scotia and the Carolinas has been charted (Schneider, et al., 1967). It was found that the occurrence of hyperbolae and prolonged echo ("mush") coincides with the course of the Western Boundary Undercurrent, confirming a correspondence observed earlier on the Blake-Bahama

Figure 23. - Relative extent of the various size ranges of regional relief (chart 1) and mean bottom slope (chart 2) in the North Atlantic.



PERCENT OF TOTAL AREA
0
10
20
30
40
← SMOOTH
ROUGH →
RELIEF, SIZE RANGE
MEAN BOTTOM SLOPE, SIZE RANGE

Outer Ridge (Heezen, et al., 1966). Schneider, et al., (1967) illustrated with core analyses that sediments deposited near the axes of the current contain higher percentages of silt than they do farther from the axes, where currents are less active.

Upon examining the topographic profiles illustrated in both reports (Heezen, et al., 1966a; Schneider, et al., 1967), we see that the Western Boundary Undercurrent occupies a broad asymmetric "channel" having a cross section similar to that observed across a bend in a meandering stream. The outer slope of this so-called channel would constitute the step-down from the upper to the lower continental rise off New York, the entire "channel" being banked westward as a result of the Coriolis effect. This "step" on the continental rise is observed in other continental rise profiles off the eastern coast of the United States.

Many of the topographic features of the continental margin, where sedimentation and erosion are active in shaping the topography, resemble those formed by similar processes in the subaerial environment. Turbidity current sedimentation on abyssal plains resembles the accumulation of ponded sediments in lakes. The natural levees which border the Hudson Submarine Canyon and some mid-ocean canyons are similar to the natural levees of subaerial streams. If the ocean bottom underlying the Western Boundary Undercurrent resembles a broad, shallow stream channel, with the channel being shaped by current-induced sedimentation and erosion, then topographic irregularities occurring within this channel could be analogous to river bars.

Channel bars are common in aggrading subaerial streams. Longitudinal current-formed bars are associated with tidal currents on Georges Bank (Stewart, et al., 1959). Longitudinal dunes parallel the prevailing wind-current direction in many desert regions of the world (Thornbury, 1954).

Channel bars build up in braided subaerial streams where conditions of velocity, as controlled by factors such as gradient, volume of flow, and shape of the channel, do not permit the stream to transport all its load (see Thornbury, 1954; Mackin, 1948). Leopold, et al., (1964) have observed bars and braided channels developing in laboratory flumes and they note that surfaceward growth of bars is accompanied by a concentration of flow, with increased velocity and transporting power, in the flanking channels.

The near-bottom current velocities (2-20 cm/sec; Schneider, et al., 1967) observed in the channel of the Western Boundary Undercurrent, when compared with the graph resulting from Hjulstrom's experiments (1935), appear to be too slow to pick up silt and clay size particles once they are deposited, but of sufficient velocity to transport these particles once they are suspended in the water column. Heezen and Hollister (1964) have compiled a composite graph from several studies in which a relationship was drawn between particle size and the transportation-sedimentation and erosion-transportation thresholds, and they point out that uncertainties exist, particularly in the marine environment, for particle sizes below 0.2 mm; but even with the uncertainties their graph shows that at the velocities under consideration a substantial percentage of the sediment load lies within the environmental conditions of transportation. In such a current environment, turbulence and obstructions on the bottom would result in local pockets of deposition and local concentrated flow resulting in erosion of particles, but the overall budget would favor net sedimentation, that is, an aggrading condition which in a subaerial stream may result in a braided channel. Bars might have been initiated by accumulation of particles on the lee side of some obstruction; for example, a shell of some expired marine organism. One would expect evidence of stronger currents within the topographic depressions of the channel, if the hyperbolae and "mush" bottom can indeed be interpreted as longitudinal current-formed features.

The highest rate of deposition would obviously occur on the banks of the channel, where velocities are high enough to carry lutites but low enough so that lutites are being deposited at rates higher than within the channel proper. The rate of deposition would be lower outside the channel margins where velocities are less than sufficient to transport lutites (as noted by Heezen, et al., 1966a); and in the axis of the channel, where in the stronger currents silts are being deposited and much of the lutite load is being transported.

Mid-Atlantic Ridge Topography and Sedimentation, Tectonics, and Volcanism

The Mid-Atlantic Ridge crest, including the rift valley, the rift mountains, and the high fractured plateaus, constitutes a 40-70 mile wide belt in which the zero slope component is notably small compared to the ridge as a whole (plates I, II, IV, and VI; figures 20, 21, and 22; table 1). Only in the northernmost crossing, where productivity and the resulting sedimentation rates are known to be high, does the frequency percentage of slopes less than 0.5 degrees exceed 10 (figure 21). Ridge crest topography consists of rugged ridge and valley terrain characterized by scarps, pointed crests, and v-shaped valleys in a wide range of relief and texture sizes. Though relief varies widely, hillside slopes are uniform; standard deviation for four crossings between latitudes 15° and 40°N vary between 9.975 and 11.166, increasing from north to south (table 1). The slope frequency curves (figure 20; figure 21; figure 22) are trimodal, modes occurring at 5-12 degrees, zero degrees, and -5 to -12 degrees. Sediments, where present at all, constitute a thin and patchy veneer having little effect on the bottom geometry resolvable with PDR records.

Table 1 -- Slope statistics for selected sections of North Atlantic topography

Column 1 contains the cruise identification for each track. Column 2, where applicable, identifies the sample with a plot of its frequency distribution in figures 34, 35, and 36. Column 3 contains a qualitative identification of topographic character. Column 4 indicates the total length of the track segment included in the sample. Column 5 gives the total number of individual slope measurements in each sample. Column 6 lists the mean, Column 7 the median, Column 8 the standard deviation, Column 9 the skewness, and Column 10 the kurtosis. Calculations were made according to the formulas listed in Table 6.

SLOPE STATISTICS

Table 1

Cruise	Group	Description	No. Miles	No. Slopes	Mean	Median	Standard Dev.	Skewness	Kurtosis
V-14	34a	East Flank of Mid-Atlantic Ridge	352.7	2640	+0.089	0.0	5.469	-0.236	8.637
	34b	East Azores Plateau	150.1	1068	+0.355	-0.397	7.494	-0.040	5.553
Halifax East	34c	West Azores Plateau	124.6	816	+0.241	+0.381	7.589	0.215	2.638
	34d	Crest of Mid-Atlantic Ridge	56.0	420	-0.043	0.0	10.649	-0.016	1.727
	34e	West Flank of Mid-Atlantic Ridge (Part 1)	127.1	1068	-0.324	0.0	5.188	2.772	31.294
	34f	" (Part 2)	240.5	1980	-0.205	0.0	3.791	-0.342	9.344
	34g	Abyssal Hills	168.4	1272	-0.098	0.0	1.588	0.221	5.737
		Sohm Abyssal Plain	131.2	996	+0.023	0.0	0.798	-9.457	216.616
		Continental Rise	288.1	1740	+0.368	+0.415	0.781	-3.412	53.310
		Continental Slope	38.4	213	+1.478	+2.323	7.702	-0.202	-0.795
		Continental Shelf	195.7	1536	+0.001	0.0	1.253	0.811	25.165

SLOPE STATISTICS (2)

Cruise	Group	Description	No. Miles	No. Slopes	Mean	Median	Standard Dev.	Skewness	Kurtosis
V-17	35a	Deep Rough	284.1	1800	+0.101	+0.359	8.076	-0.249	1.406
	35b	East Flank of Mid-Atlantic Ridge (Part 1)	200.3	1128	+0.138	0.0	7.593	-0.222	6.126
	35c	" (Part 2)	193.2	1176	+0.169	0.0	7.452	-1.001	9.263
	35d	Crest of Mid-Atlantic Ridge	50.1	372	+0.592	+0.491	9.975	0.395	0.829
	35e	West Flank of Mid-Atlantic Ridge	151.1	936	-0.145	0.0	8.324	-0.177	5.340
	35f	West Flank of Mid-Atlantic Ridge	106.3	1344	+0.061	0.0	4.492	0.125	14.533
	35g	Abyssal Hills	238.2	1608	-0.052	0.0	3.322	-0.134	12.602
Halifax SE		Abyssal Plain	403.7	2484	+0.022	0.0	0.407	-8.970	219.355
		Continental Rise	148.4	888	+0.266	0.0	0.694	1.456	17.467
		Continental Slope	47.5	336	+1.357	+1.800	5.457	0.082	22.154
V-18		NW Bermuda Rise	122.3	780	-0.158	0.0	1.879	-1.136	12.508
Bermuda NW		Abyssal Plain	82.9	480	-0.023	0.0	0.311	-0.033	3.645

SLOPE STATISTICS (3)

Cruise	Group	Description	No. Miles	No. Slopes	Mean	Median	Standard Dev.	Skewness	Kurtosis
V-18 Bermuda NW (cont'd)		Hills on the Lower Continental Rise	108.7	744	+0.162	0.0	1.283	-0.026	7.422
		Continental Rise	228.1	2124	+0.313	0.0	1.211	-0.286	46.448
WYANDOT		Continental Rise Hills	81.1	348	-0.018	0.0	1.103	-0.175	3.135
		NW Bermuda Rise	146.0	476	+0.011	0.0	0.562	1.158	6.717
Norfolk E		North Central Bermuda Rise	219.3	900	-0.060	0.0	2.040	+0.115	3.403
		NE Bermuda Rise	132.9	464	+0.122	0.0	1.391	2.288	24.150
V-14		East Bermuda Rise	125.9	804	-0.195	0.0	4.116	0.616	16.498
		Abyssal Hills	828.6	4488	+0.101	0.0	6.255	-0.763	11.944
Bermuda SE		Crest of Mid-Atlantic Ridge	39.8	288	+0.083	-0.630	10.278	0.381	0.068
		East Flank of Mid-Atlantic Ridge	120.1	960	-0.298	-0.396	7.097	0.510	2.859
V-9		Abyssal Hills	384.0	2616	+0.239	0.0	4.556	1.001	11.901
Bermuda SE		SE Bermuda Rise	345.7	2196	+1.663	+0.366	10.633	5.583	37.207

SLOPE STATISTICS (4)

Cruise	Group	Description	No. Miles	No. Slopes	Mean	Median	Standard Dev.	Skewness	Kurtosis
V-16	36a	West Flank of Mid-Atlantic Ridge (Part 1)	204.8	1344	+0.015	0.0	3.199	-1.926	29.710
	36b	West Flank of Mid-Atlantic Ridge (Part 2)	111.3	888	+0.125	+0.424	5.755	-0.035	6.805
San Juan East	36c	" (Part 3)	332.9	3156	+0.108	0.0	6.626	0.513	24.760
	36d	" (Part 4)	166.8	1188	+0.344	0.0	9.925	-0.278	2.919
	36e	Crest of Mid-Atlantic Ridge	73.1	552	-0.338	-0.432	11.166	0.265	1.311
	36f	East Flank of Mid-Atlantic Ridge (Part 1)	224.9	1668	-0.033	0.0	9.706	0.037	5.208
	36g	" (Part 2)	218.9	1844	+0.012	0.0	7.558	0.190	6.476
	36h	" (Part 3)	302.5	2016	+0.363	0.0	6.621	1.124	13.970

A scarp zone (in some profiles) or zone of strong regional slope (in other profiles) separates the crest provinces from the flank provinces. Minor accumulations of sediment occupy otherwise v-shaped valleys in the less precipitous parts of this zone, where it is characterized by a succession of ridges. Flat-floored troughs containing appreciable thicknesses of sediments lie at the base of this zone on both sides of the crest. When these scarp zones are included with the crest provinces, a belt is defined, typically 100-150 miles wide, which is relatively free of sediments (see Ewing and Ewing, 1967). On all profiles except the southernmost one the sediment-filled trough at the base of the west-facing scarp zone is about 20 miles wide and lies 80-120 miles west of the median rift. If this feature is semi-continuous it represents a major topographic feature paralleling the ridge crest.

On the flanks of the Mid-Atlantic Ridge between the scarps bounding the crest and the 2500 tau isobath the basement relief has undergone considerable burial by sedimentation (plates I, II, IV, and VI). Ridges similar in every other aspect to those of the crest provinces are separated by bowl-shaped basins. Sediments have tended to accumulate in these basins rather than on the mountainsides. On the western flank in the north, where productivity is highest, only the most prominent peaks remain exposed. Farther south, relief is more rugged and a smaller percentage of the total bottom area is occupied by the sedimentary basins.

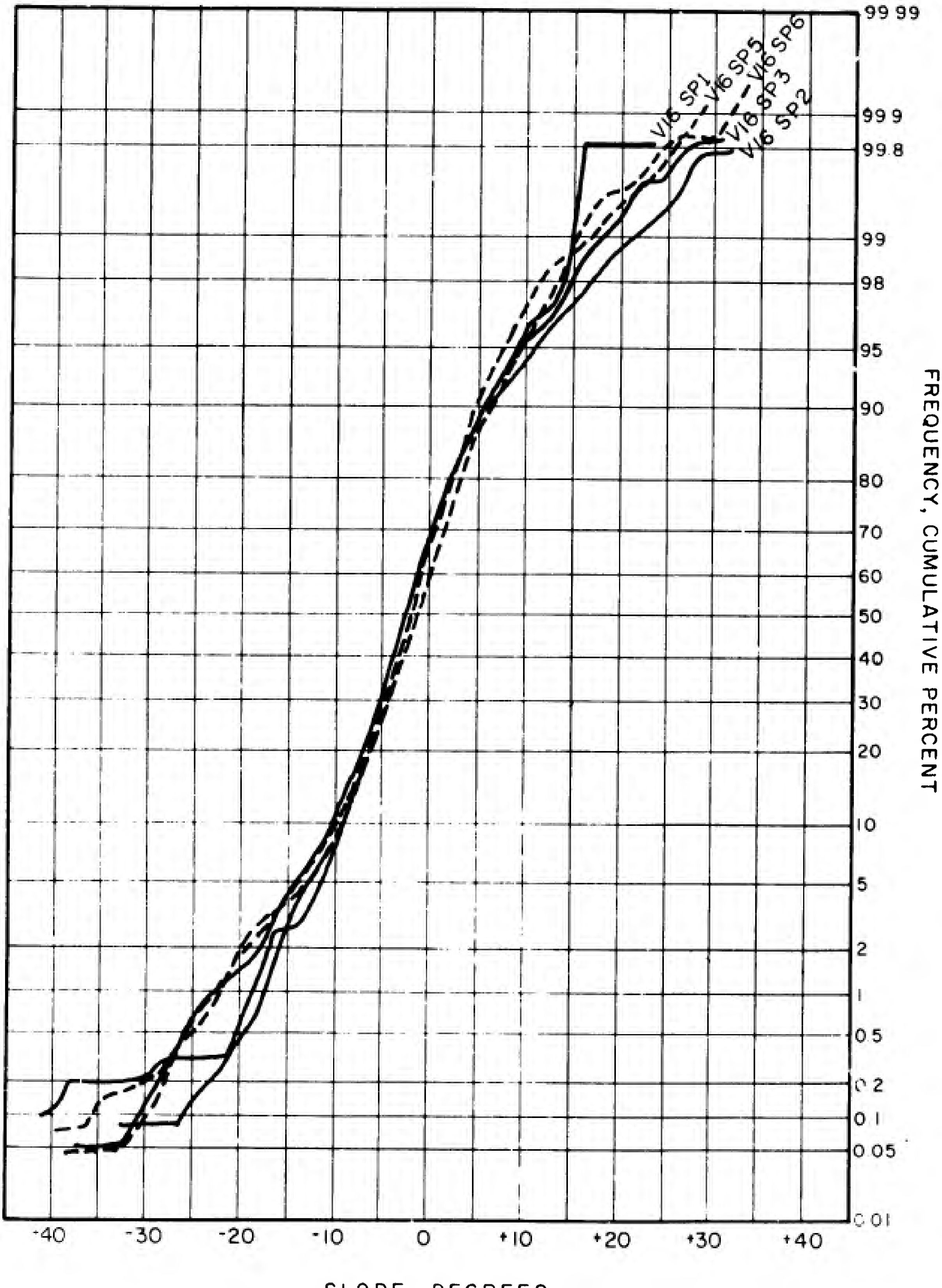
Slope frequency curves reflect hillside slopes of similar magnitude to those of the ridge crest, but they illustrate the strong zero slope component (figure 20, curves a and e; figure 21, curves b, c, and e; figure 22, curves d and f). Standard deviation figures are lower and vary more widely than those obtained from the ridge crest, ranging from 5 to 10 (table 1).

Total amount of sedimentation in the belts of high relief lying on both outer flanks of the ridge between latitudes 20°N and 30°N has been less than that accumulated on the upper ridge flanks. Flat-floored basins are generally small and of minor extent, and in some areas they are absent altogether. The zero slope component is smaller here than in all other areas of the ridge flanks (figure 21, curve a), resulting in high overall roughness indices (table 1). Hillside slopes are similar in magnitude to those occurring elsewhere on the ridge (figure 21). It is interesting to note that here the "tails" of the slope frequency distribution curves are not as prominent as they are on samples from the upper ridge flanks.

Elsewhere on the lower flanks of the Mid-Atlantic Ridge and in the abyssal hills, the degree of roughness is notably lower than that observed on the upper ridge flanks (figure 20, curves f and g; figure 21, curves f and g; figure 22, curves a, b, and c; table 1). The zero slope component is however less pronounced, the topography being gently

Figure 24. - Cumulative frequency distribution of slopes for five track segments from the flanks of the East Pacific Ridge in a crossing at about latitude 60°S.

Curves for samples from data recorded when the ship was steaming toward the ridge crest are represented by solid lines. Curves for samples from data recorded when the ship was steaming away from the ridge crest are represented by dashed lines.


V16 SP1
V16 SP5
V16 SP6
V16 SP3
V16 SP2
99 99
99 9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
FREQUENCY, CUMULATIVE PERCENT
-40
-30
-20
-10
0
+10
+20
+30
+40
SLOPE, DEGREES

undulating with sediments draped over summit, hillside, and valley (see Ewing, et al., 1964). As in other ridge categories, the total amount of sedimentation is greater at higher latitudes than at lower latitudes.

On the Pacific-Antarctic Ridge,some 1000 miles wide at latitude 50^{o}-60^{o}S, relief is moderate (50-200) over the crest and the upper flanks. On both lower flanks relief increases abruptly to the 200-400 range. On the extreme outer flanks, some relief in the 400-700 range occurs. The overall statistical parameters of slopes (table 5) compare favorably with those of the Mid-Atlantic Ridge. Standard deviation of the ridge crest sample is 14.214^{o}, higher than any obtained from the Mid-Atlantic Ridge samples. The slope frequency distribution of the crest sample is trimodal, as in the Atlantic samples.

We have noted the trimodal distribution of slopes observed in all ridge crest samples. Most of the North Atlantic ridge flank samples show modes in the 5 to 12 degree range, but have a much stronger mode in the zero range. In most North Atlantic ridge samples except those from the outer flanks, both in the high relief of latitude 20^{o}-30^{o}N and where burial by sedimentation is in a particularly advanced stage, a strong component of extreme slope values (12-30 degrees and even higher) results in "tails" on the distribution curves. South Pacific ridge samples show a smaller zero component, a strong component in the 5-12 degree range, and insignificant distribution "tails"--slopes above 12-15 degrees.

Some asymmetry is observed on the ridge flanks if slopes facing the ridge crest are compared with those facing outward (table 2; table 3). The mean slope values for ridge flank samples average 0.150 degrees facing away from the ridge crest. This is due to the higher statistical frequency in the 0-5 degree range of slopes facing down the regional slope. The regional slope is thus the dominant factor in determining the sign of the mean. Skewness, however, for the same track segments, shows a preferance for slopes facing the ridge crest (table 2; table 3). This does not in itself constitute evidence that steeper hillside slopes face the crest, since skewness is relative to the mean rather than to zero. However, frequency curves from areas not appreciably subjected to sedimentary accumulation show a stronger component of slopes facing the crest when only oriented slopes greater than 15 degrees are compared (table 4). Some asymmetry is measurable in individual samples for the 5-12 degree range of slopes, but no consistent pattern of orientation is apparent. A rather striking symmetry is observed in the South Pacific for the 0-12 degree range (figure 24).

Agapova (1965) conducted some statistical analyses of slopes measured from the bathymetry of an E-W Mid-Atlantic Ridge crossing at about latitude 38°N. This crossing is sufficiently close to the

Table 2.- Weighted slope statistics for sections of Mid-Atlantic Ridge topography.

Samples from each of the cruises indicated have been grouped according to whether the ship was steaming toward the ridge crest or away from the ridge crest, and arithmetic means weighted both by miles and by number of slopes have been obtained from the mean, skewness, and standard deviation of each sample. Weighted means are also shown for all data in each "toward" or "away" category for the three crossings combined, as well as for a combination of all data for each crossing and for all three crossings combined. All slopes are in degrees.

	How Weighted	Cruise	V-14 Halifax SE	V-16 San Juan SE	V-17 Halifax SE	Overall
Mean of Means	Miles	Toward	0.089	0.344	0.132	0.150
		Away	-0.246	-0.033	-0.060	-0.135
		Total	-0.084	+0.128	0.080	0.030
	Slopes	Toward	0.089	0.344	0.129	0.150
		Away	-0.246	-0.033	-0.234	-0.125
		Total	-0.090	0.124	0.075	0.020
Mean of Skewness	Miles	Toward	-[illegible]239	-0.278	-0.456	-0.365
		Away	0.736	0.037	-0.052	0.310
		Total	0.258	-0.098	-0.345	-0.080
	Slopes	Toward	-0.239	-0.278	-0.456	-0.355
		Away	0.750	0.037	+0.002	0.335
		Total	0.291	-0.094	-0.295	-0.030
Mean Of Standard Deviation	Miles	Toward	5.469	9.925	7.755	7.385
		Away	4.490	9.706	6.742	6.460
		Crest	10.649	11.166	9.975	10.671
		Total	5.344	9.924	7.602	7.293
	Slopes	Toward	5.469	9.925	7.764	7.290
		Away	4.280	9.706	6.066	6.155
		Crest	10.649	11.166	9.975	10.677
		Total	5.232	10.02	7.314	7.085

Table 3. - Weighted mean and skewness statistics for sections of the flanks of the Mid-Atlantic Ridge.

Samples from the upper flanks of the Mid-Atlantic Ridge, and from the outer flanks where sedimentation has not significantly subdued basement topography, have been grouped on the basis of whether the ship was steaming toward or away from the crest of the ridge. Calculation of weighted composite means has proceeded in identical fashion to that shown in table 2. Column 1 identifies each track segment and indicates, where applicable, the corresponding statistical frequency curve shown in figures 34, 35, and 36. Columns 4 and 5 show the composite means for the groups, weighted by the number of miles in each sample and by the number of slope measurements in each sample, respectively. Column 6 shows the composite means for both groups. All slopes are in degrees.

Toward Crest

	Mean	Skew	Weighted by Miles	Weighted by Slopes	Overall Mean (Abs. Value)
V14 Bermuda SE	0.101	-0.763			
V14 34a	0.089	-0.236	Mean=0.129	Mean=0.131	
V16 36d	0.344	-0.278	Skew=(-)0.528	Skew=(-)0.503	
V17 35a	0.101	-0.249			Mean Weighted by Miles=0.139
V17 35b	0.138	-0.222			Mean Weighted by Slopes = 0.144
V17 35c	0.169	1.001			
Away From Crest					
V14 Bermuda SE	-0.298	0.510			
V14 34e	-0.324	2.772	Mean=(-)0.171	Mean=(-)0.178	Skew Weighted by Miles = 0.497
V16 36f	-0.033	0.037	Skew=0.634	Skew=0.722	Skew Weighted by Slopes = 0.563
V17 35e	-0.145	-0.177			

Table 4. - Comparison of slopes greater than 15 degrees facing the ridge crest with those facing away from the ridge crest, for sections of the Mid-Atlantic Ridge in which there has been little sediment Accumulation.

Columns 1 and 2 contain cumulative frequence percentage of slopes having values greater than 15 degrees facing toward the ridge crest, and away from the ridge crest, respectively. Column 3 contains the difference obtained when column 2 is subtracted from column 1.

Toward Crest	Away from Crest	Difference
2.028	0.982	1.046
6.481	6.650	-0.169
6.235	4.916	1.319
4.398	2.111	2.287
1.181	0.646	0.535
2.917	1.771	1.146

Unweighted Mean Difference
1.027 percent higher
toward crest.

Cruise	Description	No. Miles	No. Slopes	Mean	Median	Standard Deviation	Skewness	Kurtosis
V 16	West Flank	137.0	1004	-0.036	+0.386	6.419	+0.138	3.655
	West Flank	330.4	2004	+0.117	+0.406	7.629	-0.468	2.808
East Pacific Ridge	West Flank	187.6	1260	+0.155	+0.753	6.704	-0.599	2.492
	Crest	33.1	360	-0.070	+0.866	14.214	+0.077	0.359
	East Flank	324.1	2616	-0.188	-0.635	7.317	+0.398	4.075
	East Flank	292.6	2340	+0.069	-0.460	6.591	+0.130	4.013

Table 5. - Slope statistics for a crossing of the East Pacific Ridge at about latitude 60°S.

The format and content is identical to that of table 1. All units are degrees.

Table 6. - Comparison of the methods of slope statistical analysis employed in this report with those of Agapova (1965).

In selecting the boundaries for each sample, Agapova grouped the Azores Plateau and the Ridge crest within one sample (Agapova, sample I), defining the western boundary at the base of the zone of steep regional slope separating the crest provinces from the flank provinces. In this report separate groups were defined for the Azores Plateau (samples b and c, figure 34); the western boundary of the Ridge crest belt is placed 30-40 nautical miles east of Agapova's boundary (Agapova, sample II), at the first occurrence of sediment-filled valleys west of the ridge crest. The western boundary of Agapova's "high plateau" corresponds to the western boundary of sample 34e (figure 34) in this report. Sample 34f of this report includes Agapova's sample III and sample IV on the western ridge flanks (the similarities in the statistical frequency curves and the calculated statistical parameters of Agapova's samples III and IV are striking). Agapova's sample V very nearly corresponds to the abyssal hills (sample g) sample of this report.

The difference in sign observed when comparing the mean values obtained for the Azores Plateau is understandable in that the samples of this report reflect a track run closer to the

Azores, with stronger relief and a stronger component of regional slope facing eastward. The lower mean value for sample 34e, this report, than for sample II, Agapova's report, reflects a stronger component of east-facing regional slope in this report, as a result of the 30-40 nautical mile difference in the position of the eastern boundary.

The higher standard deviations obtained in this report for the Azores Plateau and the crest of the Mid-Atlantic Ridge reflect the generally steeper slopes and higher relief associated with proximity to the Azores. The higher standard deviation of sample 34e, this report, is the result of inclusion of a section of rougher topography adjacent to the Ridge crest which is not included in Agapova's sample. A component of stronger relief in Agapova's abyssal hills sample accounts for the observed difference in standard deviation.

Skewness and kurtosis values calculated from the slope measurements expressed in degrees cannot be effectively compared with those calculated from measurements expressed in tangents, in view of the non-linearity of the tangent function and the high sensitivity of skewness and kurtosis to the numerical range of magnitude contained in the samples.

Essentials of method	This report	Agapova's Report
Spacing between individual soundings	0.15 - 0.20 n.m.	0.20 n.m.
Units of slope employed in calculations	degrees	tangents
Units of slope employed in presentation	degrees	degrees
Measures of central value employed	mean, mean of absolute values, median	mean, mean of absolute values
Measures of dispersion employed	standard deviation, skewness, kurtosis	standard deviation, skewness, kurtosis
Method of selecting sample boundaries	topographic similarity based on inspection of raw slope graphic output (plates I-VI)	topographic similarity with adherence to province boundaries established by Heezen, et al., (1959)
Slope ranges employed in determining frequence distribution	One degree, boundary at each half-degree	One degree, boundary at each half-degree
Formula employed in calculating the mean: θ slope in degrees	$\bar{\theta} = \frac{\Sigma \theta}{n}$	$\overline{\tan \theta} = \frac{\Sigma (\tan \theta \cdot m)}{n}$
m=number of slopes in each frequency pigeonhole n=total number of slopes in sample		
Formula employed in calculating standard deviation	$SD=\sqrt{\frac{\Sigma (\theta - \bar{\theta})^2}{n - 1}}$	$SD=\sqrt{\frac{\Sigma [(\tan\theta - \tan\theta)^2 \cdot m]}{n}}$
Formula employed in calculating skewness	$SK=\frac{(\theta - \bar{\theta})^3}{n\ (SD)^3}$	$SK=\frac{\Sigma [(\tan\theta-\tan\bar{\theta})^3 \cdot m]}{n \cdot (SD)^3}$
Formula employed in calculating kurtosis	$KU\ \frac{(\theta - \bar{\theta})^4}{n \cdot (SD)^4}$	$KU=\frac{\Sigma [(\tan\theta-\overline{\tan\theta})^4 \cdot m]}{n \cdot (SD)^4}$

Mean values obtained

sample	34b	0.355	
	34c	0.241	-0.750 (34b–34d)
	34d	-0.043	
	34e	-0.324	-0.570
	34f	-0.205	-0.300
			-0.300
	34g	-0.098	-0.100

Standard deviation values obtained

sample	34b	7.494	
	34c	7.589	6.283 (34b–34d)
	34d	10.649	
	34e	5.188	2.970
	34f	3.791	3.417
			2.667
	34g	1.588	2.866

northernmost crossing employed in this report that the same topographic features are easily identifiable on both profiles. The results of Agapova's work provide an interesting comparison to the slope statistical analyses of this report, because the methods employed are almost identical though arrived at independently (table 6).

The consistent magnitude and apparent symmetry of hillside slopes in the 5-12 degree range, and the remarkable qualitative resemblance of successive primary ridges and valleys--throughout the Mid-Atlantic Ridge and abyssal hills-suggests that a single process, fairly uniform and active through long periods of geologic time has been the predominant agent accounting for the observed character of the primary ridges and valleys of the basement, whatever its relief. This process is interpreted to have been volcanism associated with the central rift valley, the hillside slopes reflecting the angle of repose of lava effused into the ocean bottom through linear zones of weakness in the crust underlying the rift zone.

Krause and Menard (1965) have noted that several prominent abyssal hills in the Pacific between Hawaii and California, possess hillside slopes averaging 9-16 degrees, and they observed that this range of magnitude is probably characteristic of basaltic volcanoes, although they cite occurrences of submarine volcanic slopes up to 25 degrees. Loncarevic, et al. (1966a) found that slopes in the lower rift valley at latitude 45-46°N in the Atlantic averaged 10 degrees, and Loncarevic, et al., (1966b) suggested that the rift valley itself is a volcanic rather than a tectonic feature. Citing Iceland as an example, Menard (1967) has stated that "topography in an active rift system is produced both by volcanism along rifts and by normal faulting."

Theories involving extension of the Mid-Oceanic Ridge (Heezen, 1959, 1960, 1962; Hess, 1962; Dietz, 1962; Vine and Matthews, 1963, Ewing, et al., 1966) require an explanation of ridge topography in terms of relative migration of the oceanic crust in both directions away from the rift valley, with the accompanying extensional tectonic features. Addition of new crust via intrusion would be taking place primarily through the mid-oceanic rift, and possibly secondarily through fractures on either side of the rift. The surface expression of the volcanism associated with such intrusion is consistent with the evidence observed in bottom roughness indices of Mid-Atlantic Ridge topography.

The Mid-Atlantic Ridge basement topography possesses strong relief throughout the chart area. Flat-lying basement or features suggesting tectonic breakup of a flat-lying basement have not been observed between latitudes 10° and 46°N. However, basalt flows resulting in relatively flat-lying plateaus have occurred over large areas in the subaerial environment (for example the basalt plateaus in eastern Washington state and in southern Idaho). Iceland, astride the crest of the Mid-Oceanic Ridge, has been the site of Tertiary and Quaternary plateau basalt accumulation (Thorarinsson, 1966). Tertiary plateau basalts occur in the Faeroe Islands, on the coast of Greenland opposite Iceland, and in local areas of northern Scotland and Northern Ireland (Thorarinsson, 1966). The submarine portion of the Greenland-Iceland-Faeroe Plateau has been interpreted as a topographic expression of plateau basalt accumulation extending beneath the sea floor. It has been assumed that subsidence followed the accumulation (Litvin, 1966). Subsidence on the flanks of the Mid-Oceanic Ridge is inherent in current ridge extension concepts. It is reasonable to interpret that the plateau basalts assumed to underlie the submarine parts of the Greenland-Iceland-Faeroe Plateau were initially laid subaerially, followed by subsidence.

We suggest that the absence of basalt flows in horizontally disposed layers on the Ocean floor is the result of an inhibiting effect imposed either by the sub-ocean temperature-pressure conditions or possibly by limitations in the rate of flow in the submarine environment. Thorarinsson (1966) described the formation of the isle of Surtsey, off the southern coast of Iceland:

> "The volcanic eruption which has been going on off the south coast of Iceland since 1963 has clearly demonstrated the close relation between crater rows, the shield volcanoes, and the table mountains. The eruption started as a fissure eruption, but the activity soon became concentrated in the central part of the fissure and

developed into a central eruption. If it had occurred on land, this eruption would have built a shield volcano, but as it was, it built up a socle of tephra and pillow lava, and it started a shield volcano activity when the socle was high enough that the sea no longer had access to the vent. The result is a table mountain, the Island of Surtsey."

Heezen and Hollister (in preparation) have recorded in numerous bottom photographs much evidence of both quiet (pillow lavas) and explosive (volcanic debris) volcanic activity on the crest of the Mid-Oceanic Ridge. Menard (1964), on the other hand, has noted that lava flows have been observed to continue relatively unimpeded upon entry of water, the flow continuing beneath a thin, chilled crust on the surface of the flow. He further observed, in comparing the possible behavior of lava in the surface water with that expected at great depth, that the difference in temperature between the ocean surface and the ocean bottom would have little effect on the rate of chilling but that pressure at depth might have a significant damping effect on the explosive character of sub-oceanic extrusives.

Tectonic deformation, as evidenced by the succession of steps, scarps, and other irregularities superimposed on the primary topography, further complicates the bottom geometry of the Mid-Atlantic Ridge. Horst and graben structures, fault scarps, and gently tilted fault blocks may readily be seen in the bottom profiles. The most prominent scarps--interpreted as fault scarps--face away from the high fractured plateaus and constitute a step-down to the upper flanks of the ridge. But most of the scarps face in toward the crest, resembling fault scarps bounding gently tilted fault blocks. Tectonic slopes appear to account for the bulk of the component of slopes greater than 12-15 degrees. As we have seen, a stronger component of 12-15 degree slopes normally faces the ridge crest. Most of the tectonic deformation observed is probably secondary to the volcanism, inasmuch as volcanism would tend to obscure evidence of antecedent faulting and rifting.

The disposition of sediments pocketed in the basins of the Mid-Atlantic Ridge is an interesting one, and the pattern of distribution is important in any consideration of the history and mode of the origin of the ridge. Sediments in substantial accumulation are absent over the ridge crest and for a distance of 50-75 miles on either side of the axis. On the upper flanks, from the base of the regional step off the high fractured plateau to the 2500 tau isobath, sediments which have accumulated in basins have a rather uniform thickness which does not increase appreciably with increasing distance from the ridge crest (see Ewing and Ewing, 1967). The boundary between the axial region containing little sediments and the flank regions containing substantial accumulation of sediments is fairly abrupt. This pattern of distribution is valid not only for the North Atlantic but for the other oceans as well, and has led to the speculation that one period of expansion stopped in the late Mesozoic or early Cenozoic, during which sediments accumulated over the entire ridge with a new period of expansion beginning about 10 million years ago and continuing at the present (Ewing and Ewing, 1967).

One of the possibilities suggested by Saito, et al., (1966) which may explain the crest-flank sediment discontinuity in terms of ridge expansion is that recurring volcanism has obscured the evidence of sedimentation in the crest zone. It is not difficult to imagine that volcanism could recur subsequently to that forming the primary relief. Tectonic activity must be associated with the entire crest zone, and particularly with the scarps bounding the high fractured plateau.

Sediments accumulating in the scarp zones that bound the high fractured plateaus, might eventually come to rest in the trough at its base, in view of the regional steepness of this scarp zone and the tendency of sediments to accumulate in basins on the upper ridge flanks. Seismic activity in the crest zone could initiate some of the downslope movement. The photographic evidence for bottom currents in the crest zone (Heezen and Hollister, in preparation) suggests that perhaps bottom currents, intensified in the shallow water of the crest zone could be transporting sediment into the deeper troughs on the upper flanks.

Another discontinuity occurs on the Mid-Atlantic Ridge, between the moderate relief of the upper ridge flanks and the high relief of the deep, rough areas on both outer flanks of the ridge (and in the abyssal hills) between latitudes 20°N and 30°N. This discontinuity is seen in both relief and sedimentation, the total sediment accumulation decreasing abruptly on the outer flanks. The sediment discontinuity may of course be partially explained in terms of the carbonate compensation threshold, but the abrupt change in relief, reflected in the geometry and texture of the basement, must be related to the tetonic history of the Mid-Atlantic Ridge.

Mid-Atlantic Ridge Topography and Sea Floor Expansion

The Mid-Atlantic Ridge is symmetrical throughout the North Atlantic Ocean. Almost every major change in the character of the topography on one side of the ridge appears to have its counterpart on the opposite side. Seamounts of the Corner Rise lie directly opposite seamounts on the eastern ridge flank. The Bermuda Rise lies opposite the Krylov Rise, although the Bermuda Rise occupies greater areal extent. Belts of high relief lie on both ridge flanks between the two rises. This symmetry is seen in magnetic as well as topographic patterns (Pitman and Heirtzler, 1966).

The North Atlantic Ocean basin is wider by some 1000-2000 nautical miles at latitude 20°-30°N than it is at latitude 45°N and at 10°N. The western North Atlantic margin is characterized by a pronounced westward convexity. No such eastward convexity exists on the eastern margin. Within the area of greatest width lies the zone of highest relief. The ridge crest is offset left-laterally along fracture zones at latitudes 10-15°N (Heezen, et al., 1967), and right-laterally along fracture zones at 30°-40°N (for example, Fox, et al., 1967). This offset coincides with a general widening of the ridge. Measuring the width of the ridge along a line directly west of the Cape Verde Abyssal Plain at latitude 12°N, one obtains about 1200 nautical miles. Another measurement across the ridge from the northern part of the Madeira Abyssal Plain to the outermost tip of the Newfoundland Ridge gives a width of about 900 nautical miles. The width of the ridge along an east-west line at about latitude 25°N is about 2000 miles, not including the Bermuda Rise. The westward offset of the latitude 20°-30°N ridge crest is about 450 nautical miles, about half the difference between the previously mentioned maximum and minimum width of the Mid-Atlantic Ridge.

The measured rates of extension increase from north to south at a rate which is insufficient to account for observed differences in the total width of the ridge but which agree with the widths obtained by excluding the deep, rough zones (i.e., the outer flanks of the ridge, latitude 20°-30°N). Half rates of extension of 0.3-1 cm/yr. are accepted for Iceland, (Thorarinsson, 1960). A half rate of extension of 1 cm/yr. over the last 10 million years has been interpreted for the Mid-Atlantic Ridge south of Iceland (Pitman and Heirtzler, 1966). Farther south, Phillips (1967) has determined extension half rates of 1.25-1.65 cm/yr. near latitude 27^{o}N and 1.4-1.7 cm/yr. near latitude 22^{o}N.

Menard (1967) has reached the conclusion that the amplitude of sea floor relief is inversely proportional to the rate of crustal extension. This does not agree with the fact that, in the North Atlantic, the belts of highest relief lie in the belt having the greatest widths and the highest crustal expansion rates. However, if the deep, high relief belts on the outer flanks in latitudes $20\text{-}30^{o}$ are excluded, this apparent contradiction can be partially resolved: The latitudinal decrease in relief on the ridge flanks from south to north can be explained as the result of the degree of burial through sedimentation rather than as the result of major changes in the size of basement relief (figure 16; plates I, II, IV, and VI; also see seismic reflection profiles in Ewing, et al., 1964; Ewing and Ewing, 1967). Strong relief on the ridge is present as far north as the Mohns Ridge northeast of Jan Mayen Island (Johnson and Heezen, 1967).

If we accept the Menard's proposal, it is reasonable to account for the anomalously high relief in the deep, rough zones by a slower rate of extension. We have already noted the rather abrupt change in basement geometry marking the boundary between these zones and the upper ridge flanks. It may be that this abrupt topographic boundary indicates a change in the rate and/or pattern of extension simultaneous with the initial opening of the Norwegian-Greenland Sea, interpreted as having occurred in early

Eocene time (Avery, et al., 1968; Vogt, et al., 1969; Avery, et al., 1969). Extrapolating Phillips' expansion rates at latitudes 22° and 27°N (the reasonably consistent size of basement relief suggests that, whether episodic or not, the expansion producing the topography could not have been markedly different over the upper ridge flanks), an age of 50-60 million years could be assigned to this boundary, in agreement with that observed farther north. This could place the deep, rough zones in an earlier era of slower and very possibly differently oriented expansion, completely antedating the initial opening of the Norwegian-Greenland Sea. An alternate explanation would be that correspondingly slower expansion farther north during an earlier era was of insufficient rate to produce strong relief.

Conclusions

The smooth topography of the North Atlantic quite generally reflects a geomorphic history of sedimentation and some erosion, whereas the rough topography reflects the combined effects of volcanism and tectonics.

The fine textured ridges of the continental rise, which underlie the Western Boundary Undercurrent, appear to be longitudinal current-formed features that may be the ocean-floor equivalent of channel bars in a braided stream.

Three slope ranges describe the observed characteristics of the slope frequency distribution curves obtained from samples of Mid-Oceanic Ridge topography. The zero slope component reflects the sediment-filled flat floored valleys. The component resulting in modes between 5 and 12 degrees reflects the hillside slopes of the primary basement relief, which are interpreted as being controlled by the angle of repose of lavas extruded on the ocean bottom. The component that includes the steepest slopes (mostly 12-15 degrees) is the result of the tectonic scarps.

The three components of slope, although mixed in varying proportions, are recognizable in all areas of the Mid-Oceanic Ridge considered in this study. There seems to be no direct relationship between the size and texture of relief and the magnitude of hillside slopes, which are everywhere fairly uniform.

The high relief belts on the outer flanks of the Mid-Atlantic Ridge between latitudes 20°N and 30°N are separated from the upper ridge flanks by a discontinuities in relief, wavelength, and total amount of sedimentation. These belts may belong to an earlier era of sea floor extension having a different rate and/or pattern from that assumed to have been active over the past 50-60 million years.

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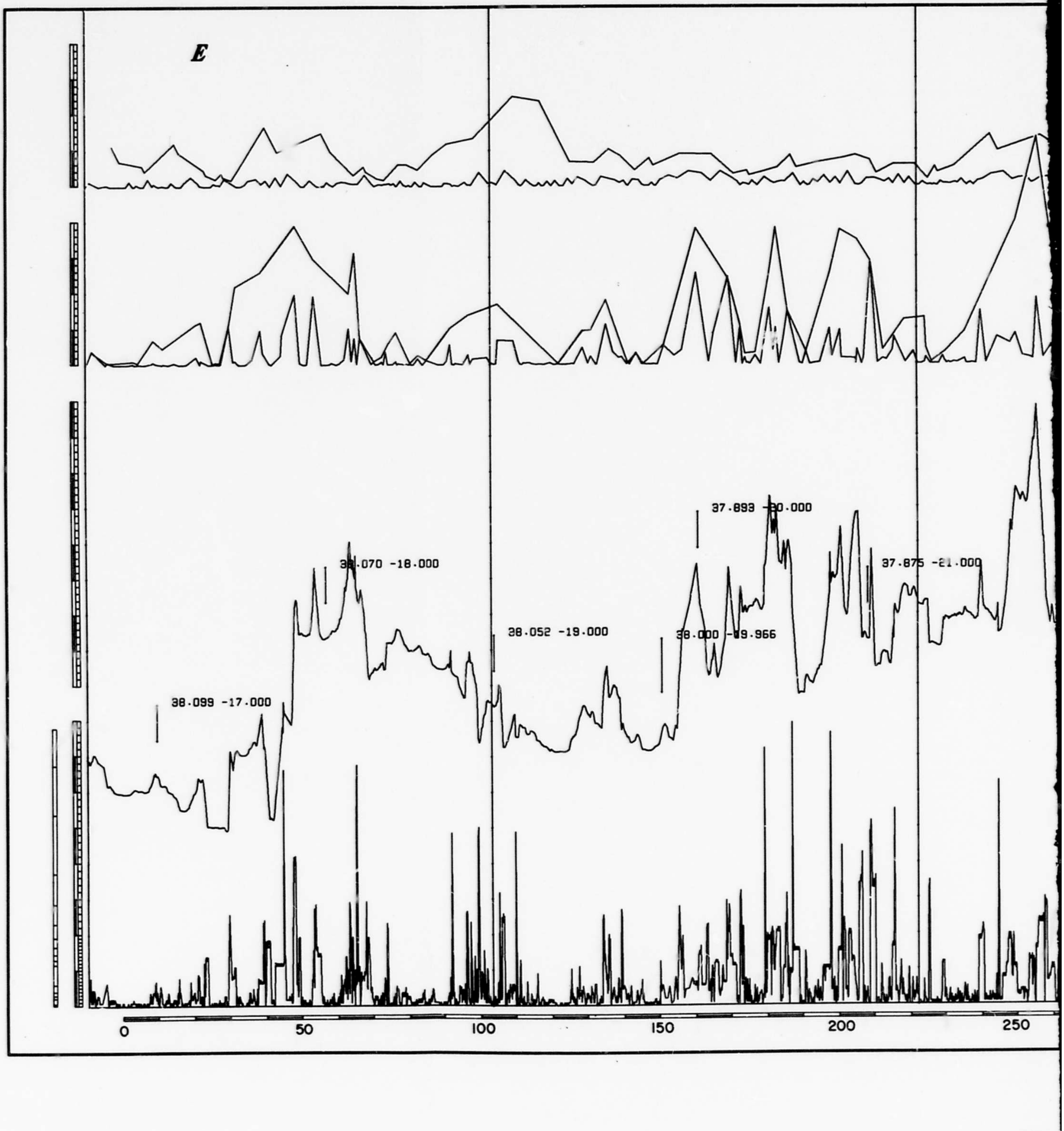
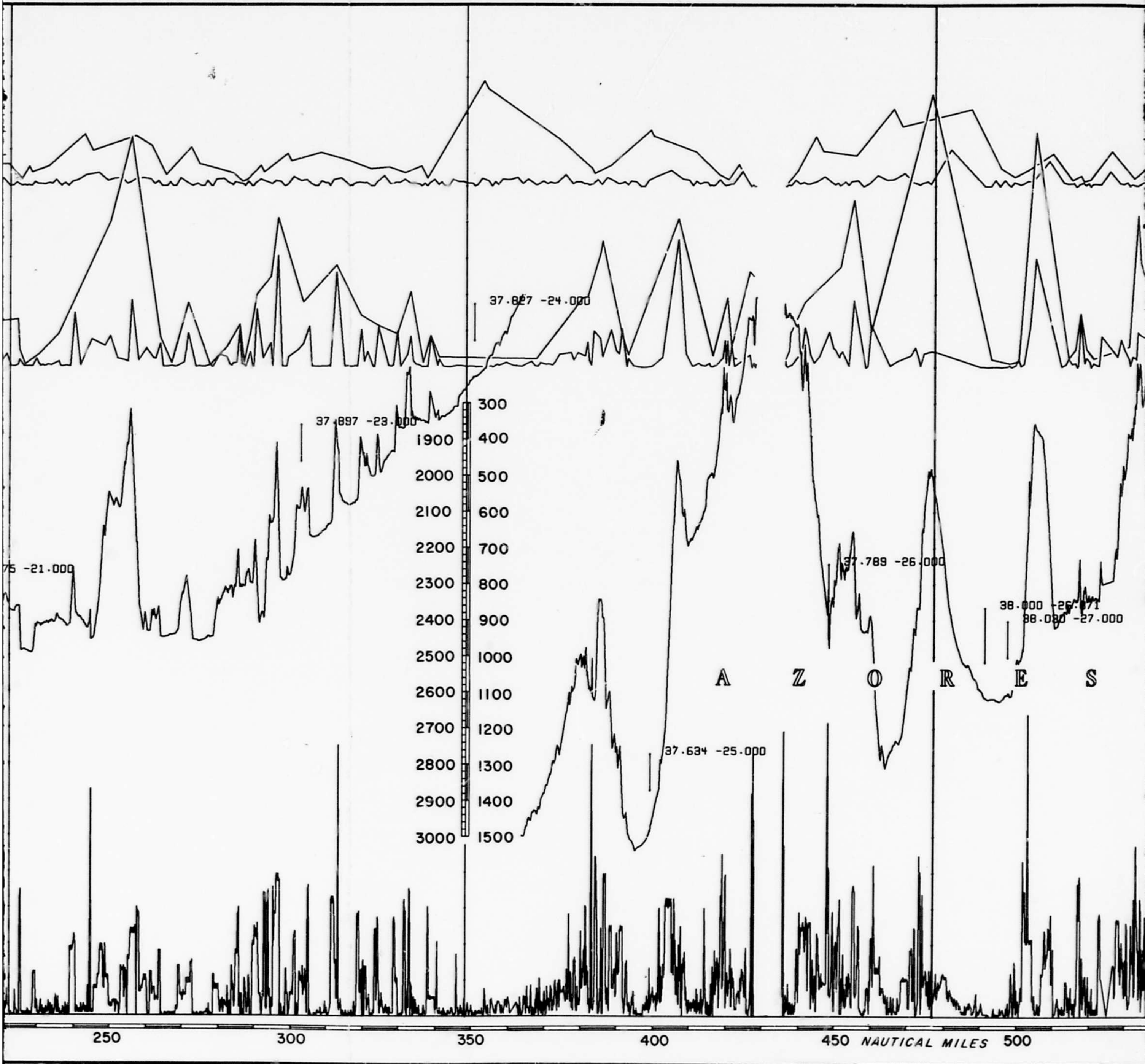
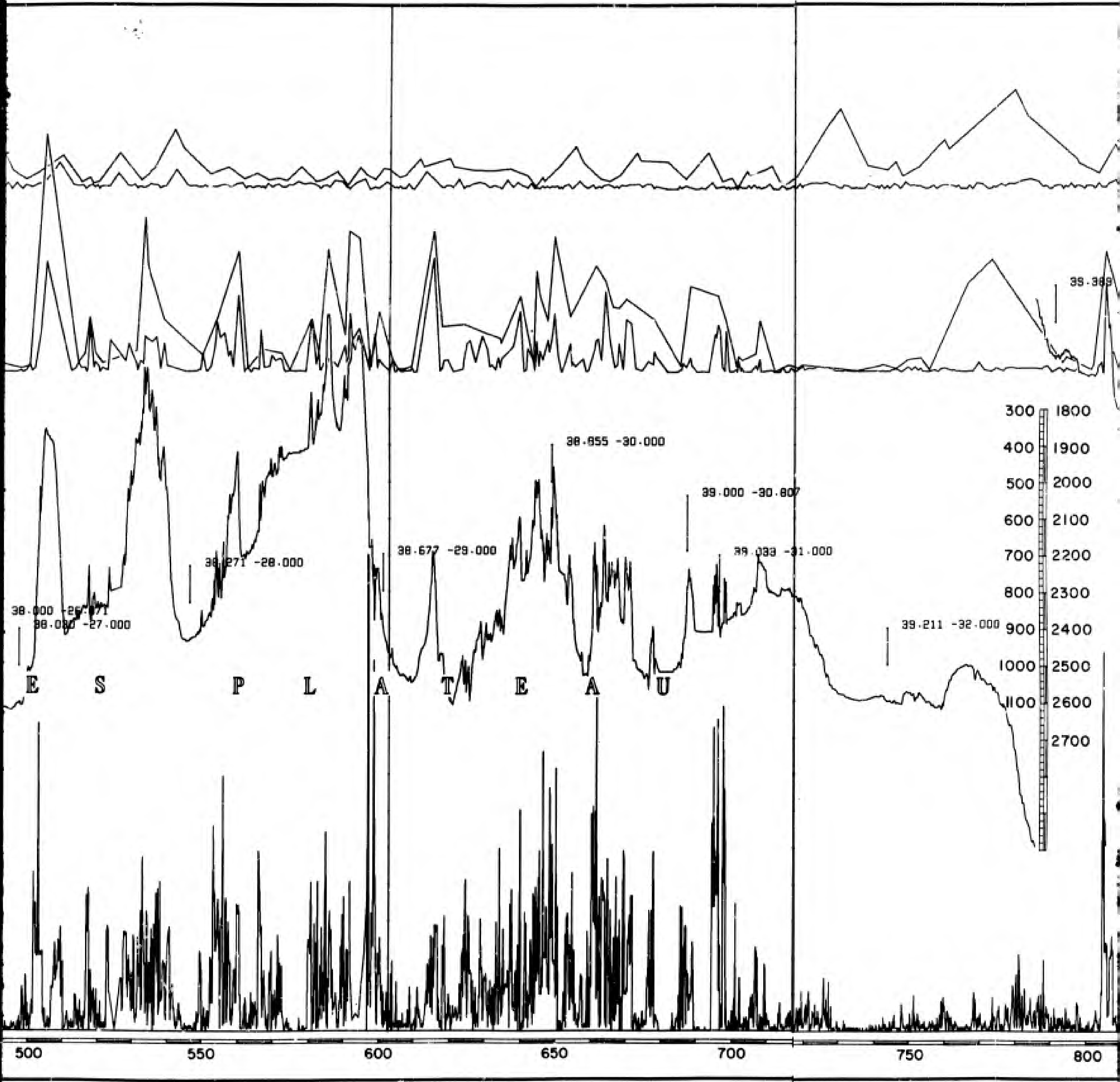


A.


37.827 -24.000
37.897 -23.000
75 -21.000
37.789 -26.000
38.000 -26.871
38.080 -27.000
37.634 -25.000
A Z O R E S
1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000
300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500
250 300 350 400 450 NAUTICAL MILES 500

B.



38.855 -30.000
39.000 -30.807
38.271 -28.000
38.677 -29.000
39.033 -31.000
39.211 -32.000
E S P L A T E A U
300 1800
400 1900
500 2000
600 2100
700 2200
800 2300
900 2400
1000 2500
1100 2600
2700
500
550
600
650
700
750
800

C.

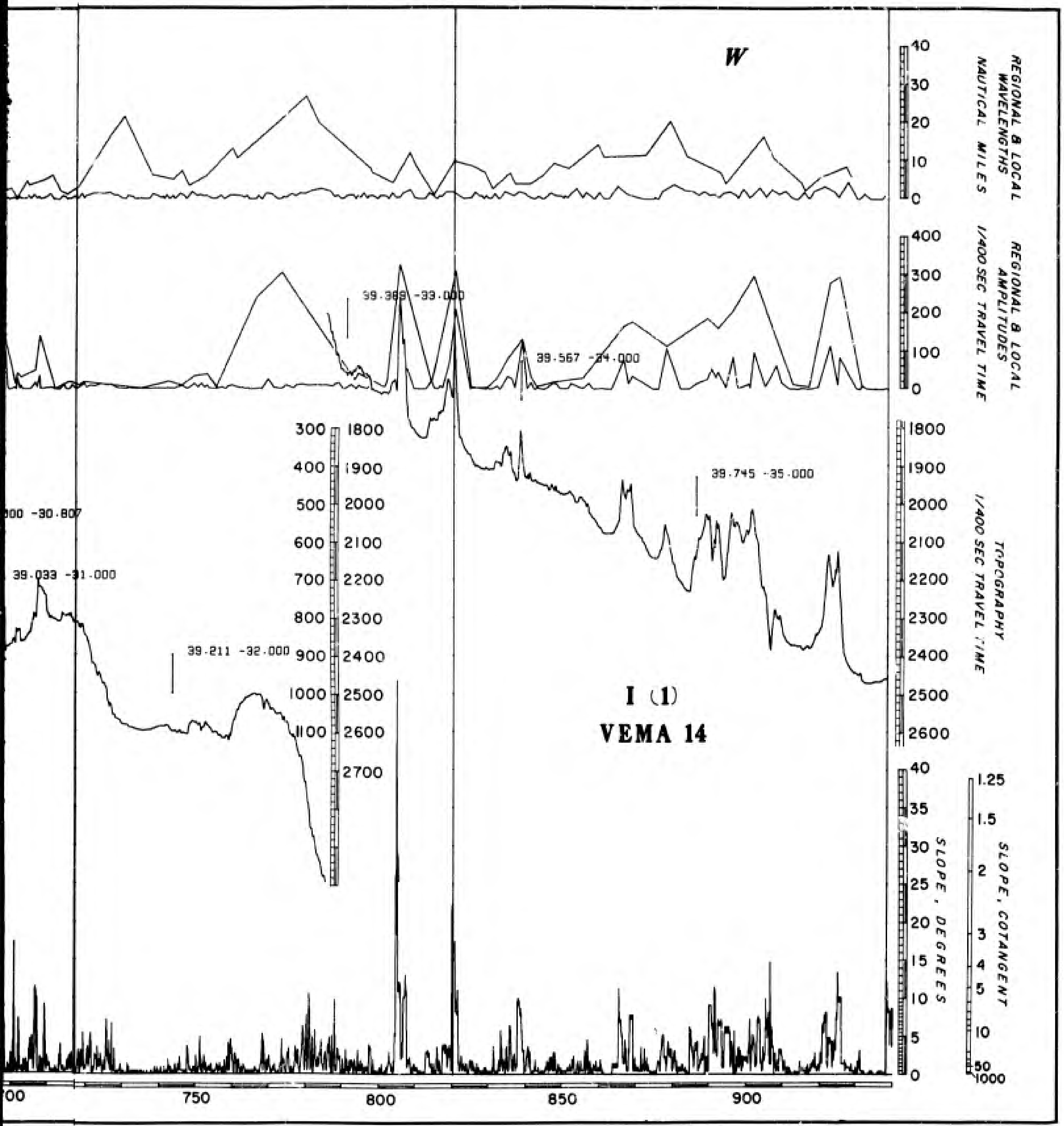
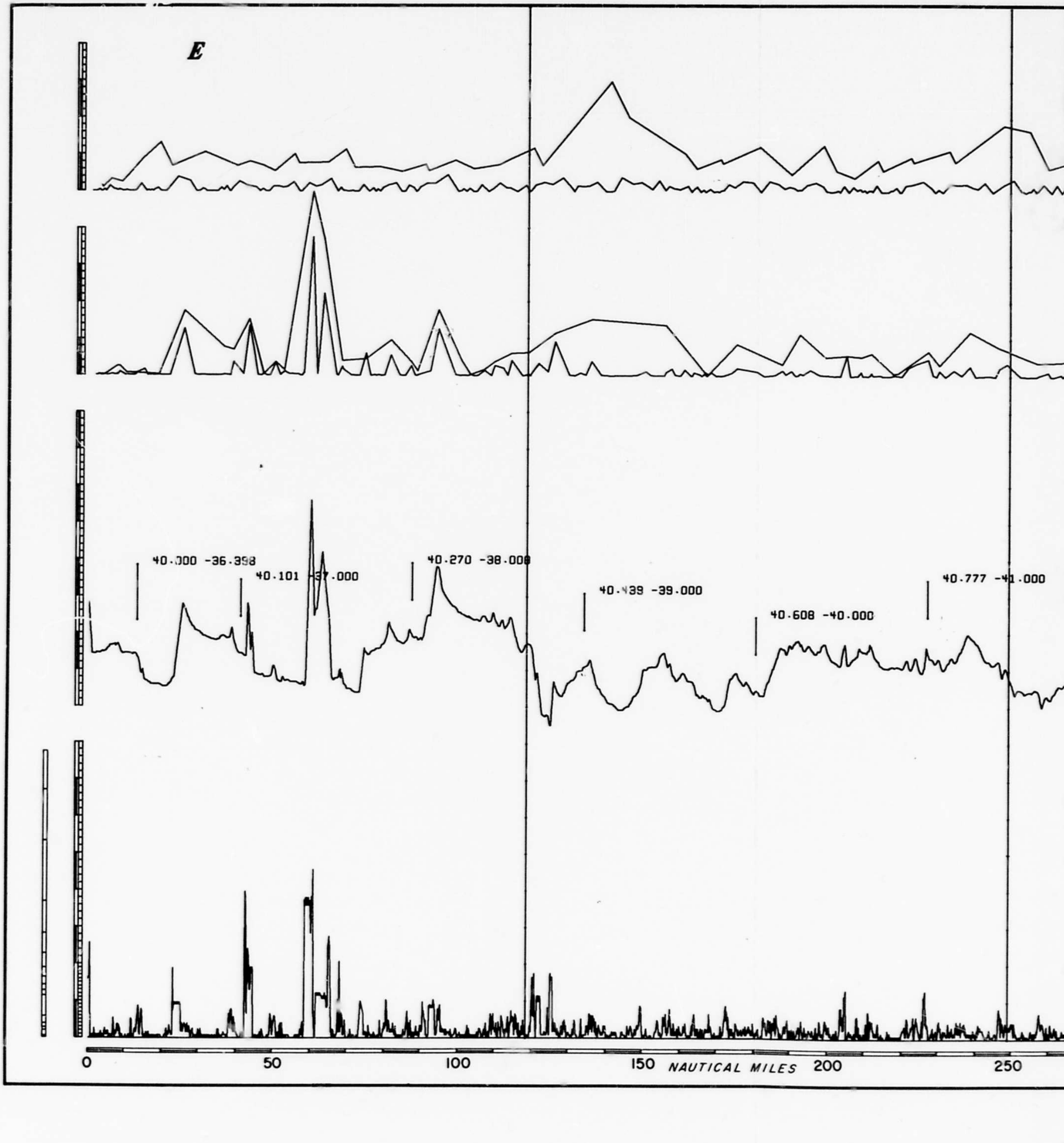

W
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
TOPOGRAPHY
1/400 SEC TRAVEL TIME
SLOPE, DEGREES
SLOPE, COTANGENT
39.389 -33.000
39.567 -34.000
39.745 -35.000
39.033 -31.000
39.211 -32.000
I (1)
VEMA 14
750
800
850
900

Plate I (1)

D.



E
40.000 -36.398
40.101 -37.000
40.270 -38.000
40.439 -39.000
40.608 -40.000
40.777 -41.000
0
50
100
150
NAUTICAL MILES
200
250

A.

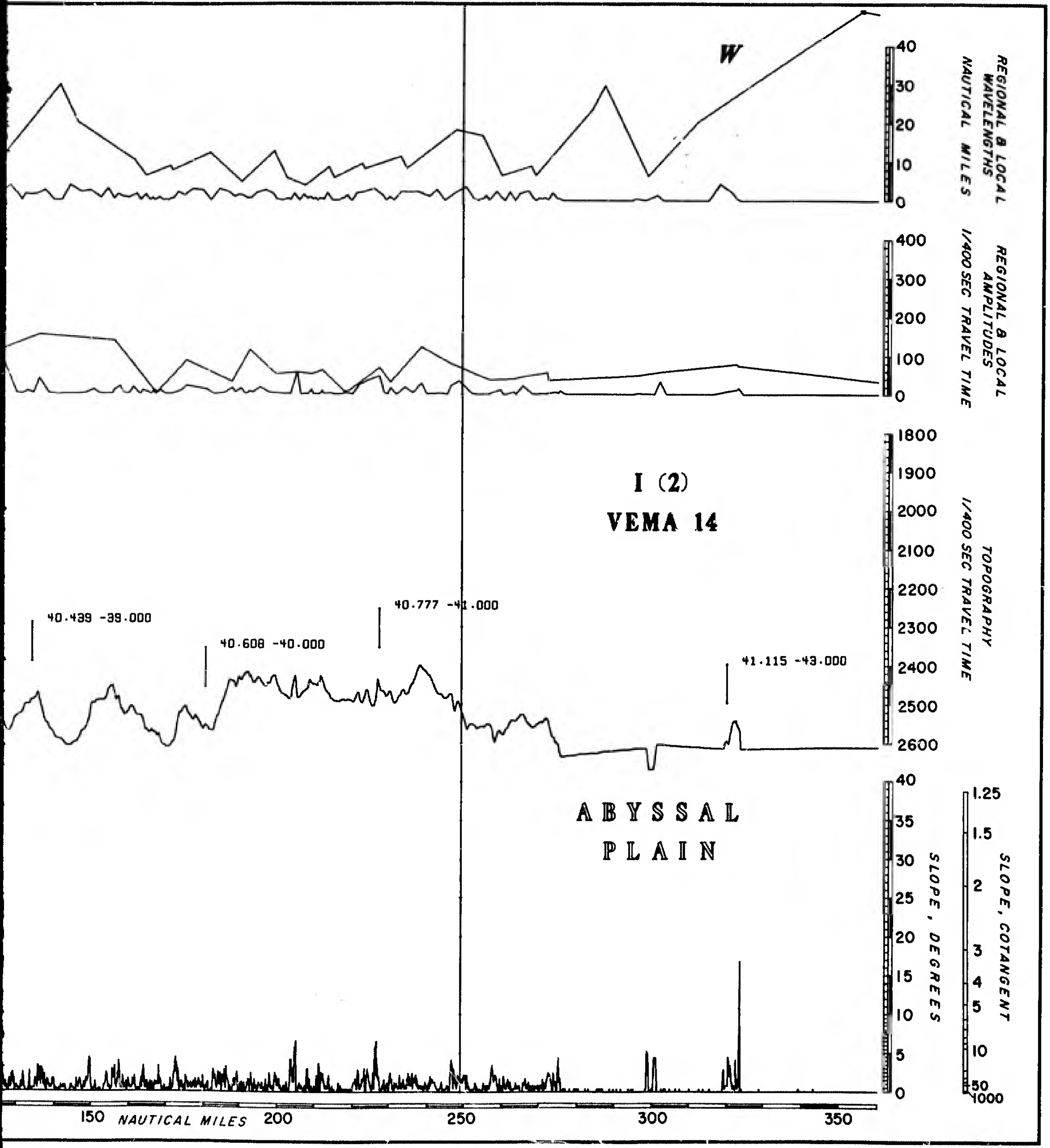
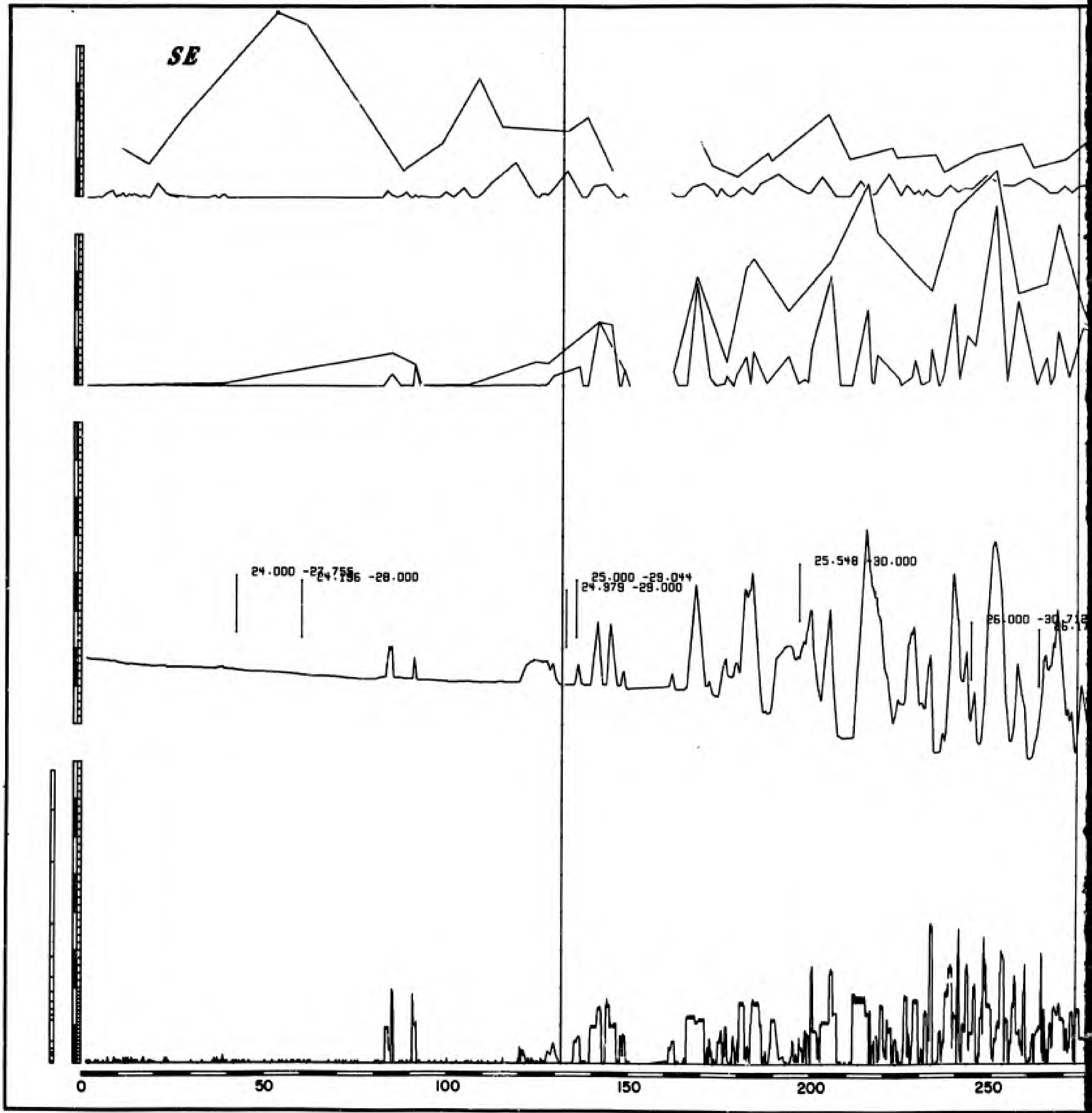
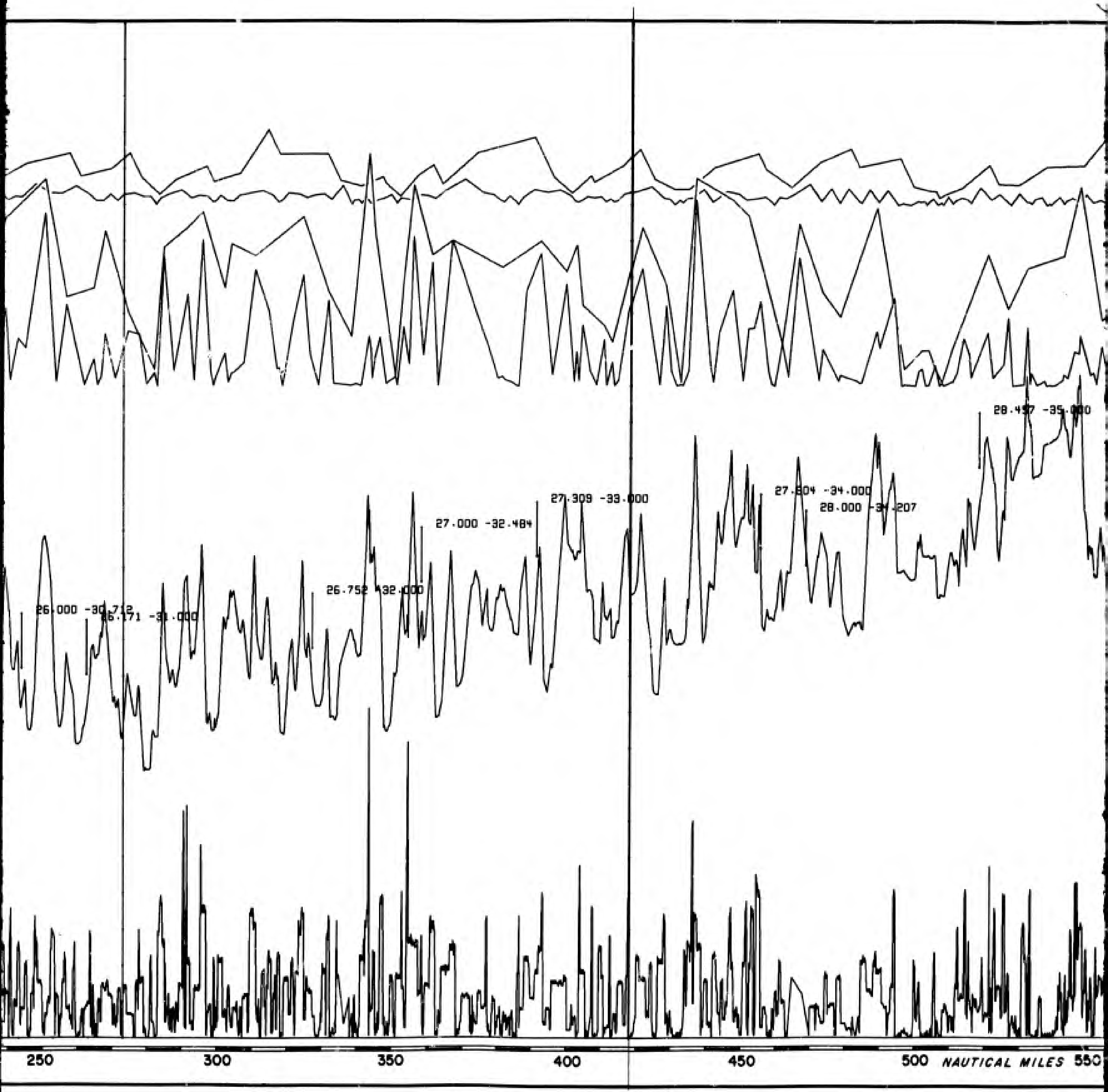

W
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
40
30
20
10
0
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
400
300
200
100
0
I (2)
VEMA 14
TOPOGRAPHY
1/400 SEC TRAVEL TIME
1800
1900
2000
2100
2200
2300
2400
2500
2600
40.439 -39.000
40.608 -40.000
40.777 -41.000
41.115 -43.000
ABYSSAL PLAIN
SLOPE, DEGREES
40
35
30
25
20
15
10
5
0
SLOPE, COTANGENT
1.25
1.5
2
3
4
5
10
50
1000
150
NAUTICAL MILES
200
250
300
350

Plate I (2)

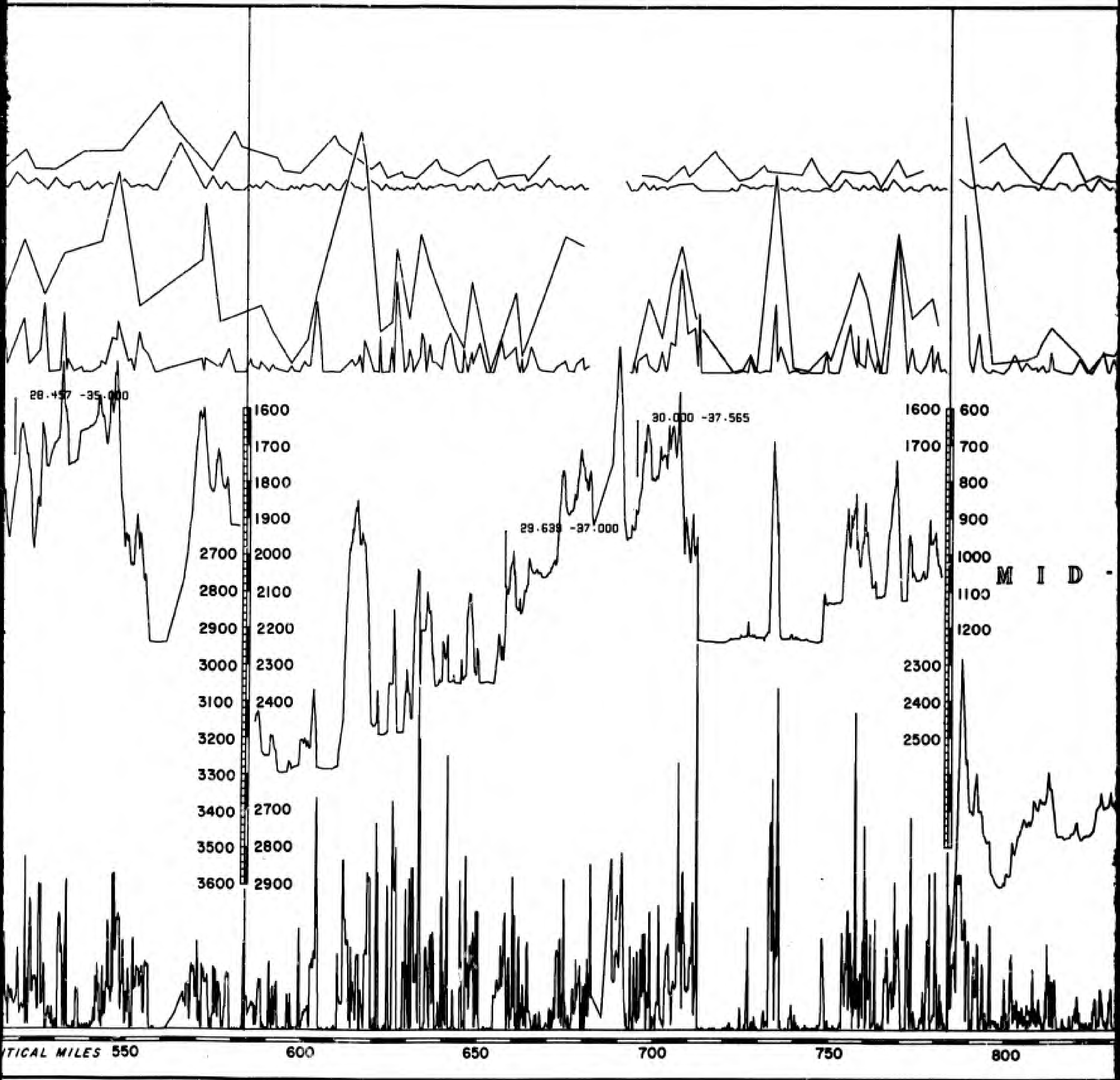

SE
24.000 -27.755
24.196 -28.000
25.000 -29.044
24.979 -29.000
25.548 -30.000
26.000 -30.712
0
50
100
150
200
250

A.



26.000 -30.712
26.171 -31.000
26.752 -32.000
27.000 -32.484
27.309 -33.000
27.804 -34.000
28.000 -34.207
28.457 -35.000
250
300
350
400
450
500
NAUTICAL MILES
550

B.



28.457 -35.000
29.639 -37.000
30.000 -37.565
1600
1700
1800
1900
2000
2100
2200
2300
2400
2700
2800
2900
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
1600
1700
2300
2400
2500
600
700
800
900
1000
1100
1200
M I D -
...TICAL MILES 550
600
650
700
750
800

C.

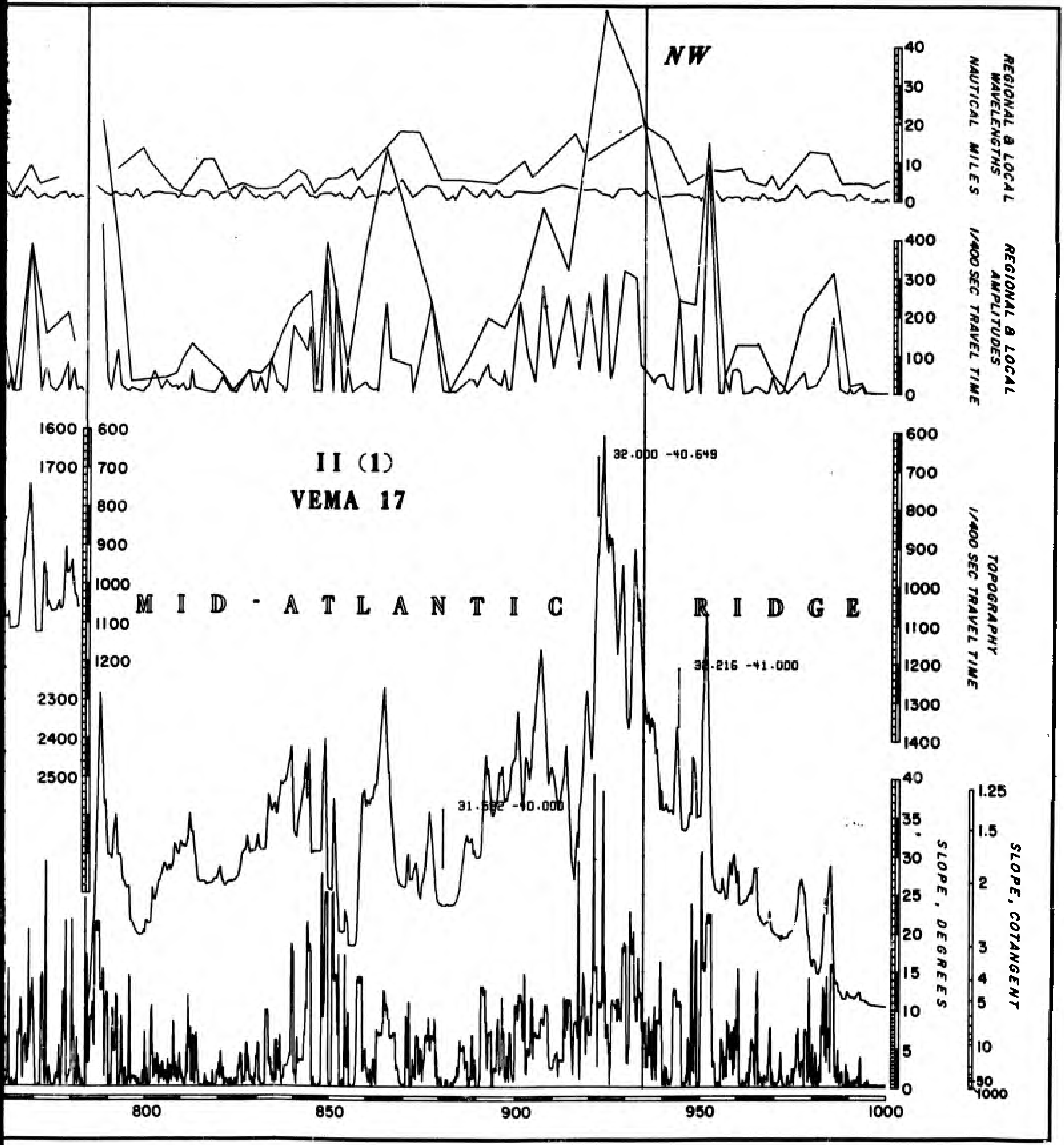
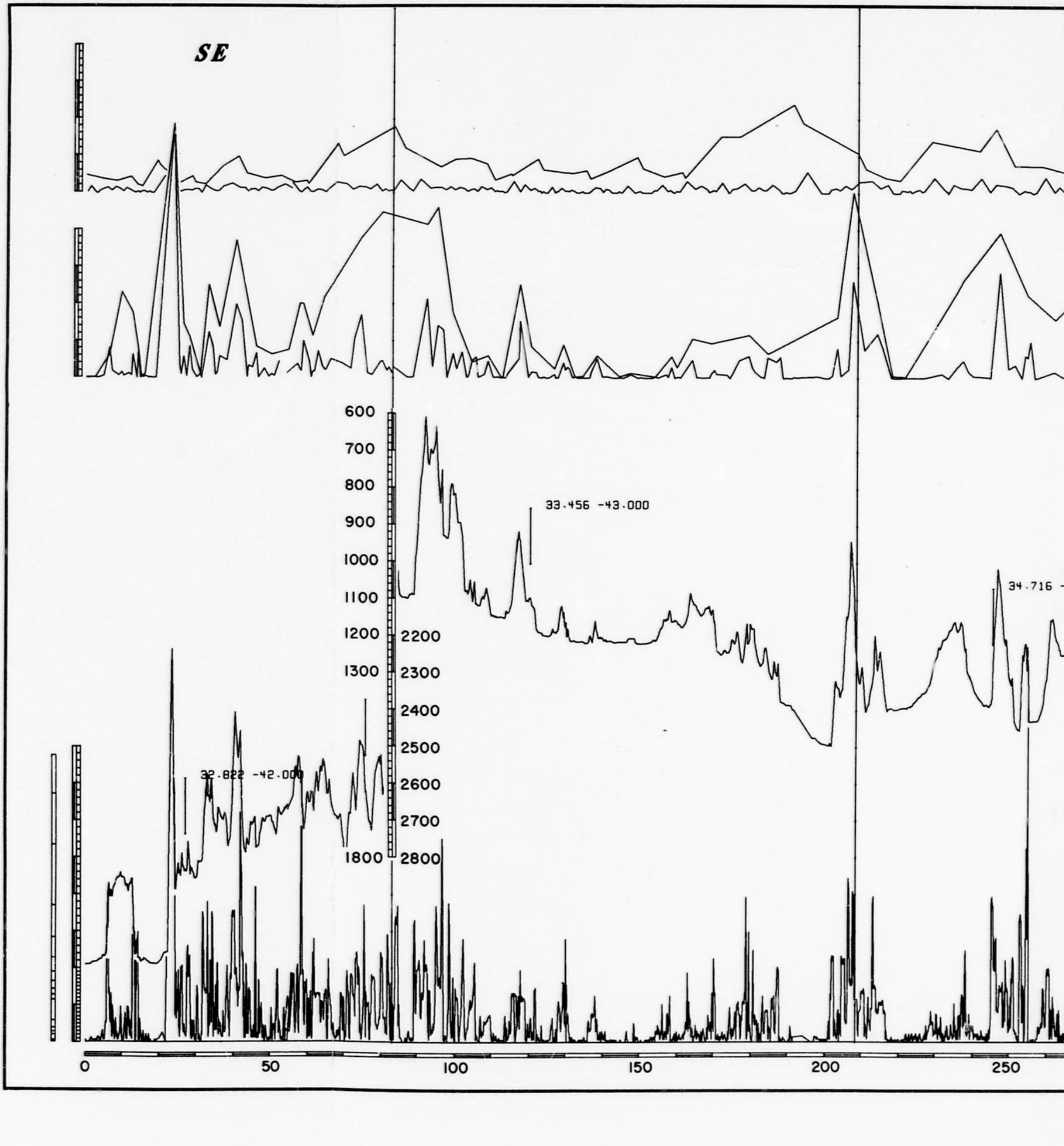
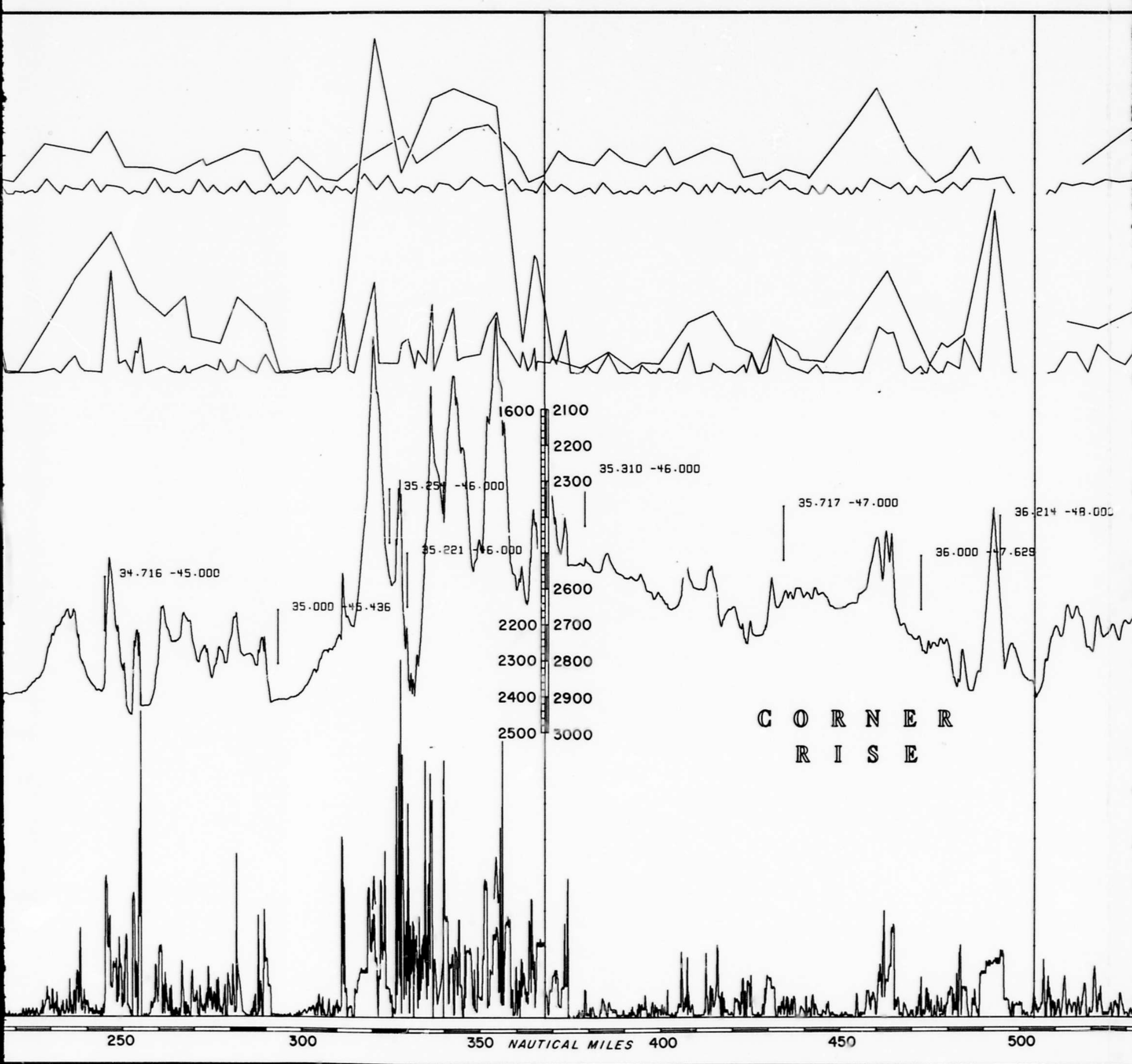

NW
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
II (1)
VEMA 17
MID-ATLANTIC RIDGE
TOPOGRAPHY
1/400 SEC TRAVEL TIME
SLOPE, DEGREES
SLOPE, COTANGENT
800
850
900
950
1000

Plate II (1)


SE
600
700
800
900
1000
1100
1200
1300
1800
2200
2300
2400
2500
2600
2700
2800
33.456 -43.000
32.822 -42.000
0
50
100
150
200
250

A.



1600
2200
2300
2400
2500
2100
2200
2300
2600
2700
2800
2900
3000
34.716 -45.000
35.000 -45.436
35.254 -46.000
35.221 -46.000
35.310 -46.000
35.717 -47.000
36.000 -47.629
36.214 -48.000
CORNER
RISE
250
300
350
NAUTICAL MILES
400
450
500

B.

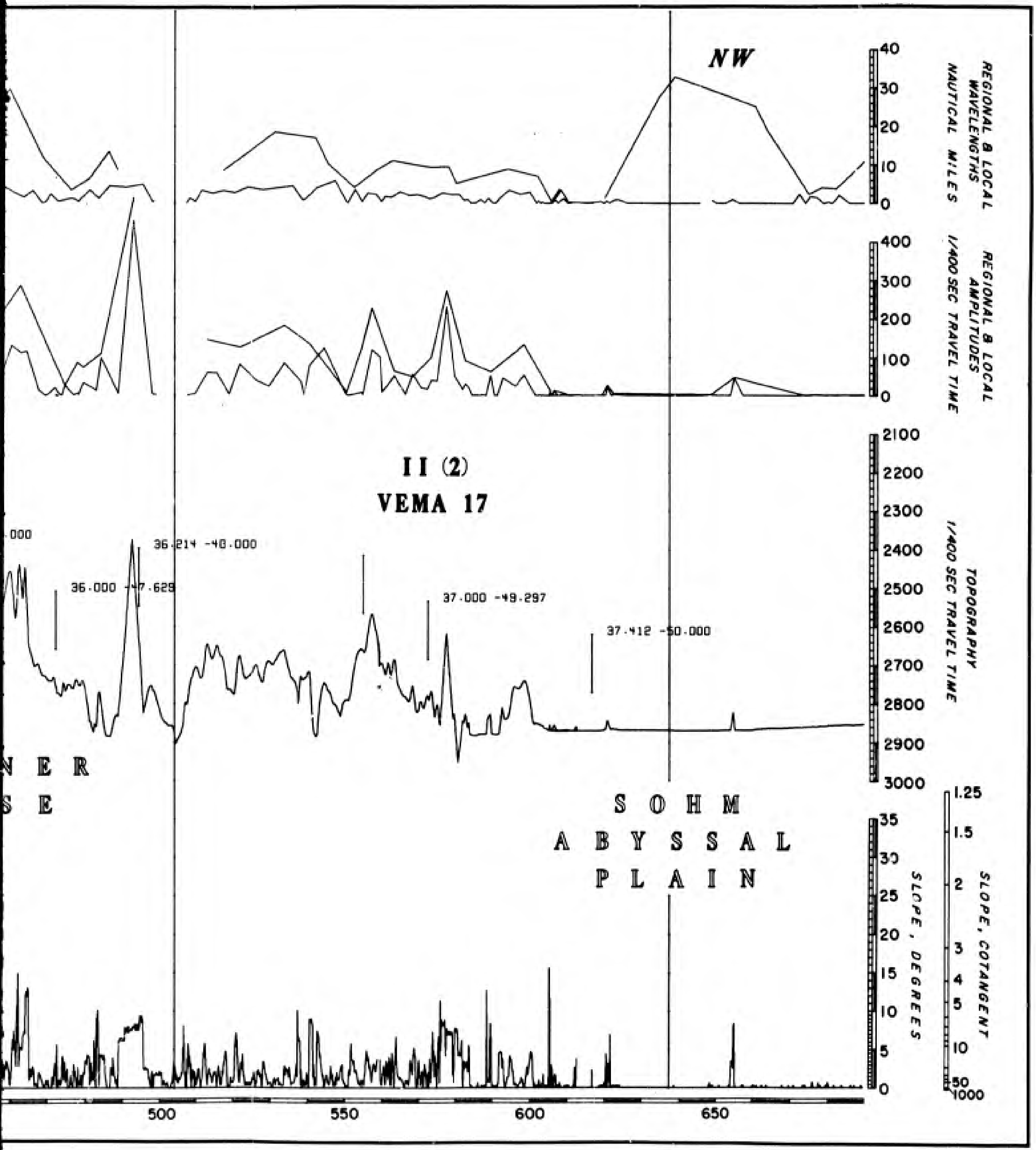
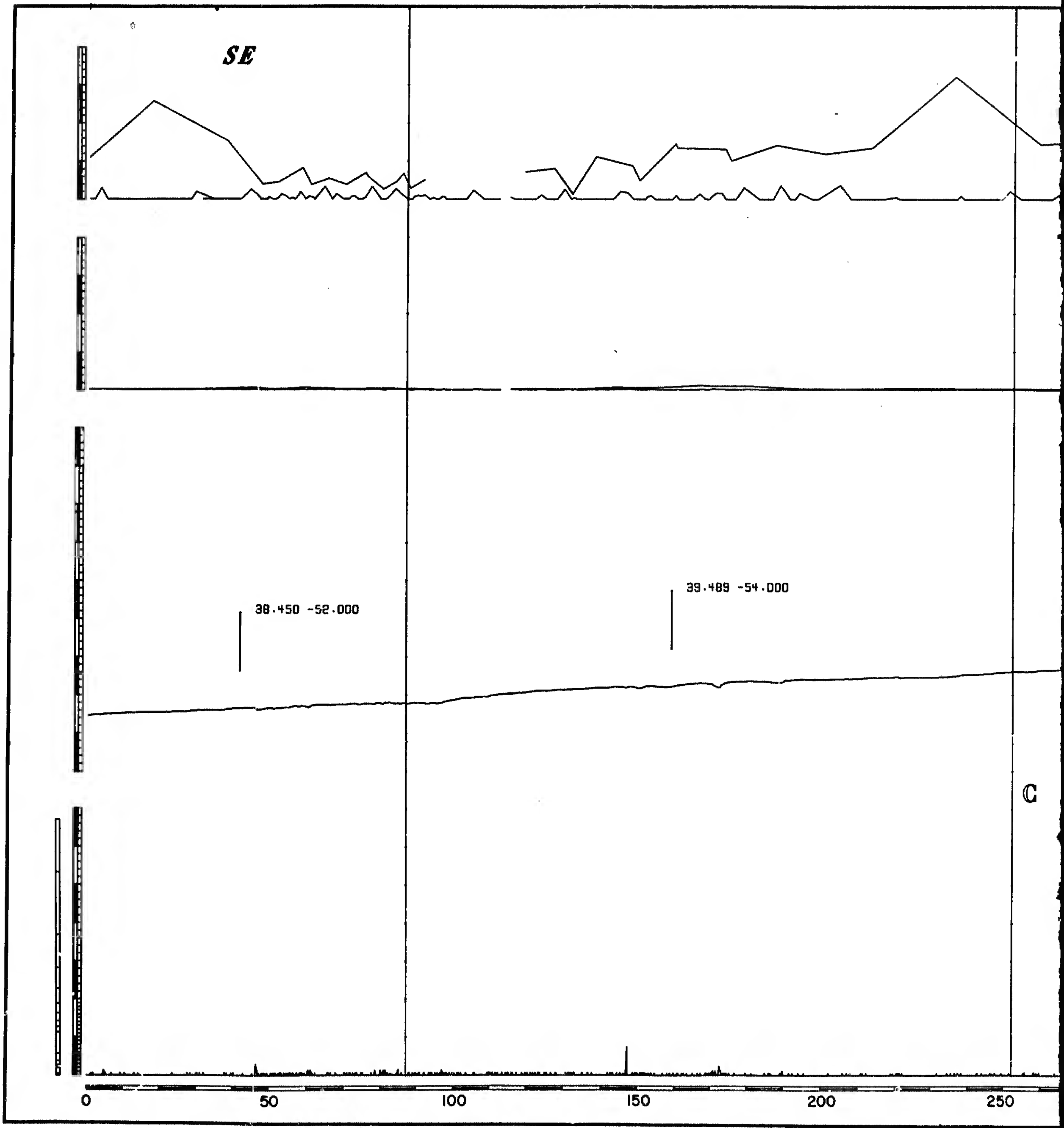
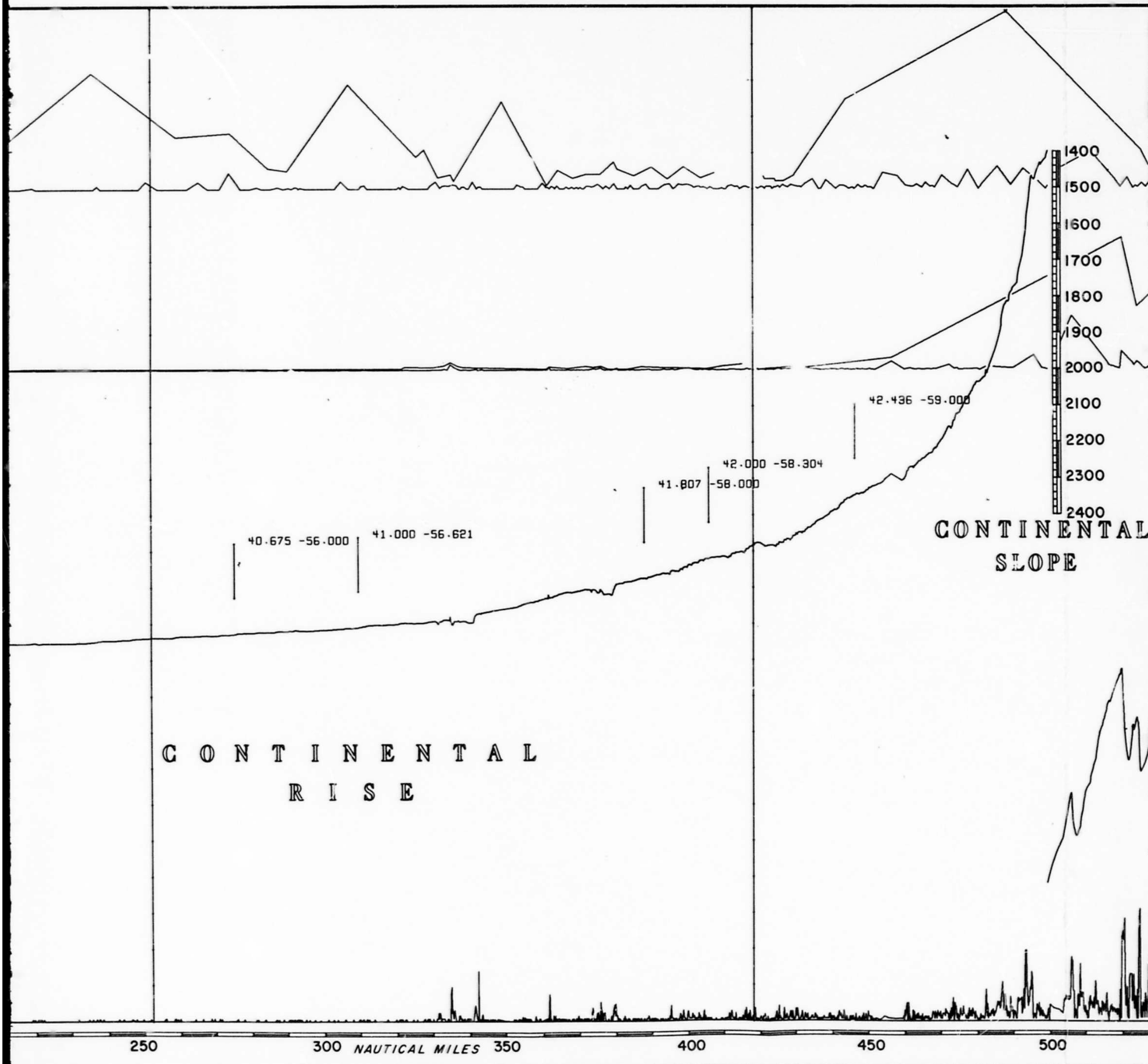

NW
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
II (2)
VEMA 17
TOPOGRAPHY
1/400 SEC TRAVEL TIME
36.214 -48.000
36.000 -47.629
37.000 -49.297
37.412 -50.000
N E R
S E
SOHM
ABYSSAL
PLAIN
SLOPE, DEGREES
SLOPE, COTANGENT
500
550
600
650

Plate II (2)



A.



1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
42.436 -59.000
42.000 -58.304
41.807 -58.000
40.675 -56.000
41.000 -56.621
CONTINENTAL SLOPE
CONTINENTAL RISE
250
300
NAUTICAL MILES
350
400
450
500

B.

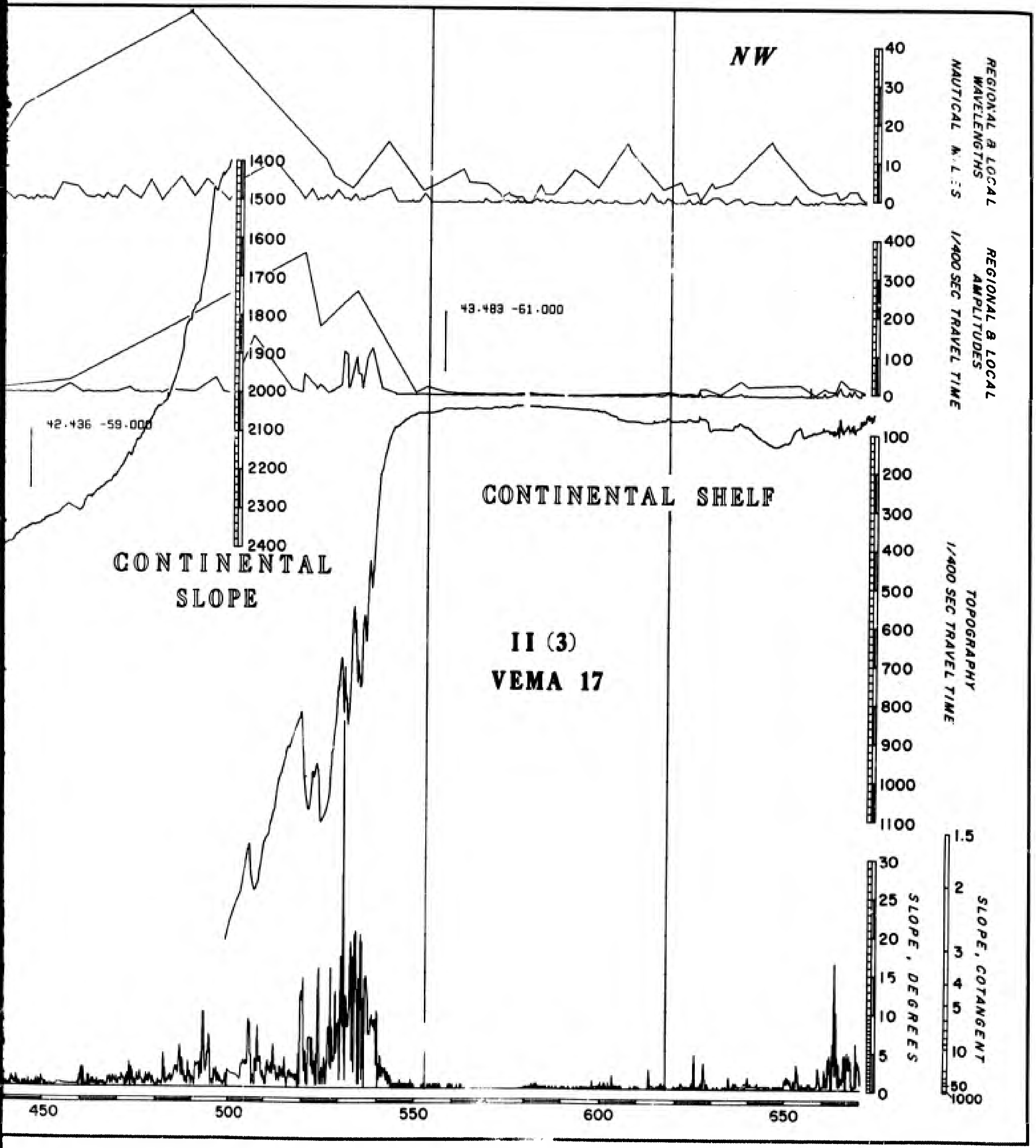
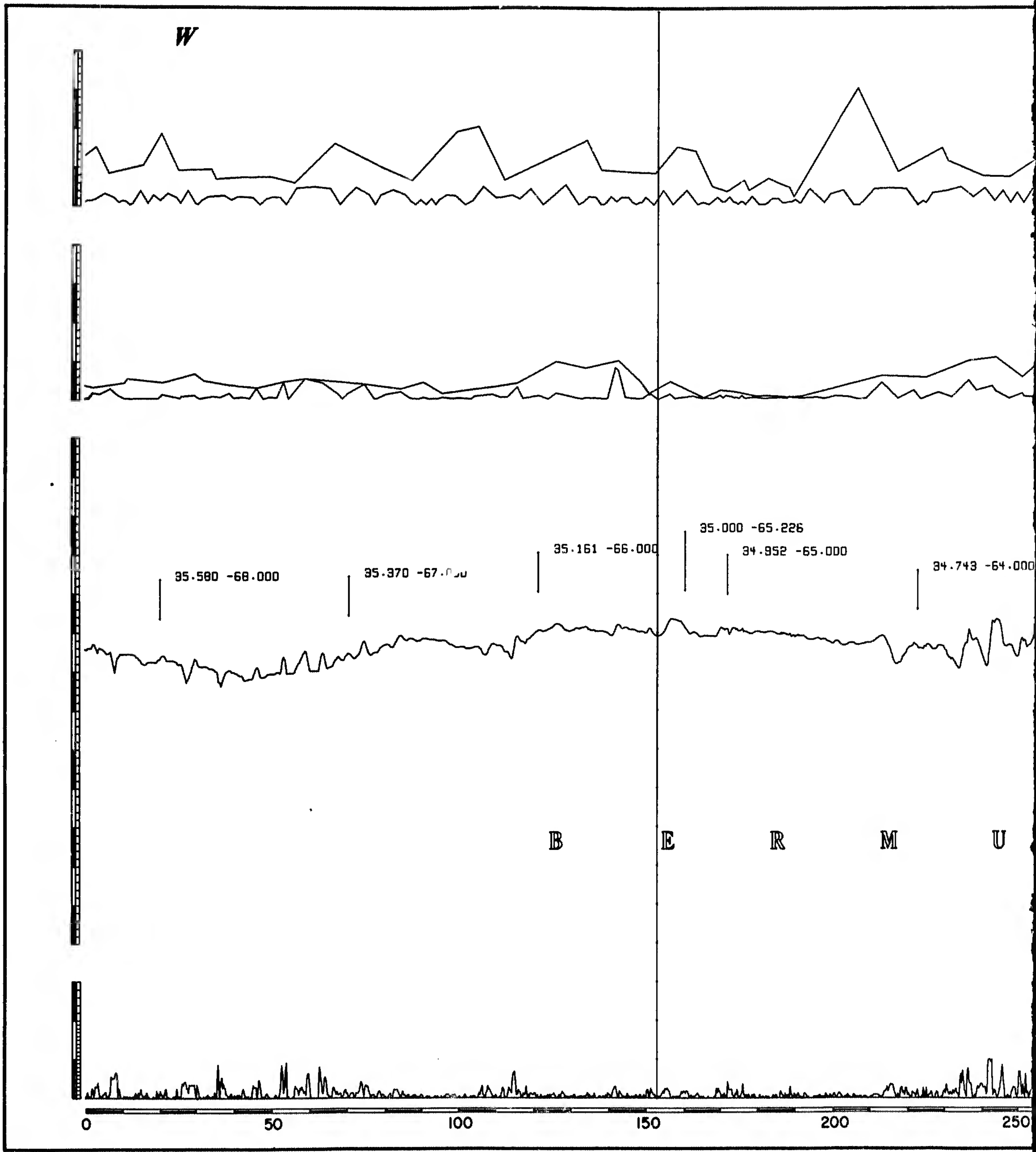
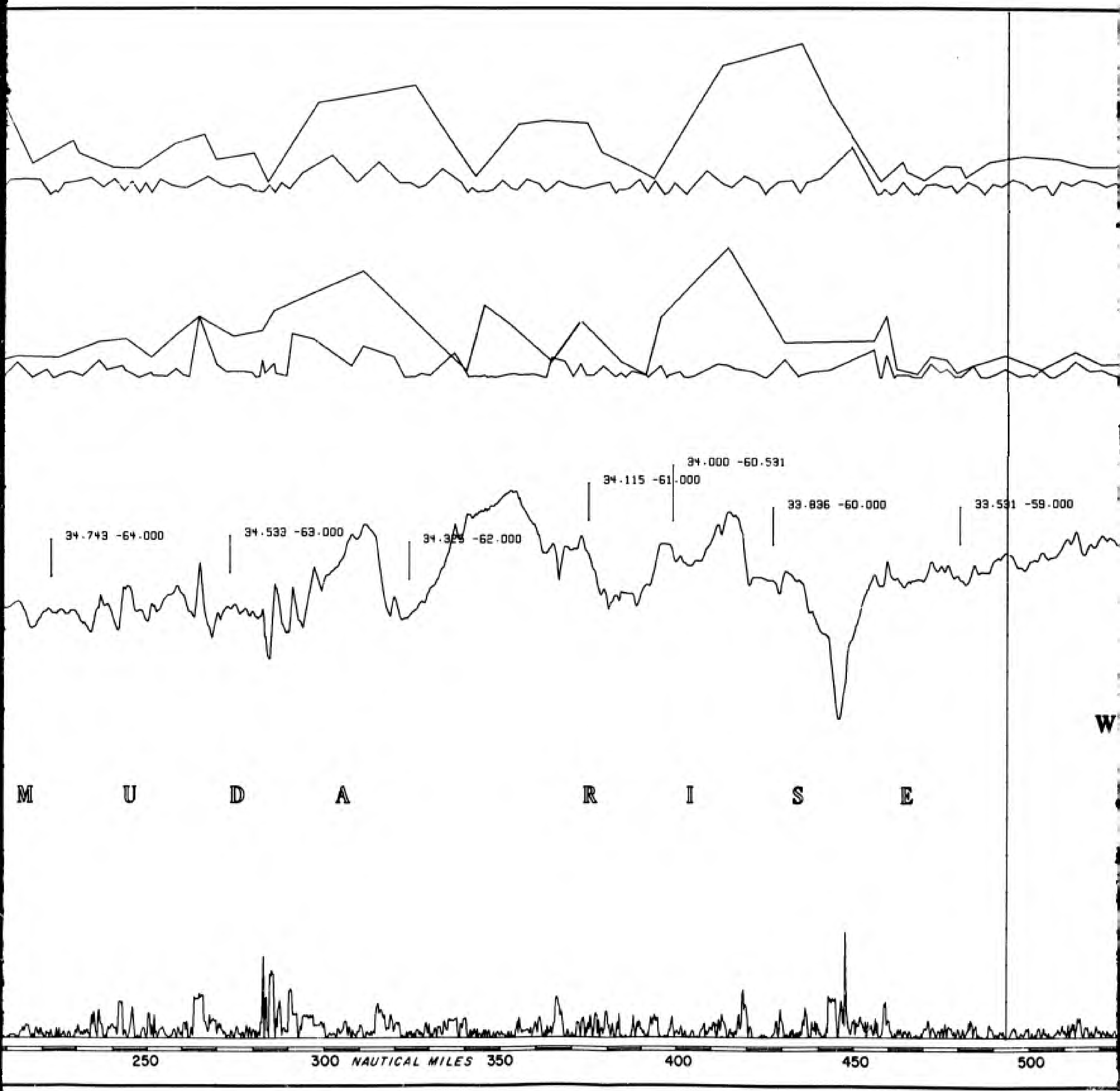

NW
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL
0 10 20 30 40
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
0 100 200 300 400
TOPOGRAPHY
1/400 SEC TRAVEL TIME
100 200 300 400 500 600 700 800 900 1000 1100
1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400
SLOPE, DEGREES
0 5 10 15 20 25 30
SLOPE, COTANGENT
1.5 2 3 4 5 10 50 1000
43.483 -61.000
42.436 -59.000
CONTINENTAL SHELF
CONTINENTAL SLOPE
II (3)
VEMA 17
450 500 550 600 650

Plate II (3)



W
35.580 -68.000
35.370 -67.000
35.161 -66.000
35.000 -65.226
34.952 -65.000
34.743 -64.000
B E R M U
0
50
100
150
200
250

A.



34.743 -64.000
34.533 -63.000
34.325 -62.000
34.115 -61.000
34.000 -60.531
33.836 -60.000
33.531 -59.000
W
M U D A R I S E
250
300 NAUTICAL MILES 350
400
450
500

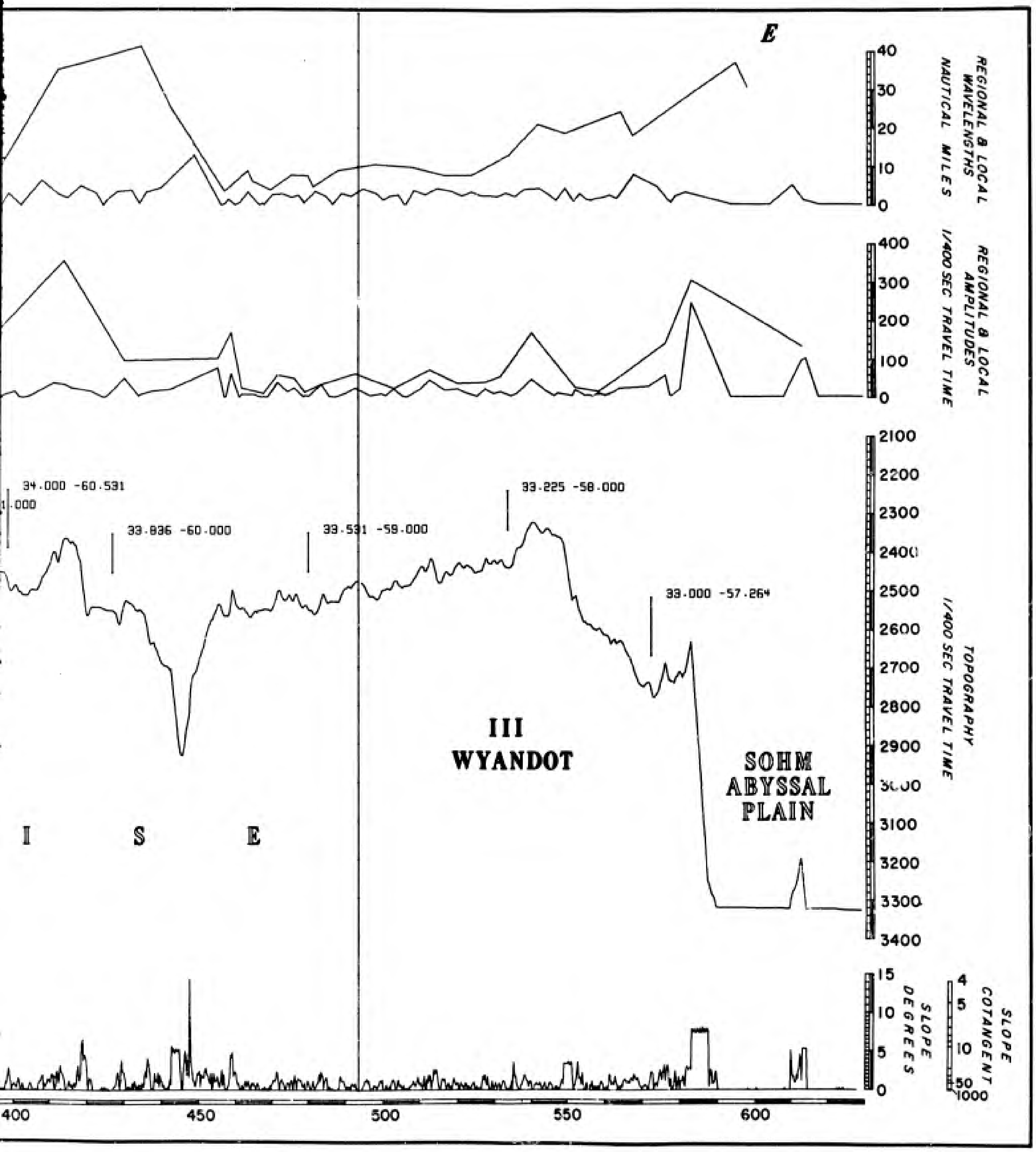
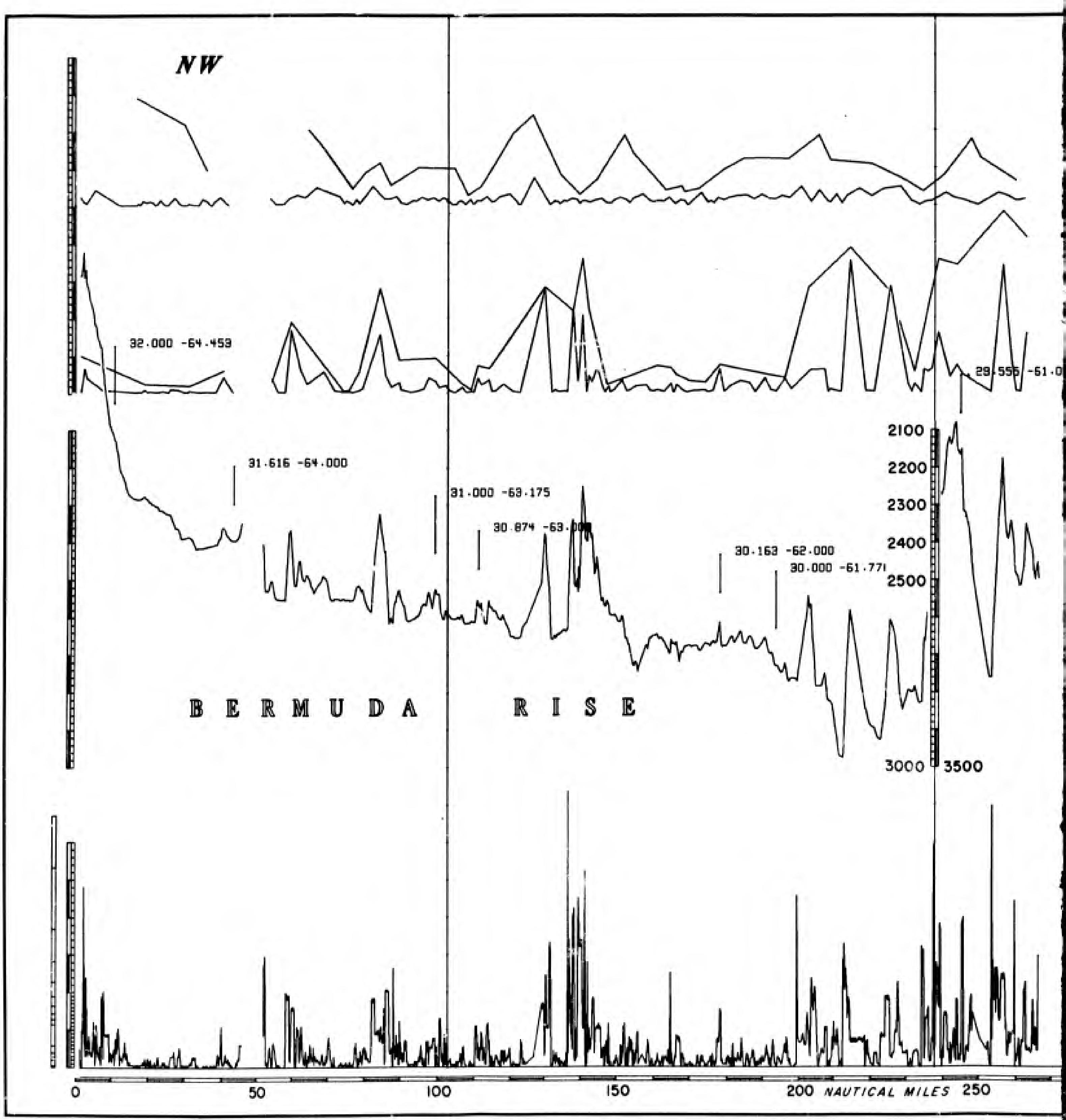
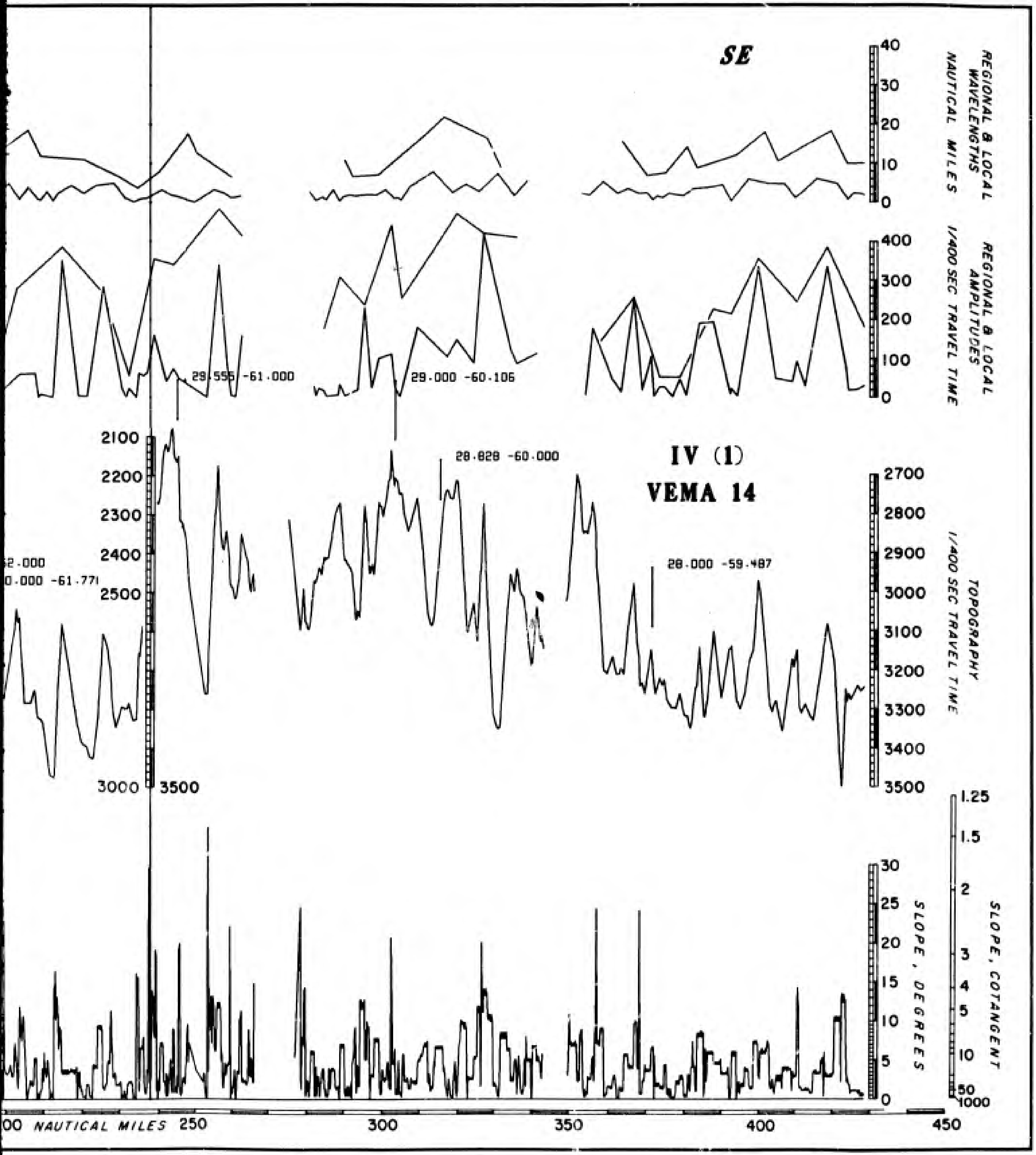

E
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
40
30
20
10
0
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
400
300
200
100
0
34.000 -60.531
33.836 -60.000
33.531 -59.000
33.225 -58.000
33.000 -57.264
III
WYANDOT
SOHM
ABYSSAL
PLAIN
I S E
TOPOGRAPHY
1/400 SEC TRAVEL TIME
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
SLOPE DEGREES
15
10
5
0
SLOPE COTANGENT
4
5
10
50
1000
400
450
500
550
600

Plate III



NW
32.000 -64.453
31.616 -64.000
31.000 -63.175
30.874 -63.000
30.163 -62.000
30.000 -61.771
29.555 -61.0
2100
2200
2300
2400
2500
3000
3500
B E R M U D A R I S E
0
50
100
150
200 NAUTICAL MILES 250

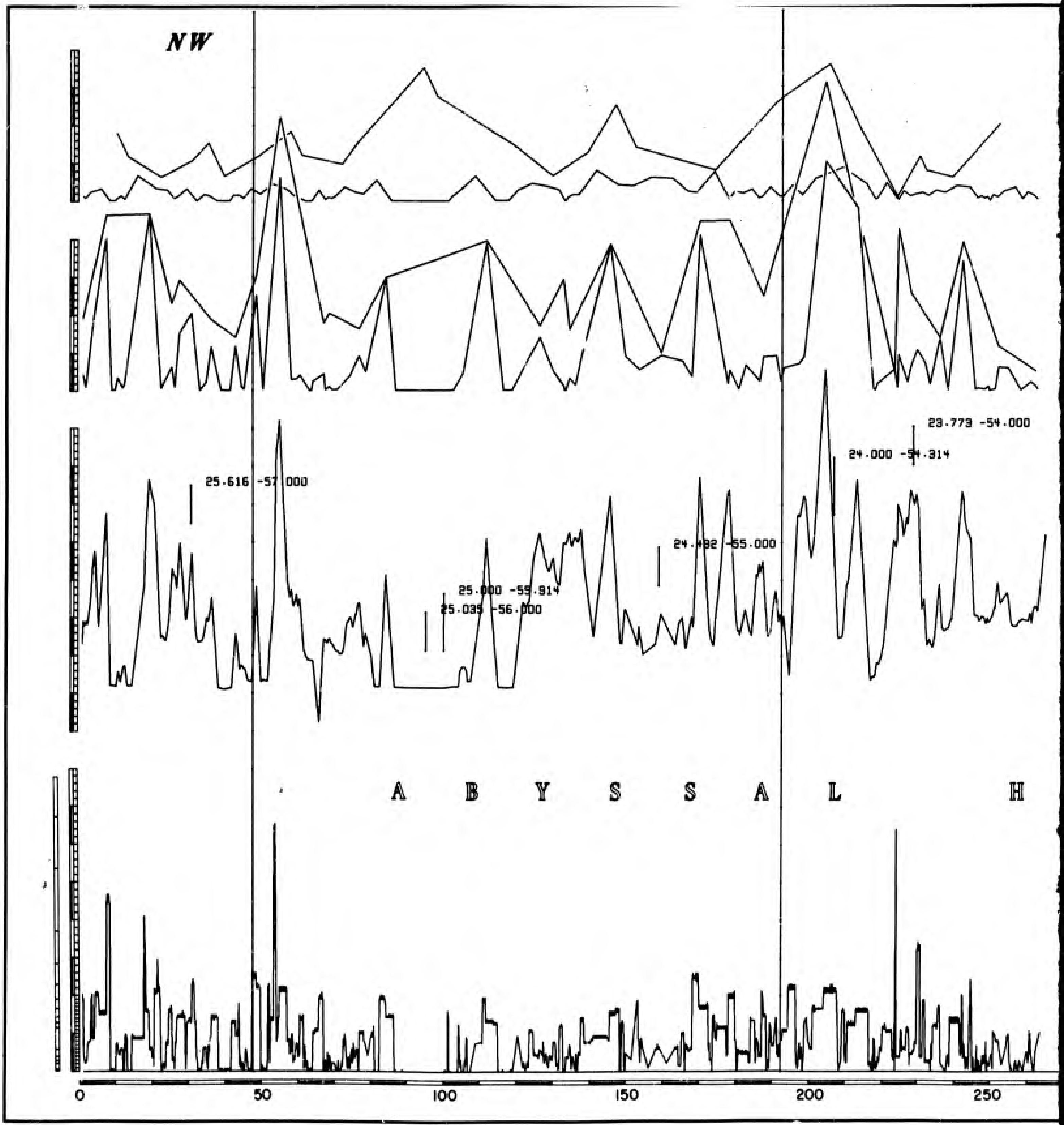
A,



SE
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
40
30
20
10
0
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
400
300
200
100
0
29.555 -61.000
29.000 -60.106
28.828 -60.000
28.000 -59.487
IV (1)
VEMA 14
2100
2200
2300
2400
2500
3000
3500
2.000
0.000 -61.771
TOPOGRAPHY
1/400 SEC TRAVEL TIME
2700
2800
2900
3000
3100
3200
3300
3400
3500
SLOPE, DEGREES
30
25
20
15
10
5
0
SLOPE, COTANGENT
1.25
1.5
2
3
4
5
10
50
1000
00 NAUTICAL MILES 250
300
350
400
450

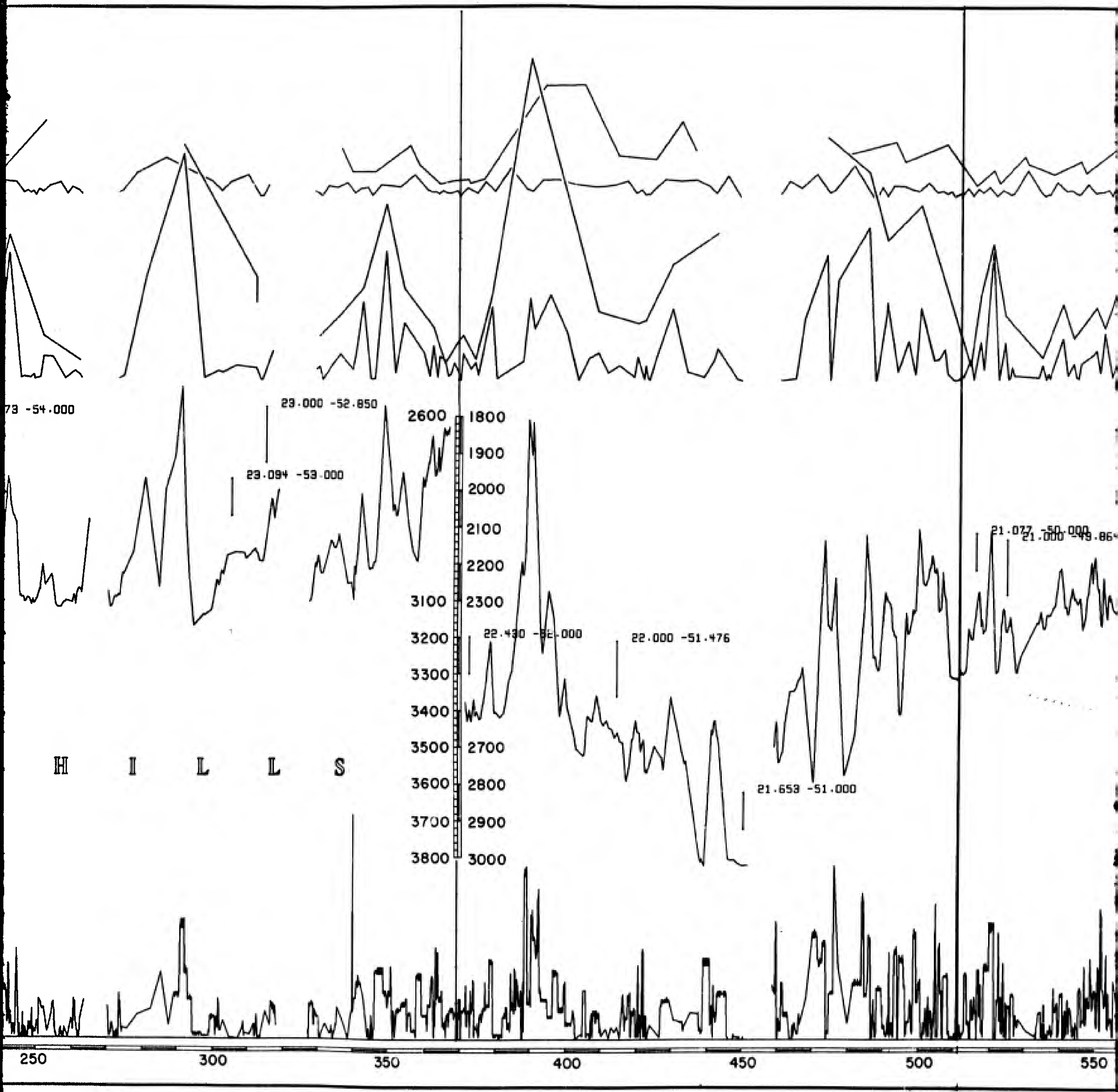
Plate IV (1)

B.



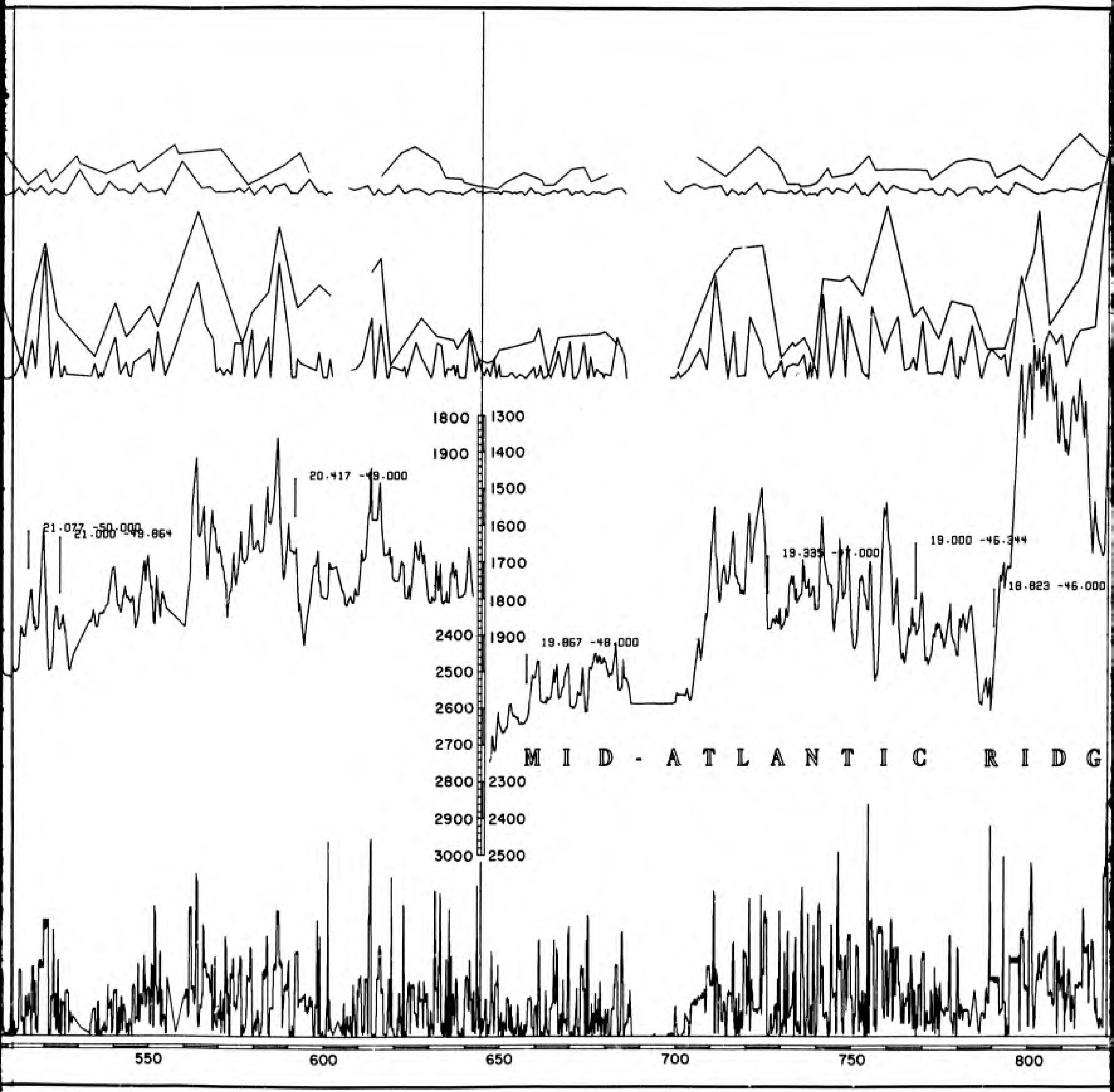
NW
25.616 -57.000
25.000 -55.914
25.035 -56.000
24.482 -55.000
24.000 -54.314
23.773 -54.000
A B Y S S A L H
0
50
100
150
200
250

A.



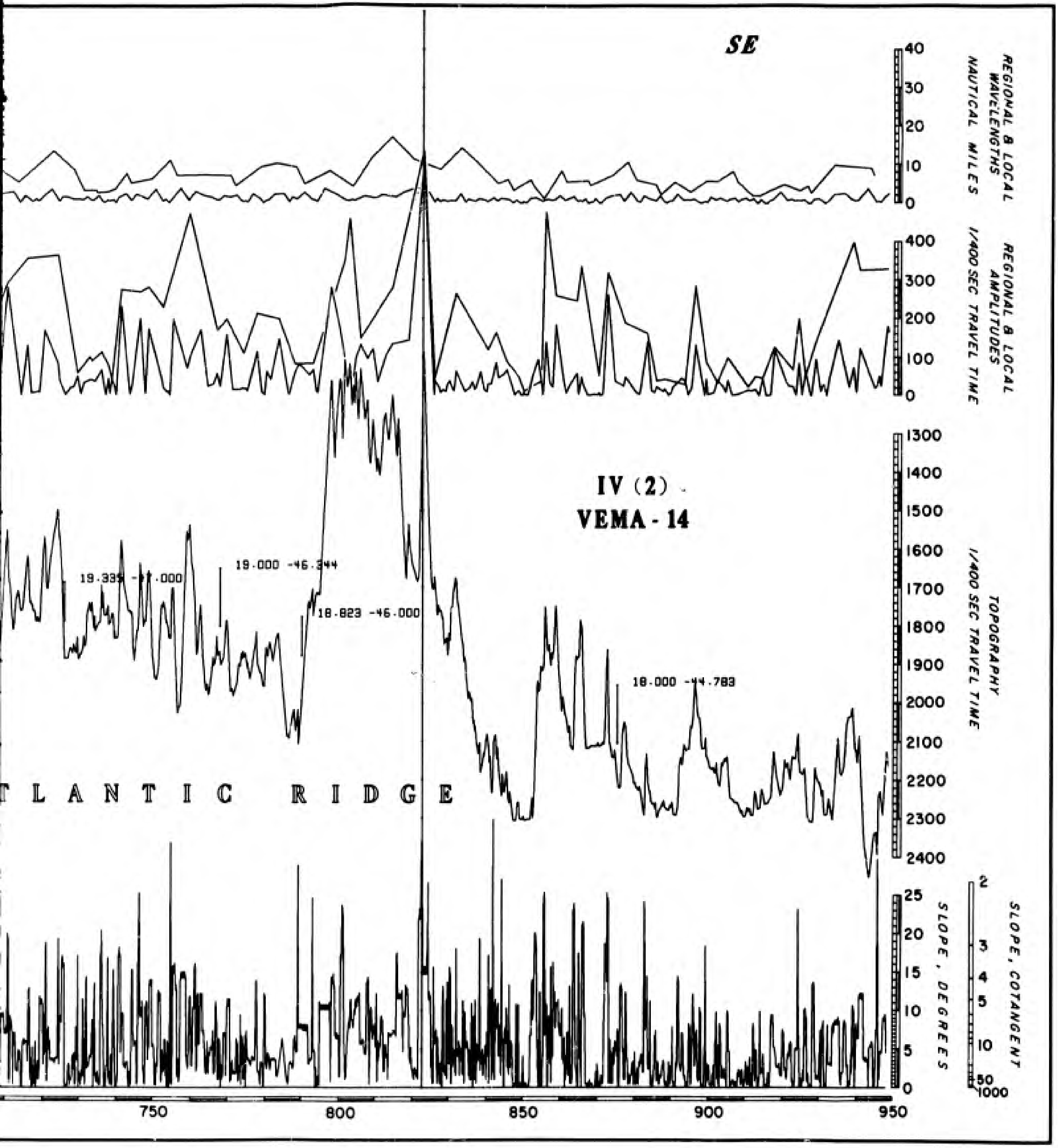
23.000 -52.850
23.094 -53.000
22.000 -51.476
21.653 -51.000
2600
3100
3200
3300
3400
3500
3600
3700
3800
1800
1900
2000
2100
2200
2300
2700
2800
2900
3000
H I L L S
250
300
350
400
450
500
550

B.



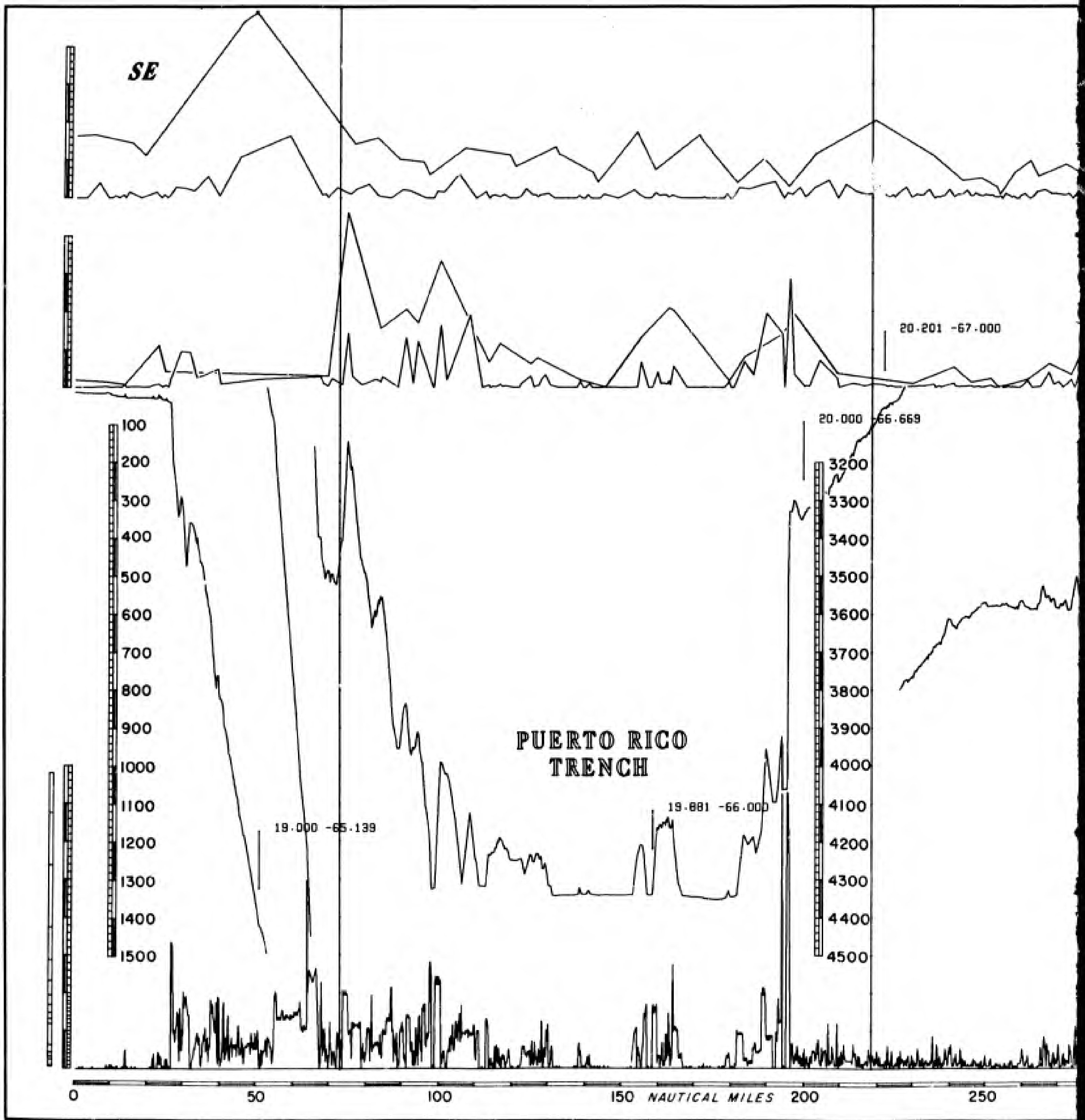
1800
1900
2400
2500
2600
2700
2800
2900
3000
1300
1400
1500
1600
1700
1800
1900
2300
2400
2500
21.077 -50.000
21.000 -49.864
20.417 -49.000
19.867 -48.000
19.335 -47.000
19.000 -46.344
18.823 -46.000
MID-ATLANTIC RIDG
550
600
650
700
750
800

C.



SE
40
30
20
10
0
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
400
300
200
100
0
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
TOPOGRAPHY
1/400 SEC TRAVEL TIME
IV (2)
VEMA - 14
19.000 -46.344
18.823 -46.000
18.000 -44.783
TLANTIC RIDGE
25
20
15
10
5
0
SLOPE, DEGREES
2
3
4
5
10
50
1000
SLOPE, COTANGENT
750
800
850
900
950

Plate IV (2)


SE
20.201 -67.000
20.000 -66.669
PUERTO RICO
TRENCH
19.000 -65.139
19.881 -66.000
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
4300
4400
4500
0
50
100
150 NAUTICAL MILES 200
250

A.

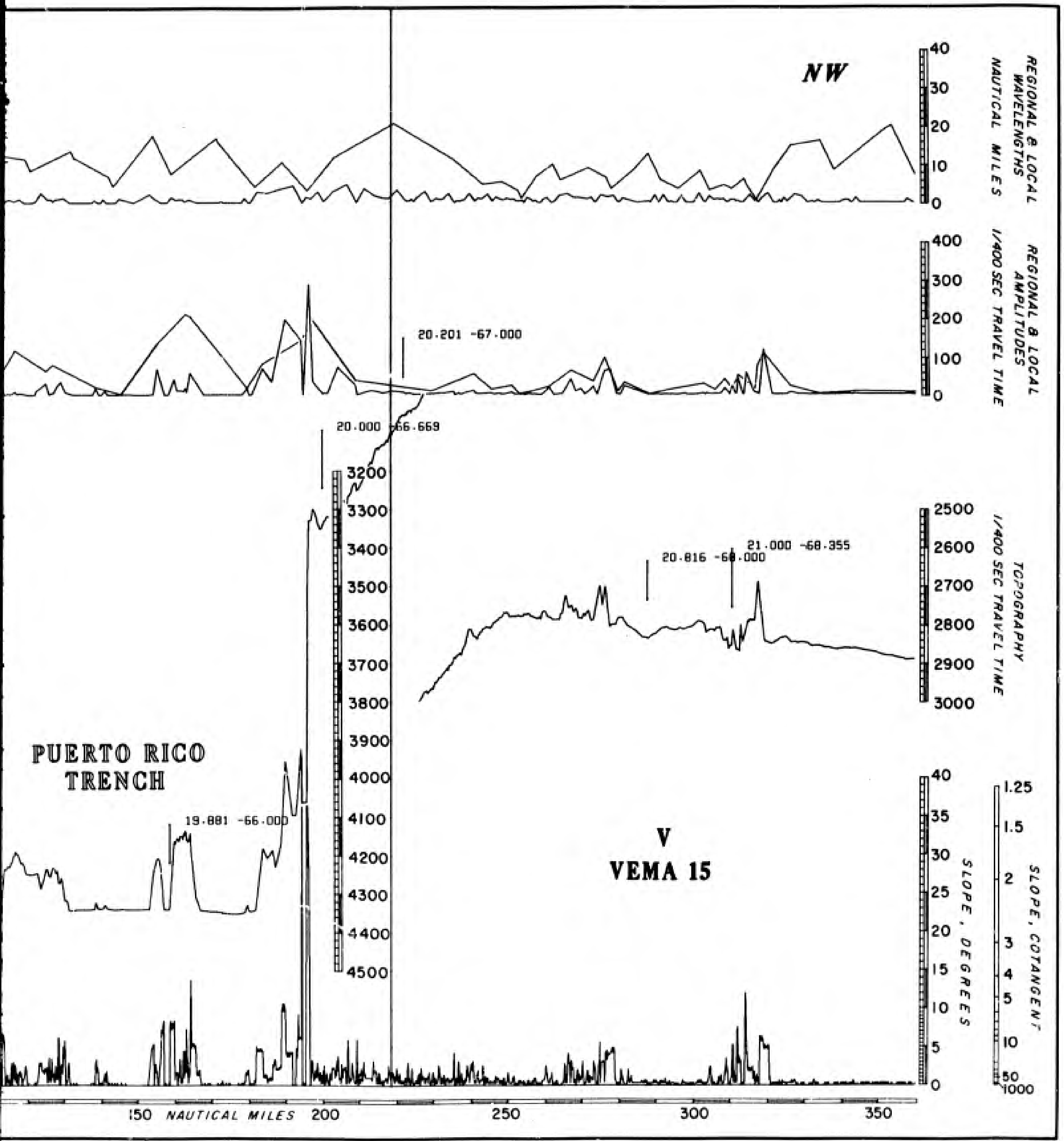
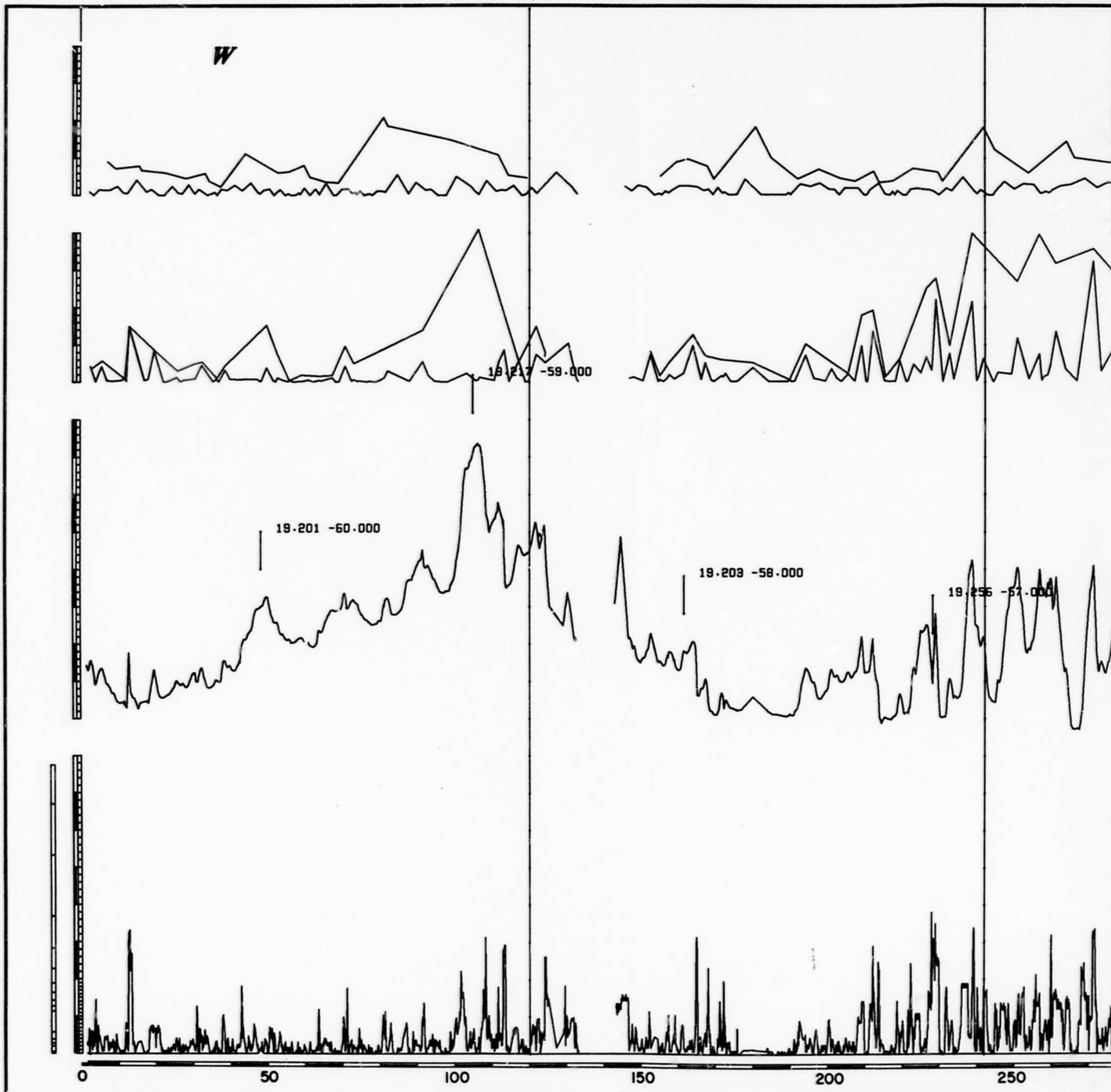
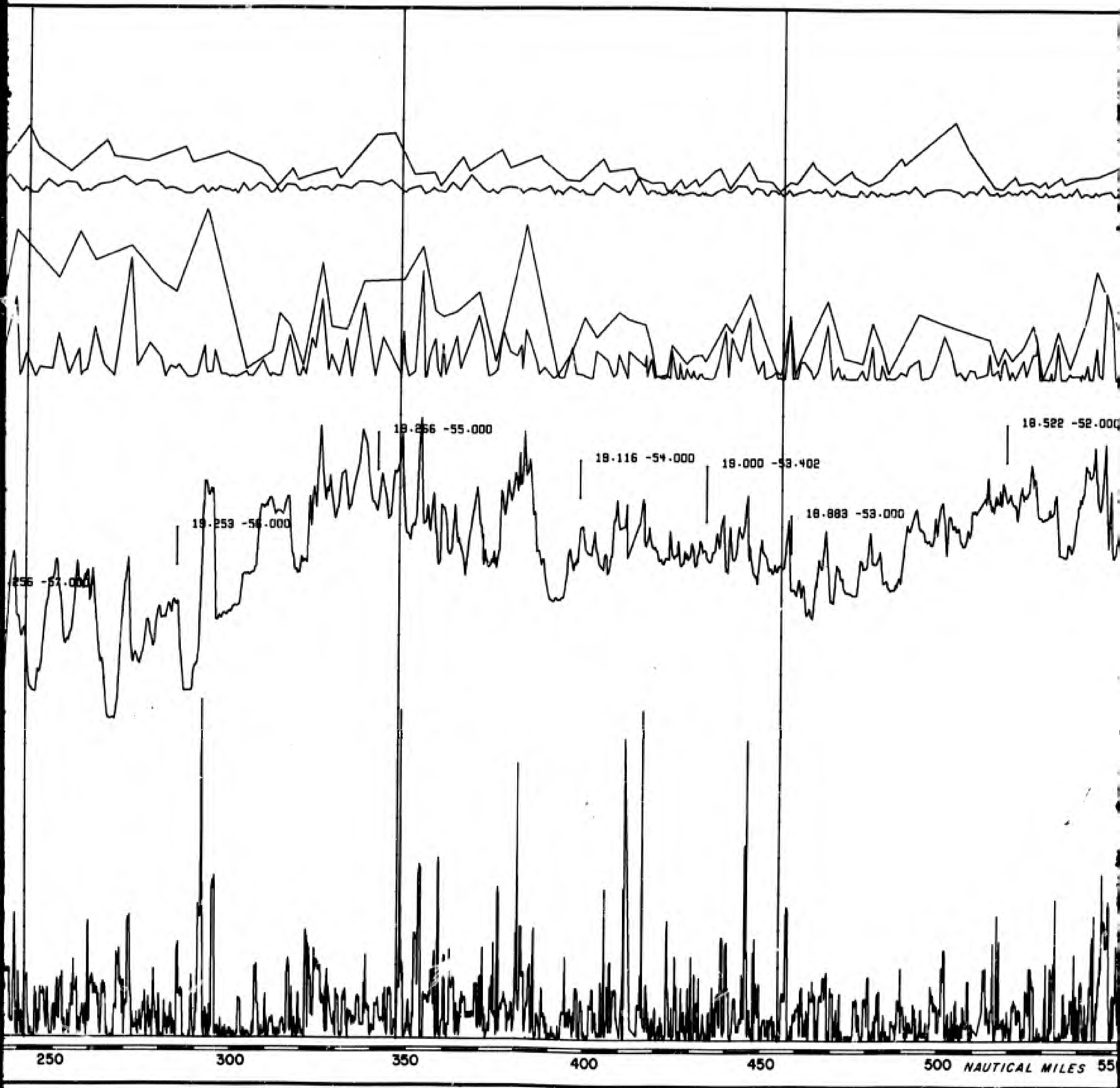

NW
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
TOPOGRAPHY
1/400 SEC TRAVEL TIME
SLOPE, DEGREES
SLOPE, COTANGENT
20.201 -67.000
20.000 -66.669
21.000 -68.355
20.816 -68.000
19.881 -66.000
PUERTO RICO TRENCH
V
VEMA 15
150 NAUTICAL MILES 200
250
300
350

Plate V

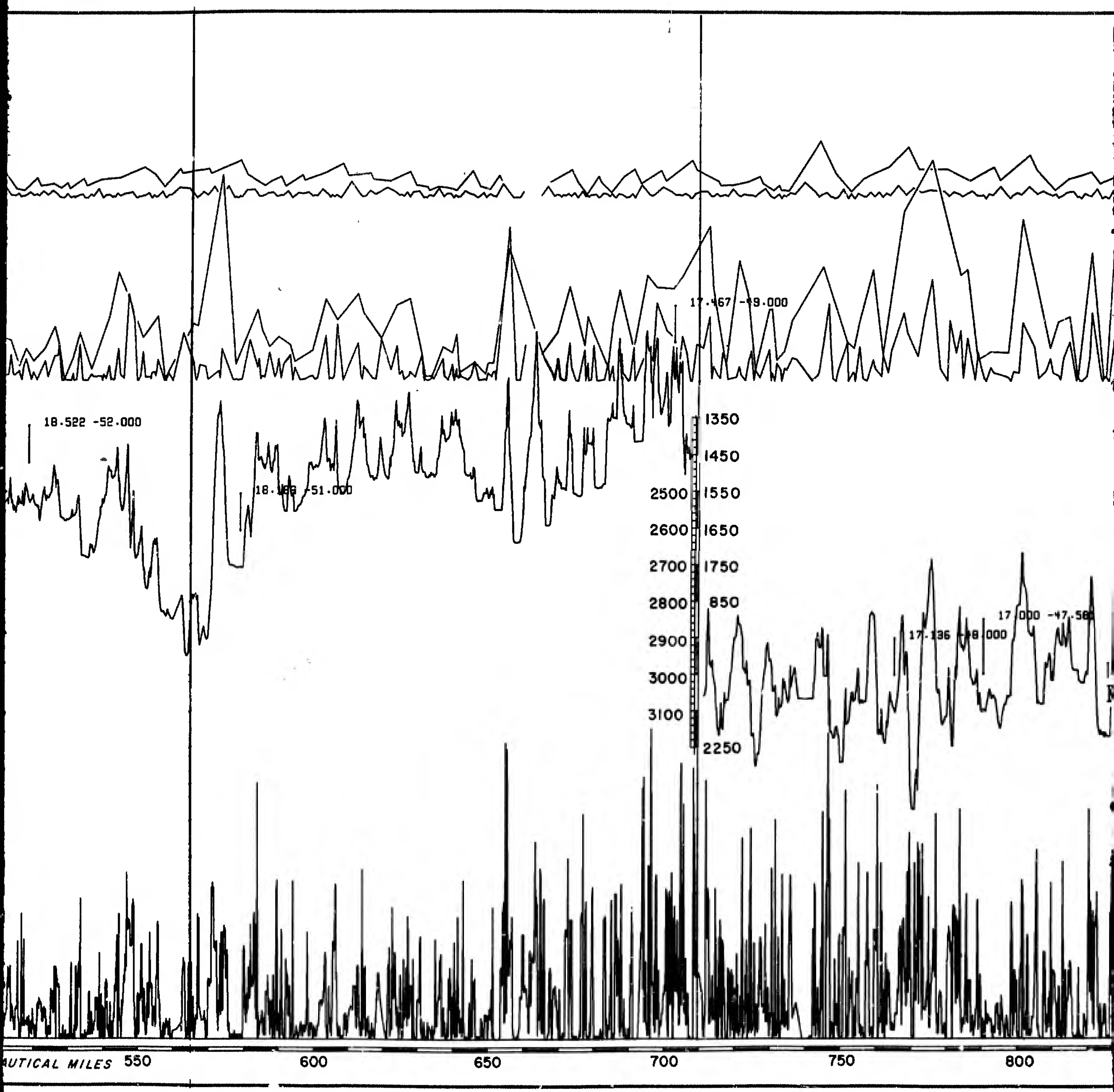

W
19.212 -59.000
19.201 -60.000
19.203 -58.000
19.256 -57.000
0
50
100
150
200
250

A.



19.253 -56.000
19.256 -55.000
19.116 -54.000
19.000 -53.402
18.883 -53.000
18.522 -52.000
250
300
350
400
450
500 NAUTICAL MILES

B.



18.522 -52.000
17.467 -49.000
1350
1450
2500
1550
2600
1650
2700
1750
2800
850
2900
3000
3100
2250
17.136
17.000 -47.5
AUTICAL MILES
550
600
650
700
750
800

e.

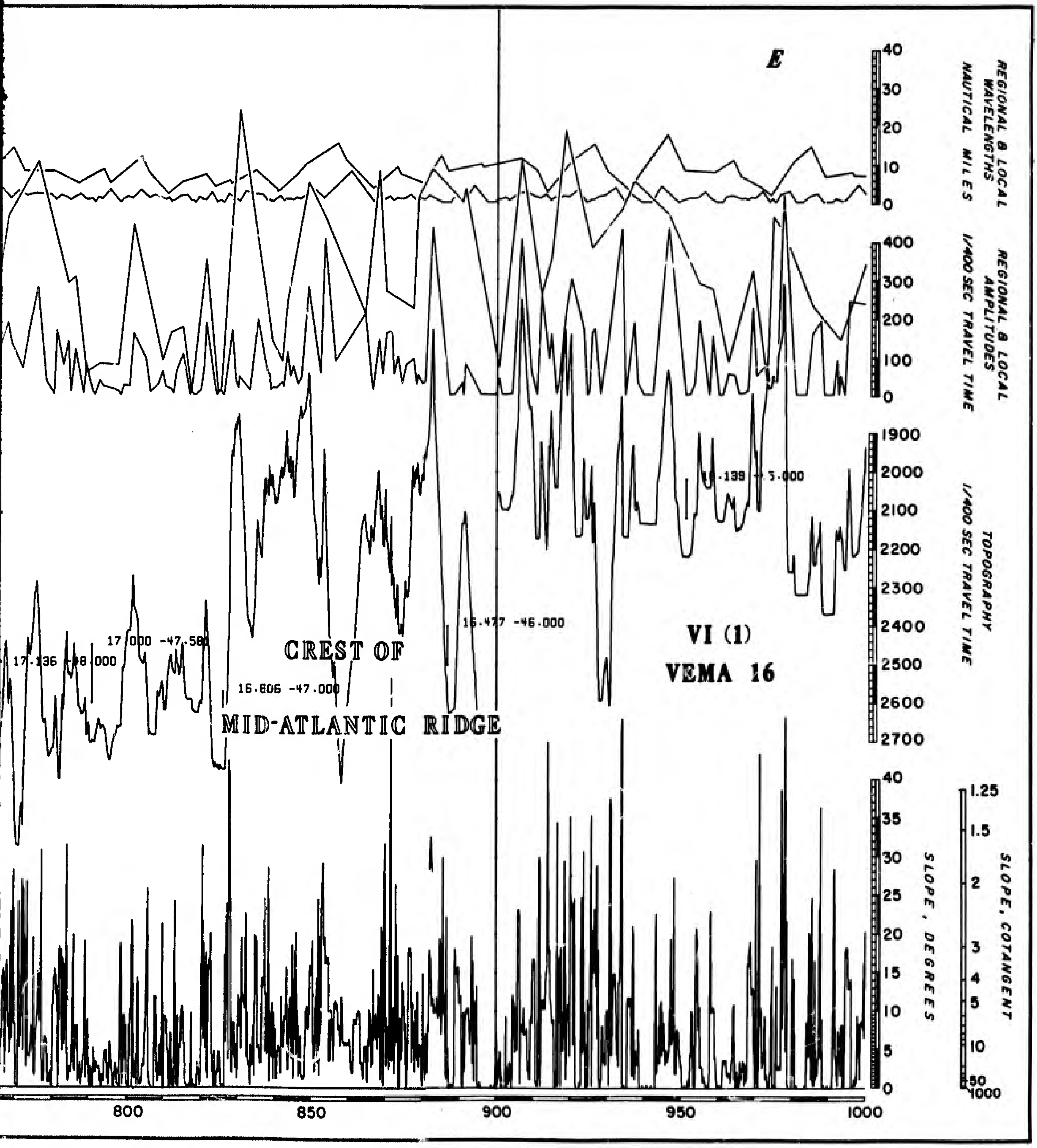
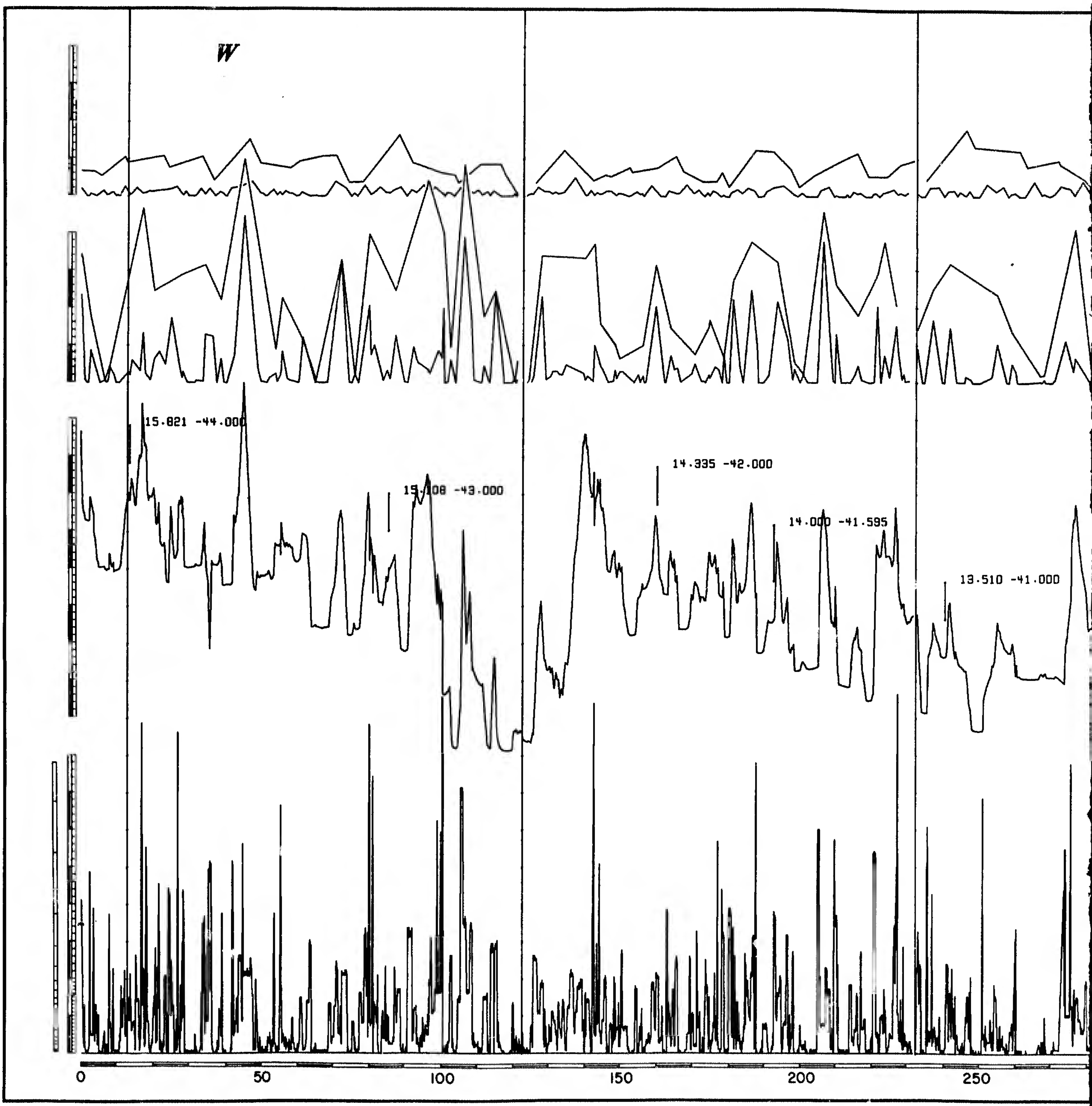
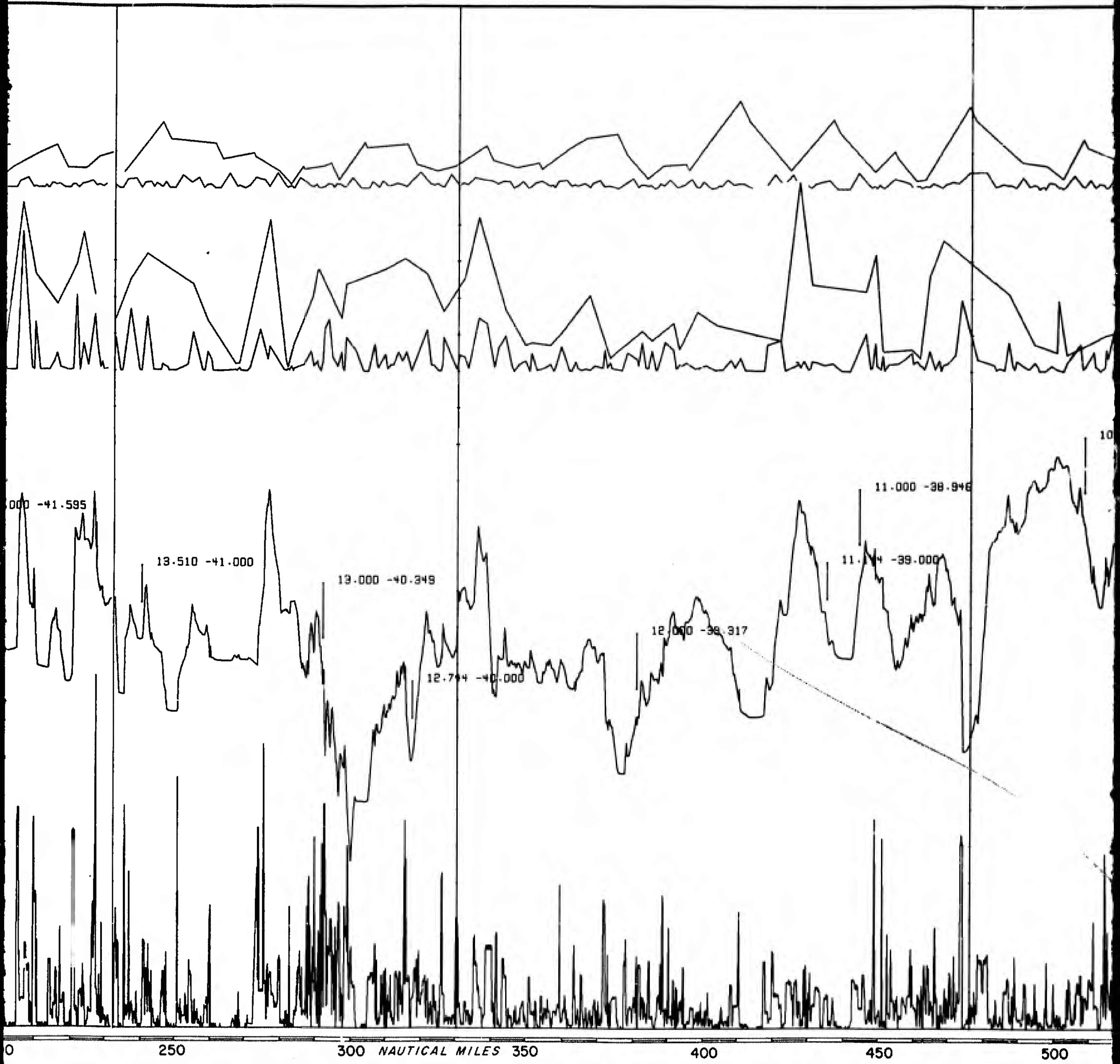

E
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
TOPOGRAPHY
1/400 SEC TRAVEL TIME
SLOPE, DEGREES
SLOPE, COTANGENT
16.606 -47.000
CREST OF
MID-ATLANTIC RIDGE
VI (1)
VEMA 16
800
850
900
950
1000

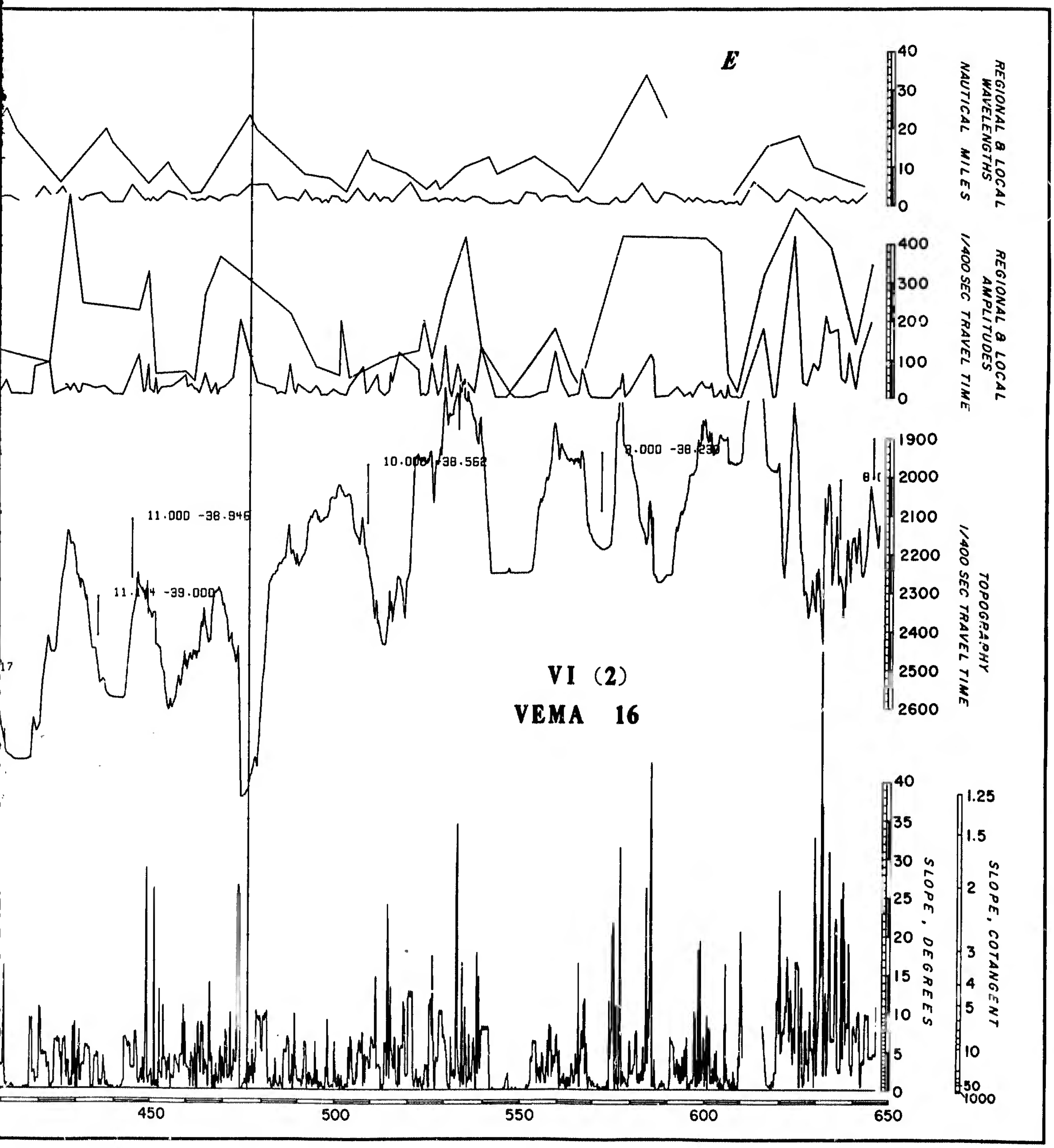
Plate VI (1)


W
15.821 -44.000
15.108 -43.000
14.335 -42.000
14.000 -41.595
13.510 -41.000
0
50
100
150
200
250

A1


13.510 -41.000
13.000 -40.349
11.000 -38.946
250
300
NAUTICAL MILES
350
400
450
500

B.



E
REGIONAL & LOCAL WAVELENGTHS
NAUTICAL MILES
REGIONAL & LOCAL AMPLITUDES
1/400 SEC TRAVEL TIME
TOPOGRAPHY
1/400 SEC TRAVEL TIME
11.000 -38.946
11.1?4 -39.000
10.000 -38.562
9.000 -38.23?
VI (2)
VEMA 16
SLOPE, DEGREES
SLOPE, COTANGENT
450
500
550
600
650

Plate VI (2)

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

PATTERNS OF RELATIVE RELIEF, SLOPE, AND TOPOGRAPHIC TEXTURE IN THE NORTH ATLANTIC OCEAN

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (Last name, first name, initial)

Holcombe, Troy L.
Heezen, Bruce C.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 11, 1970	133	57

8a. CONTRACT OR GRANT NO. Navships Ocean Science Programs b. PROJECT NO. SR 104 0301 Task 8112 c. Contract N00024-67-C-1186 d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report #8 CU-8-70 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Naval Ship Systems Command Washington, D. C. 20360

13. ABSTRACT

Charts have been constructed which quantitatively define the distribution patterns of relative relief, slope, and topographic texture in the North Atlantic Ocean. Precision fathograms collected over a 12-year period at Lamont-Doherty Geological Observatory of Columbia University were reread at 1-minute intervals of ships's time, and these data, totaling about 300 thousand soundings, were digitized for computer processing. Six quantitative parameters, two for relative relief, two for slope, and two for topographic texture, were selected to describe and characterize the topography. These parameters were computed from the data and plotted as charts. Profiles of the raw parameters were plotted for illustrative purposes and for comparative studies. Roughness patterns were extrapolated by employing the North Atlantic physiographic provinces chart of Heezen, et al. (1959).

Once the quantitative characteristics of each physiographic province and sub-province were distinguishable, the slope data were then sub-divided into samples on the basis of physiographic similarity. Frequency distribution of slopes, and statistical parameters measuring central value and dispersion were then calculated.

The analyses of relative relief and mean bottom slope provide a basis of sub-dividing the North Atlantic into smooth provinces and rough provinces. Smooth provinces, where processes of sedimentation have been the dominant geomorphic

(continued)

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Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
North Atlantic patterns of relative relief						
North Atlantic slope						
North Atlantic topographic texture						
North Atlantic geomorphology						
Mid-Atlantic Ridge topography and sedimentation tectonics, and volcanism						
Mid-Oceanic Ridge and abyssal hills						
North Atlantic Physiographic provinces						
Precision Depth Recorder (PDR) echograms						
North Atlantic seamounts						
North Atlantic abyssal plains						
North Atlantic plateaus						
North Atlantic outer ridges						

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Unclassified

Security Classification

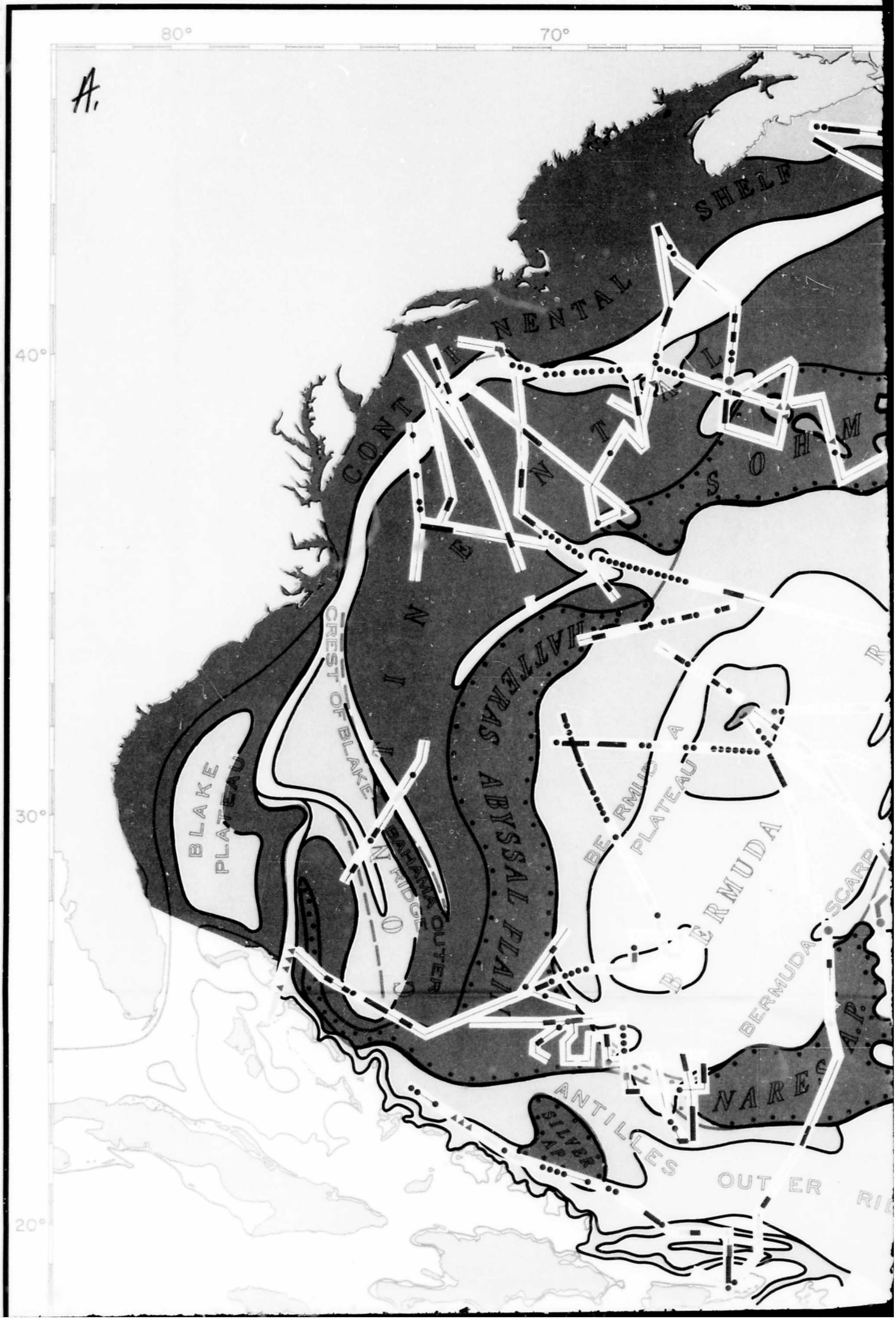
Abstract (continued)

agent, were defined as having relief generally less than 50 echo time units (tau) and mean bottom slope generally less than 1:50. Rough provinces, were tectonism and volcanism have been predominant in shaping the topography, were defined as having relief generally greater than 50 tau and mean bottom slope generally greater than 1:50.

The abyssal plains, obviously, constitute the areas of lowest relief and slope in the North Atlantic. Generally low though locally moderate relief, gentle slopes (except on the continental slope), and many areas of small-scale texture characterize the continental margin provinces. A wide range of roughness, from gently undulating, low relief topography to local belts of extremely rugged topography, occur on the North Atlantic oceanic rises. The highest relief and steepest slopes in the North Atlantic characterize the crest of the Mid-Atlantic Ridge throughout its extent as well as the outer flanks of the ridge and the abyssal hills between latitudes 20° and 30°N. In contrast: The relief and slopes of the ridge flanks north of latitude 30° and south of latitude 20° are gently undulating to rough, varying with the degree of burial by sedimentation.

Slopes for much Mid-Atlantic Ridge topography fall into three categories: 1) gentle slopes, generally less than 5 degrees with a strong mode at zero degrees, reflecting flat-floored sedimentary basins and gently undulating sediment-subdued topography, 2) intermediate range slopes, generally 5-15 degrees, which characterize the hillside slopes of the primary basement relief, and 3) the steep slopes, generally greater than 12-15 degrees, which describe the steep-faced tectonic scarps.

The hillside slopes of the basement relief are remarkably symmetrical and of fairly uniform steepness. They are thought to reflect the angle of repose of extrusive lavas associated with the extensional tectonics of the Mid-Oceanic Ridge crest. Most of the tectonic activity involved in shaping the present ocean bottom is thought to be secondary to the volcanism, acting on the already rugged basement relief. No direct relationship is observed between the steepness of the hillside slopes of the primary relief and either the size of the relief or the rate of sea-floor extension.


A.
80°
70°
40°
30°
20°
CONTINENTAL SHELF
BLAKE PLATEAU
CREST OF BLAKE
BAHAMA OUTER RIDGE
HATTERAS ABYSSAL PLAIN
BERMUDA PLATEAU
BERMUDA
BERMUDA SCARP
BERMUDA
NARES A.P.
SILVER A.P.
ANTILLES OUTER RIDGE

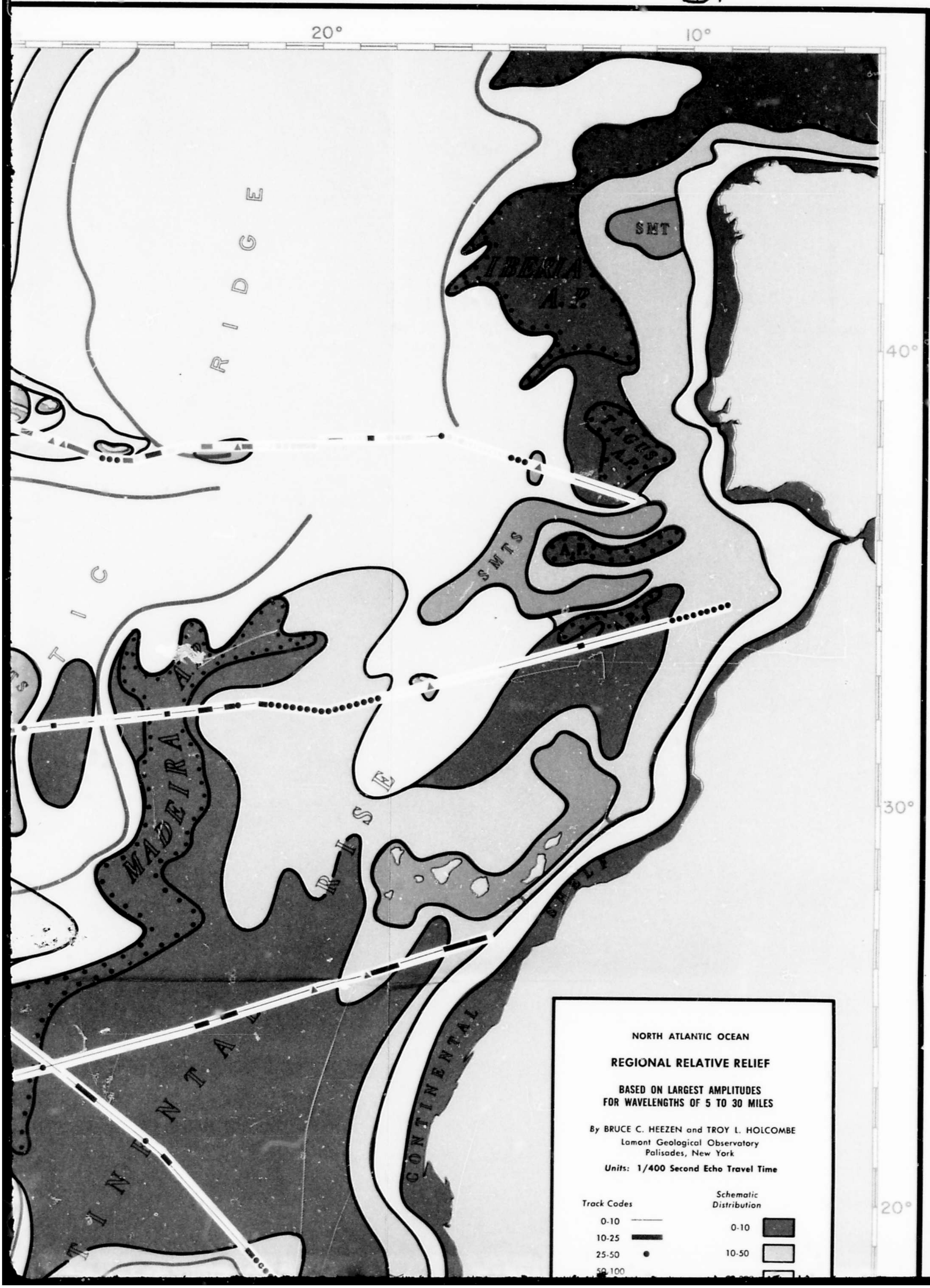
B.


60°
50°
40°
SHELF
R I S E
NEWFOUNDLAND RIDGE
S O H M
A B Y S S A L P L A I N
CORNER
RISE
RISE
BERMUDA
ZONE
SCARP
BERMUDA
Abyssal
Hills
NARES
OUTER RIDGE
Aby ssal
Hil
ATLANTIC
MID

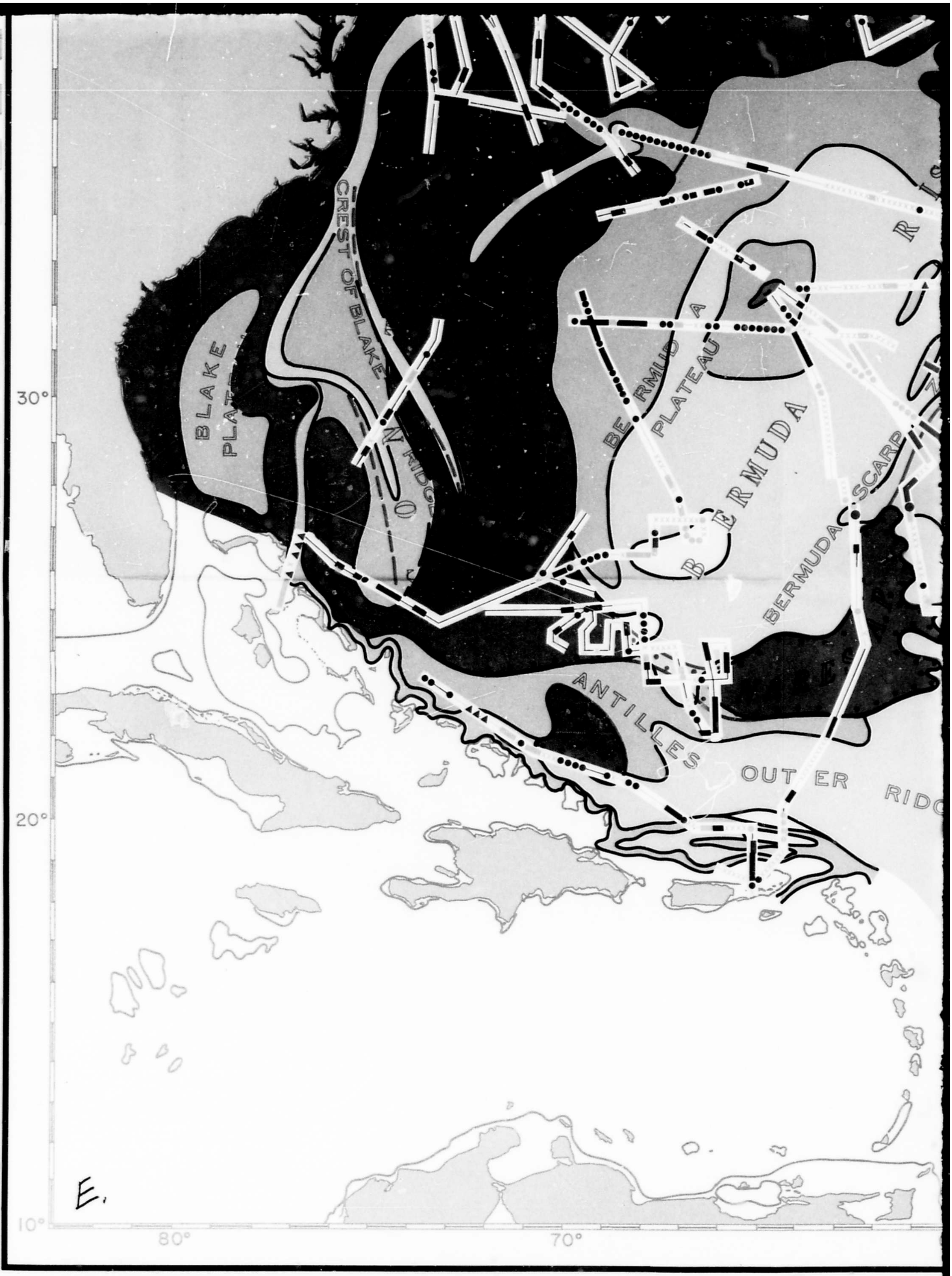
C.

40°
30°
20°
ABYSSAL PLAIN
Abyssal Hills
RIDGE
ATLANTIC RIDGE
MID ATLANTIC
SMTS
MADEIRA AP
KRYLOV RISE
RISE
Hills

D.



20°
10°
40°
30°
20°
RIDGE
SMT
IBERIA A.P.
TAGUS A.P.
SMTS
A.P.
MADEIRA A.P.
RISE
CONTINENTAL SHELF
NORTH ATLANTIC OCEAN
REGIONAL RELATIVE RELIEF
BASED ON LARGEST AMPLITUDES
FOR WAVELENGTHS OF 5 TO 30 MILES
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: 1/400 Second Echo Travel Time
Track Codes
0-10
10-25
25-50
50-100
Schematic Distribution
0-10
10-50



Geographic Distribution of Bottom Roughness in the North Atlantic — December 1965

CORNER
RISE
RISE
ATLANTIC
ZONE
MUDA
SCARP
BERMUDA
Abyssal
Hills
MID
OF MID
ATL
OF M
OUTER RIDGE
FLANK OF
CREST OF MID
FLANK
FL
F.
60°
50°
40°

ATLANTIC
KRYLOV RISE
CAPE VERDE
PLATEAU
CAPE VERDE A.P.
GAMBIA A.P.
SMTS
G.
40°
30°

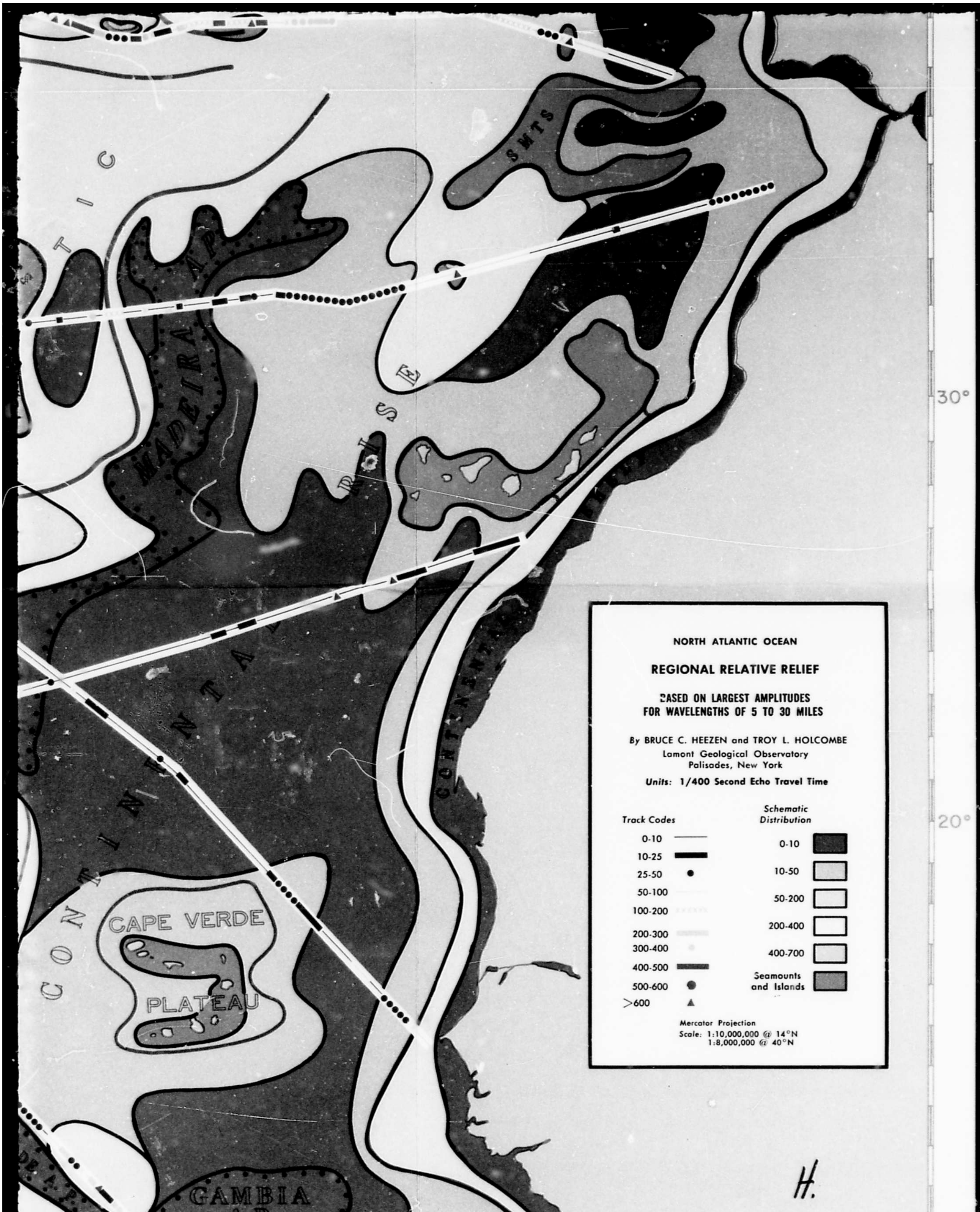
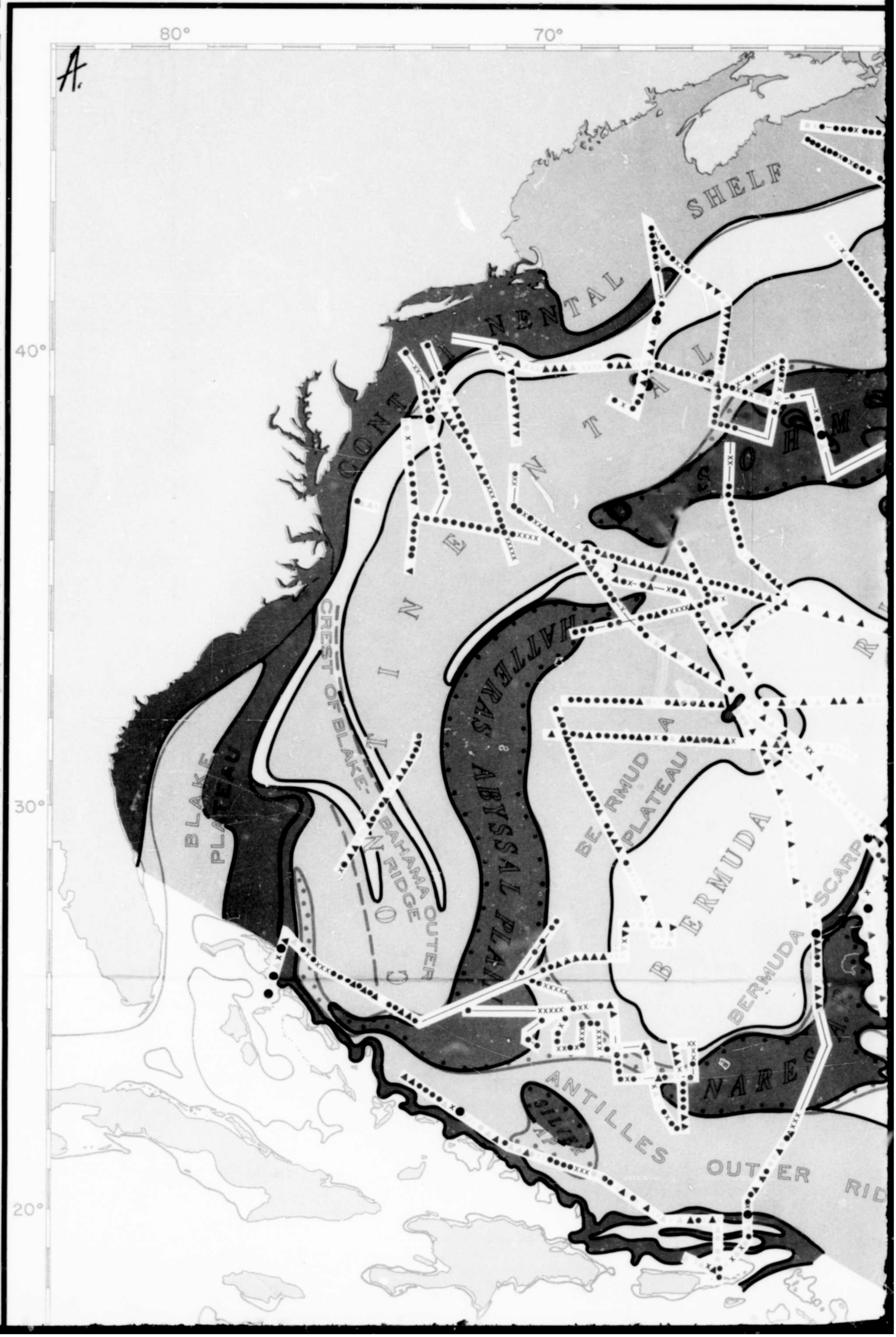

NORTH ATLANTIC OCEAN
REGIONAL RELATIVE RELIEF
BASED ON LARGEST AMPLITUDES FOR WAVELENGTHS OF 5 TO 30 MILES
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: 1/400 Second Echo Travel Time
Track Codes
0-10
10-25
25-50
50-100
100-200
200-300
300-400
400-500
500-600
>600
Schematic Distribution
0-10
10-50
50-200
200-400
400-700
Seamounts and Islands
Mercator Projection
Scale: 1:10,000,000 @ 14°N
1:8,000,000 @ 40°N
SMTS
MADEIRA A.P.
RISE
CONTINENTAL
CONTINENTAL
CAPE VERDE
PLATEAU
GAMBIA A.P.
DAVID C. JOHNSON
H.
30°
20°
10°
20°
10°

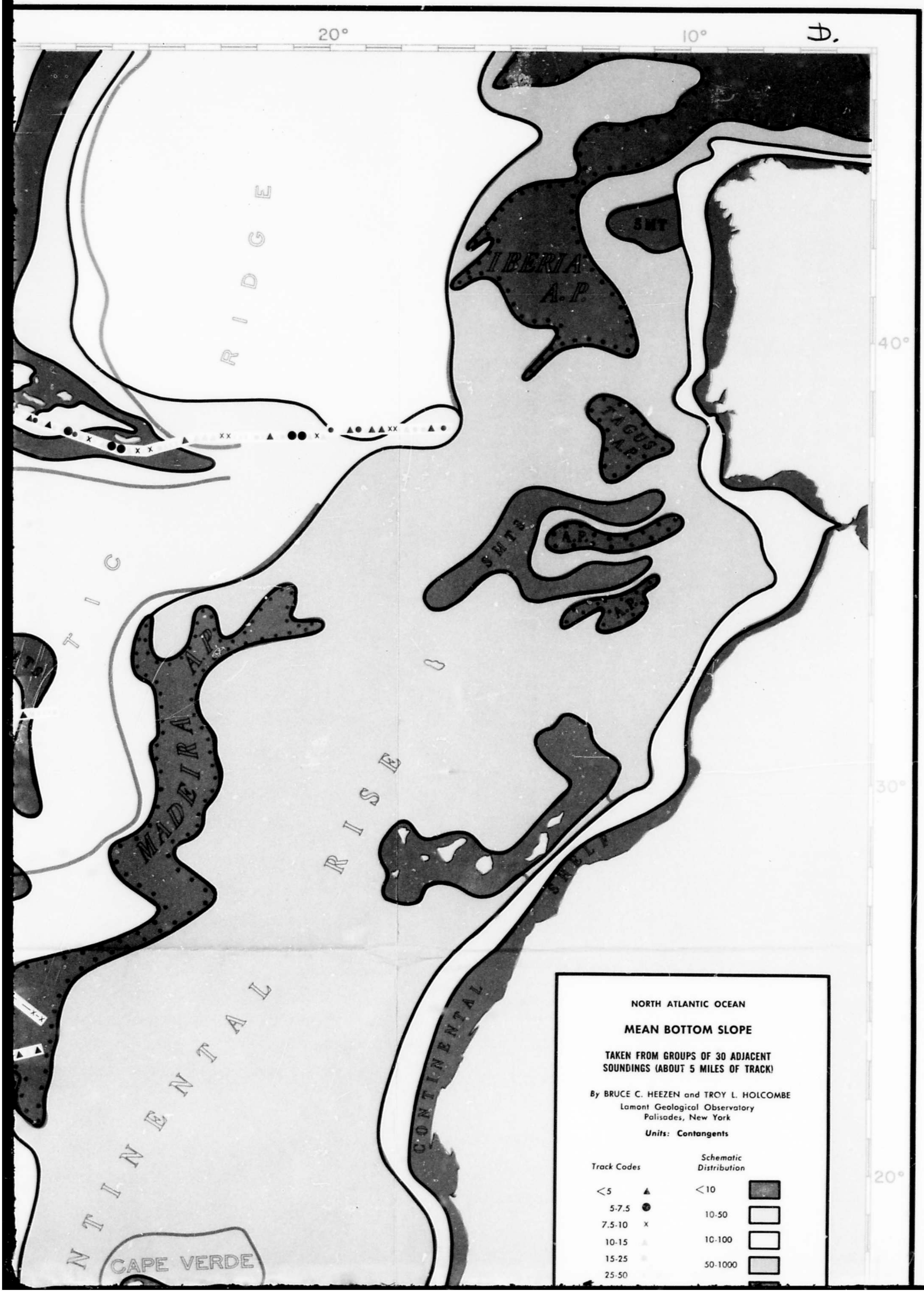
CHART 1


A.
80°
70°
40°
30°
20°
CONTINENTAL SHELF
CONTINENTAL RISE
HATTERAS ABYSSAL PLAIN
SOHM
BLAKE PLATEAU
CREST OF BLAKE-BAHAMA OUTER RIDGE
BERMUDA PLATEAU
BERMUDA
BERMUDA SCARP
BERMUDA RISE
NARES
ANTILLES OUTER RIDGE
SILVER APR

B.


60°
50°
40°
SHELF
RISE
NEWFOUNDLAND RIDGE
SOHM
ABYSSAL PLAIN
Abyssal Hills
CORNER RISE
RISE
BERMUDA
BERMUDA SCARP ZONE
Abyssal Hills
NARES
OUTER RIDGE
MID ATLANTIC
OF MID
CREST
FLANK OF


40°
30°
20°
NEWFOUNDLAND ABYSSAL PLAIN
Abyssal Hills
RIDGE
RIDGE
RIDGE
MID ATLANTIC RIDGE
ATLANTIC
ATLANTIC
ATLANTIC
FLANK OF MID ATLANTIC RIDGE
MADEIRA AP
Hills
KRYLOV RISE
NTINENTAL RISE
CAPE VERDE


D.
20°
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RIDGE
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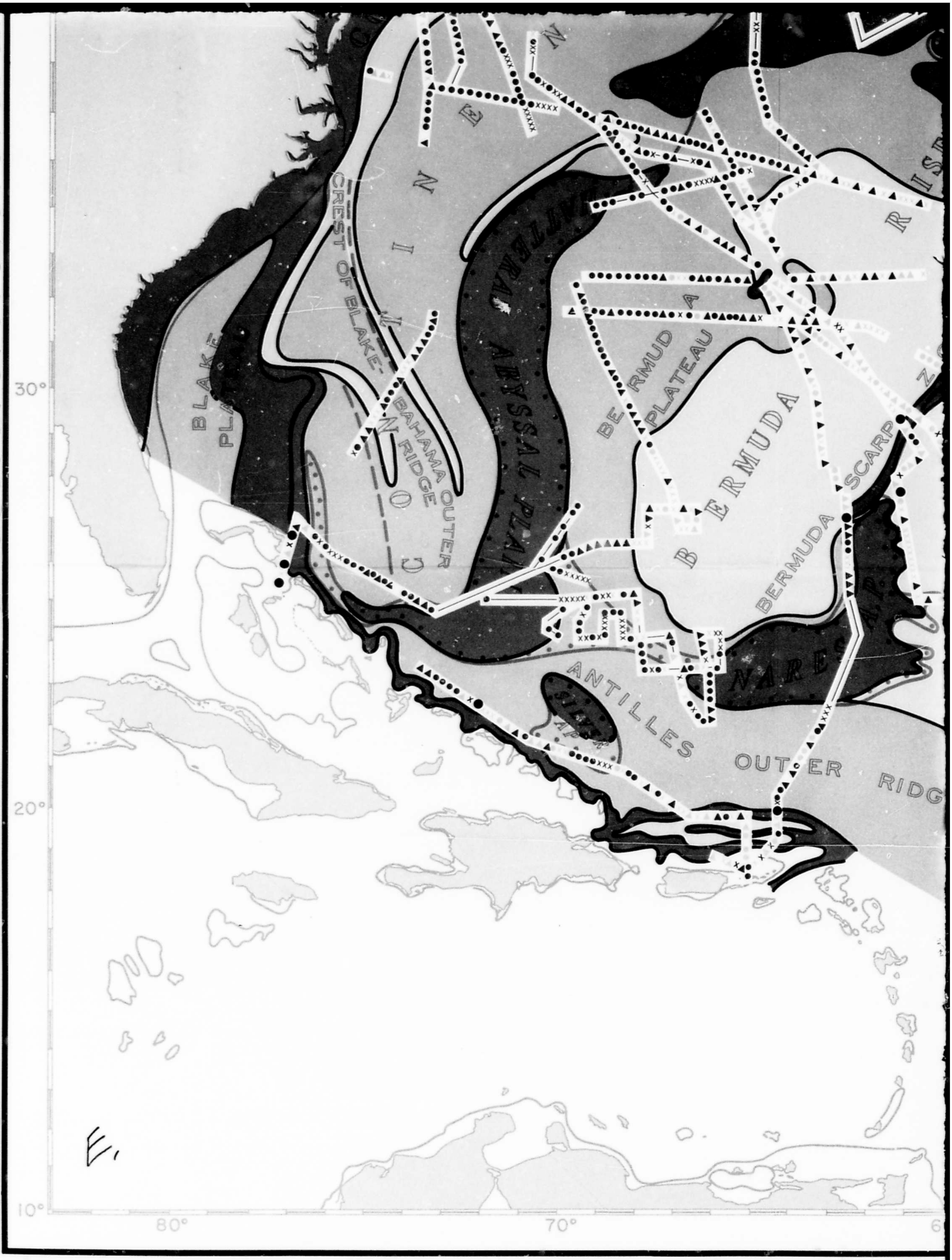
IBERIA A.P.
TAGUS A.P.
SMTS
A.P.
A.P.
MADEIRA A.P.
RISE
NTINENTAL
CONTINENTAL SHELF
CAPE VERDE
NORTH ATLANTIC OCEAN
MEAN BOTTOM SLOPE
TAKEN FROM GROUPS OF 30 ADJACENT SOUNDINGS (ABOUT 5 MILES OF TRACK)
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Contangents
Track Codes
<5
5-7.5
7.5-10
10-15
15-25
25-50
Schematic Distribution
<10
10-50
10-100
50-1000



Geographic Distribution of Bottom Roughness in the North Atlantic — December 1965


RISE
CORNER
ISE
ATLANTIC
ZONE
SCARP
BERMUDA
UDA
Abyssal
Hills
ARES
A.P.
OF MID
MID
OF
FLANK OF
CREST
FLANK
OUTER RIDGE
F.
60°
50°
40°


ATLANTIC
ATLANTIC
MID ATLANTIC
FLANK OF MID ATLANTIC
MADEIRA A.P.
RISE
CONTINENTAL RISE
Abyssal Hills
KRYLOV RISE
CAPE VERDE PLATEAU
CAPE VERDE A.P.
GAMBIA A.P.
CONTINENT
G.
40°
30°
20°

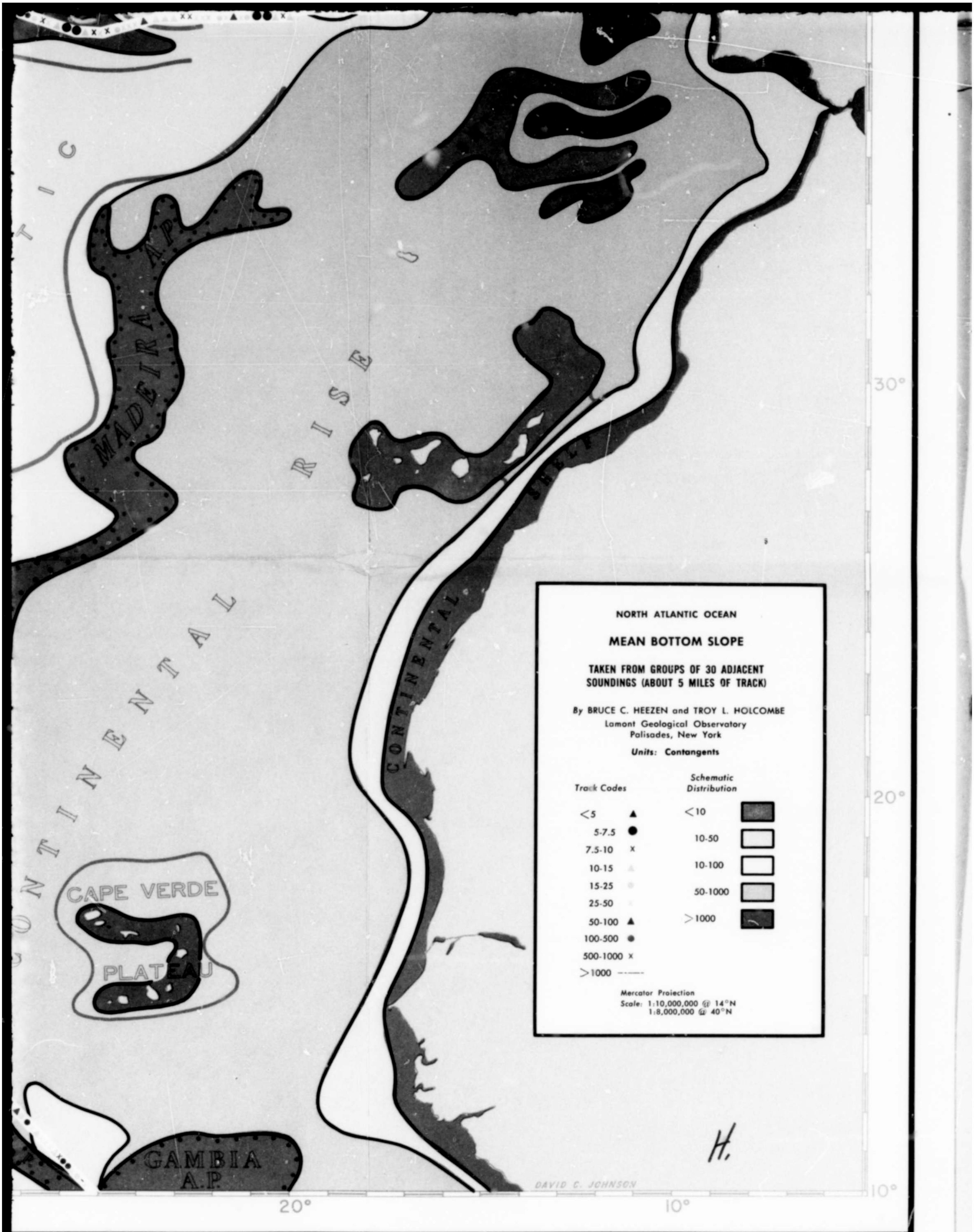

NORTH ATLANTIC OCEAN
MEAN BOTTOM SLOPE
TAKEN FROM GROUPS OF 30 ADJACENT SOUNDINGS (ABOUT 5 MILES OF TRACK)
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Contangents
Track Codes
<5
5-7.5
7.5-10
10-15
15-25
25-50
50-100
100-500
500-1000
>1000
Schematic Distribution
<10
10-50
10-100
50-1000
>1000
Mercator Projection
Scale: 1:10,000,000 @ 14°N
1:8,000,000 @ 40°N
MADEIRA A.P.
CONTINENTAL RISE
CONTINENTAL SHELF
CAPE VERDE PLATEAU
GAMBIA A.P.
DAVID C. JOHNSON
H.
30°
20°
10°
20°
10°

CHART 2

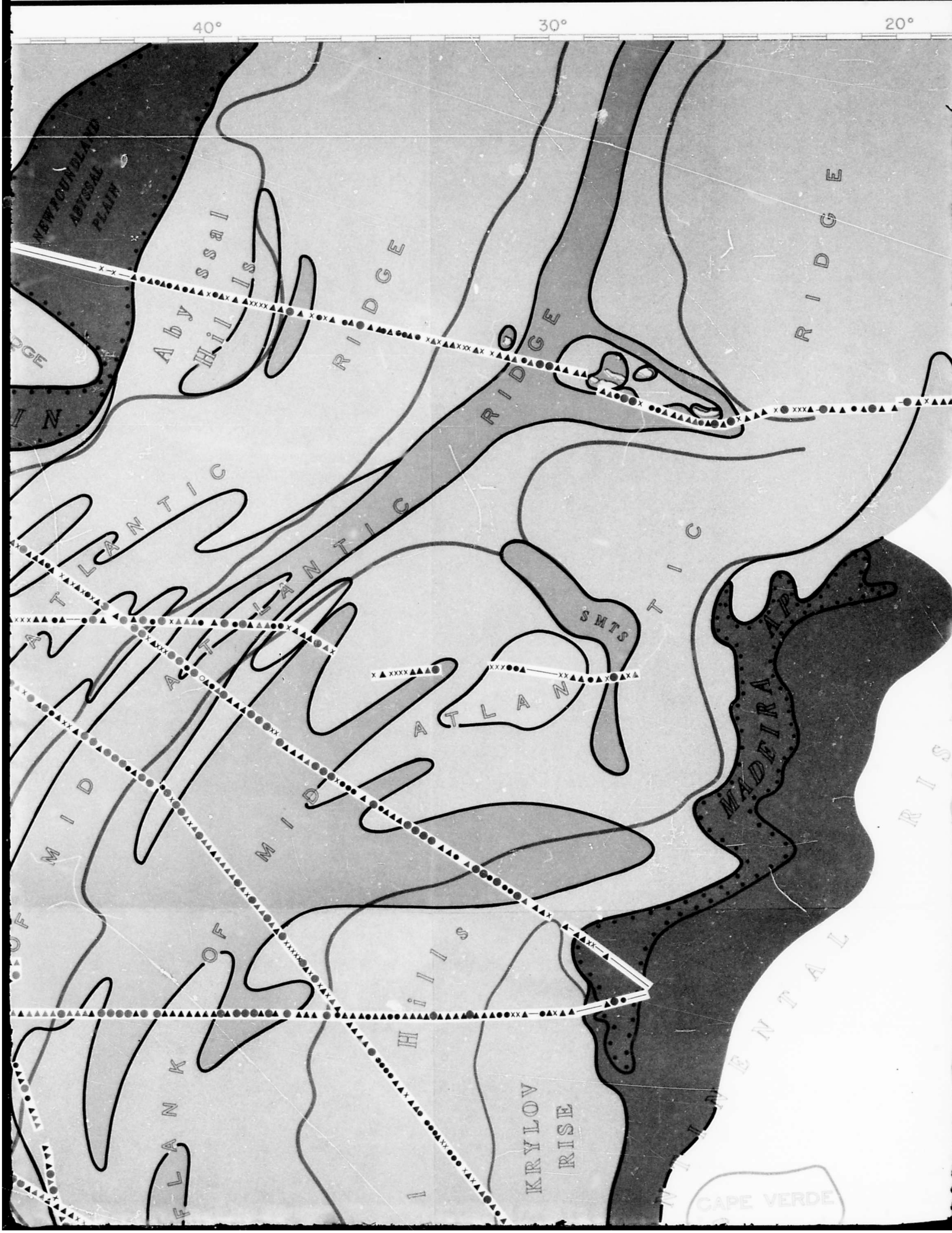
A.

80°
70°
40°
30°
20°
CONTINENTAL SHELF
BLAKE PLATEAU
CREST OF BLAKE-BAHAMA OUTER RIDGE
HATTERAS ABYSSAL PLAIN
BERMUDA PLATEAU
BERMUDA
BERMUDA SCARP
BERMUDA
SOHM
NARES A.P.
SILVER A.P.
ANTILLES
OUTER

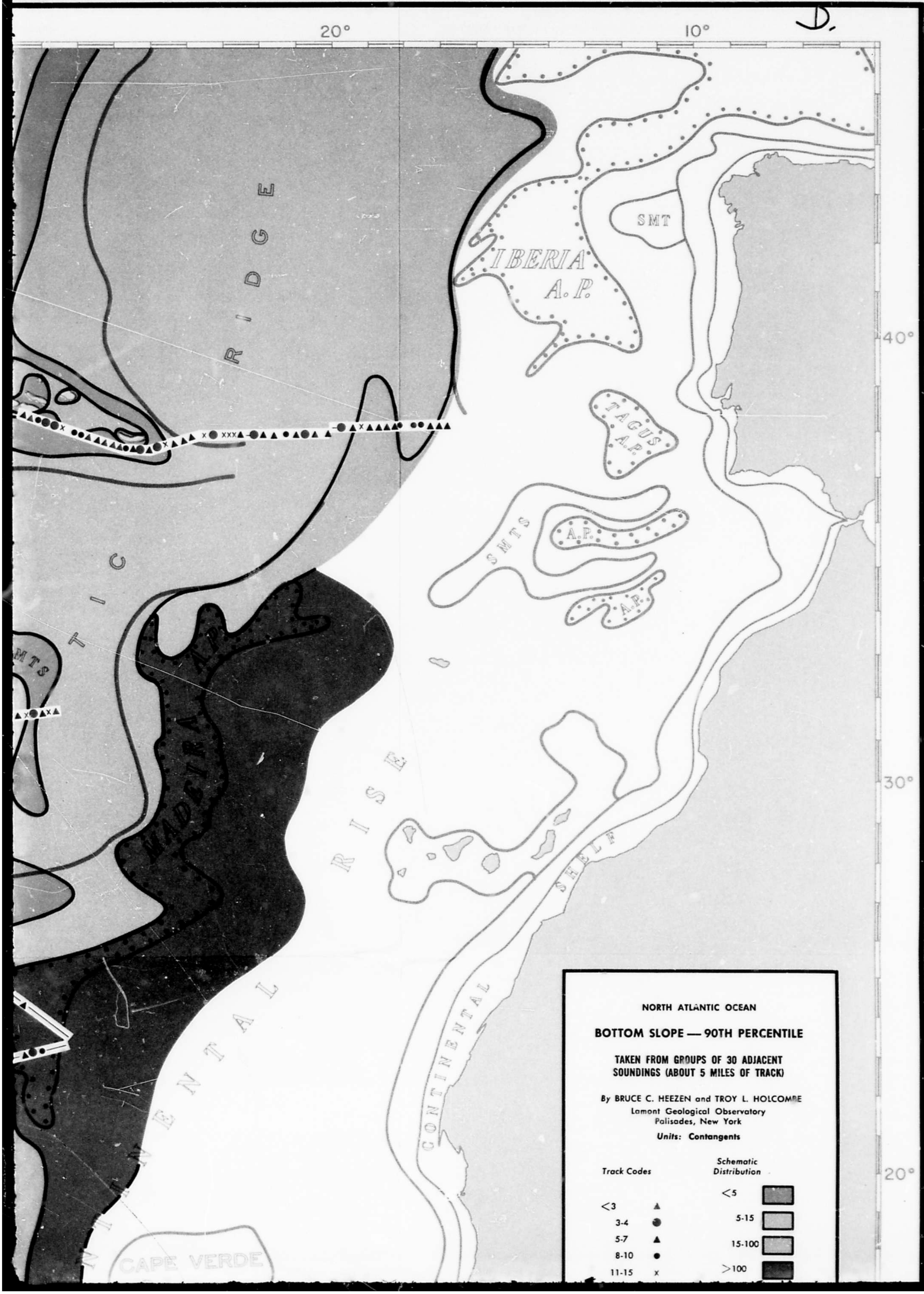
B.

60°
50°
40°
SHELF
RISE
NEWFOUNDLAND RIDGE
NEWFOUNDLAND ABYSSAL PLAIN
SOHM ABYSSAL PLAIN
CORNER RISE
RISE
Abyssal Hills
BERMUDA
BERMUDA
SCARP ZONE
NARES A.P.
OUTER RIDGE
CREST OF MID
MID ATLANTIC

C,



40°
30°
20°
NEWFOUNDLAND ABYSSAL PLAIN
Abyssal Hills
RIDGE
RIDGE
RIDGE
RIDGE
ATLANTIC
MID ATLANTIC
SMTS
ATLAN
MADEIRA AP
KRYLOV RISE
Hills
CAPE VERDE



D.
20°
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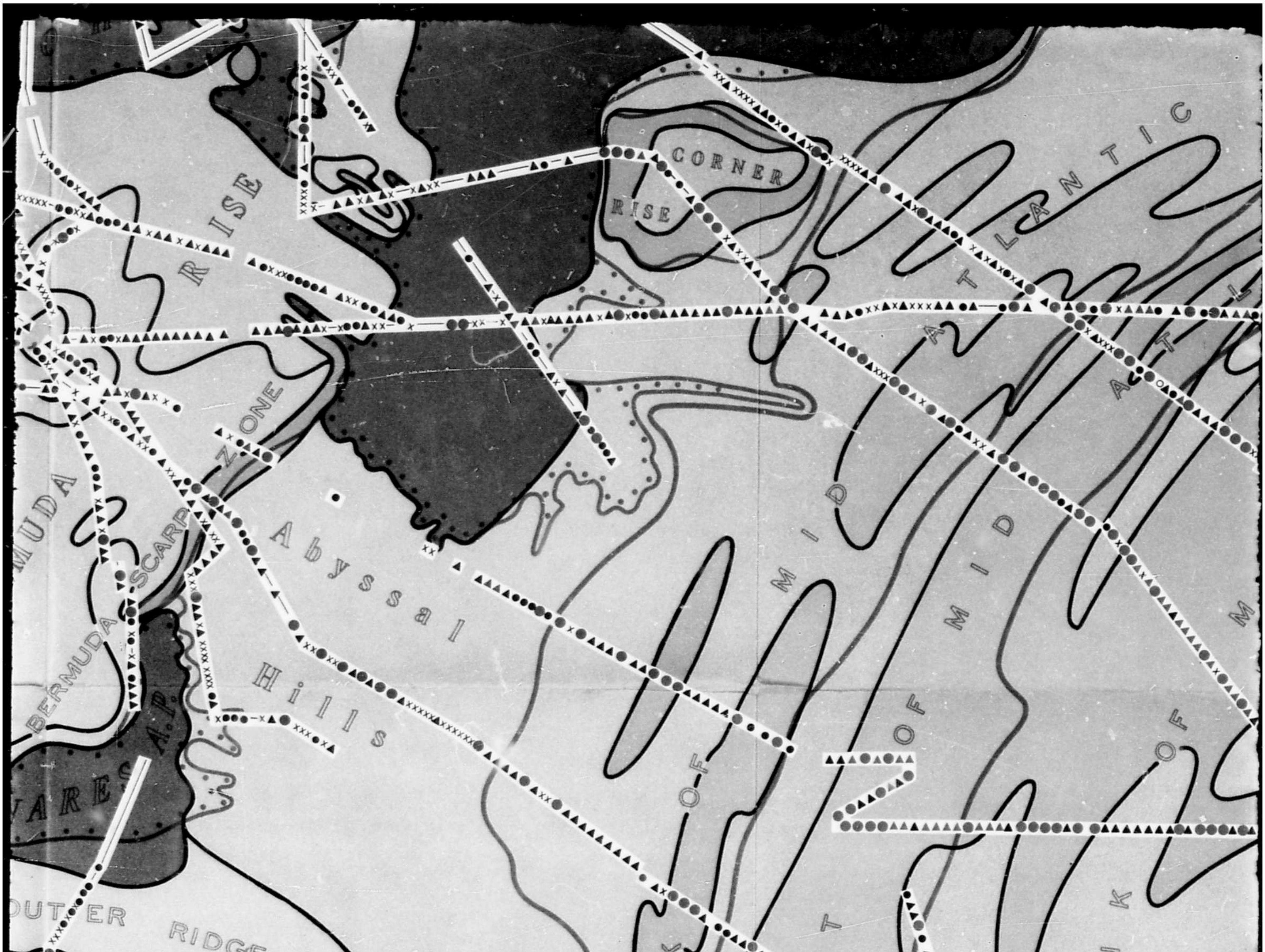
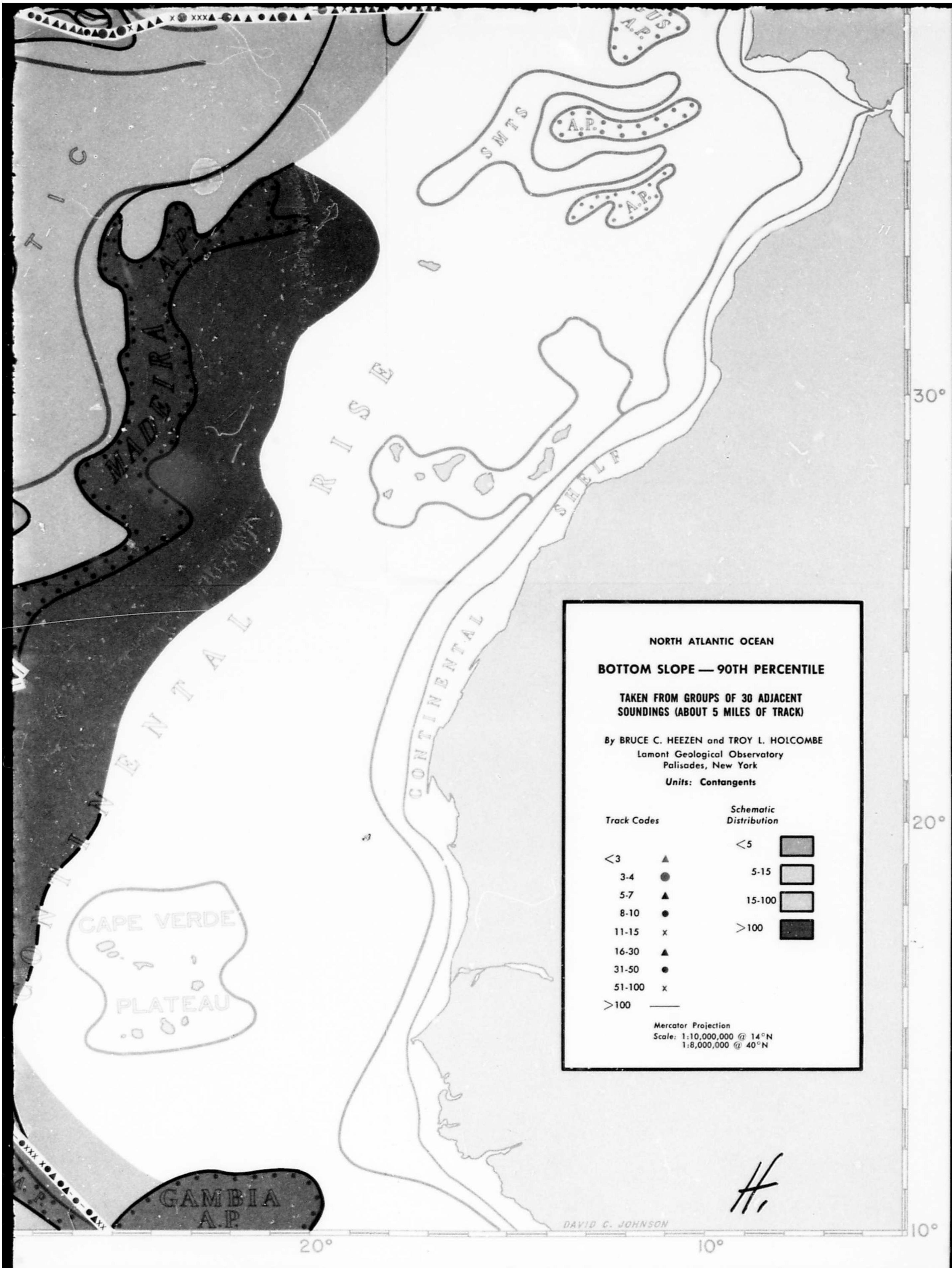
40°
30°
20°
RIDGE
SMT
IBERIA A.P.
TAGUS A.P.
SMTS
A.P.
A.P.
MADEIRA A.P.
CONTINENTAL RISE
CONTINENTAL SHELF
CAPE VERDE
NORTH ATLANTIC OCEAN
BOTTOM SLOPE — 90TH PERCENTILE
TAKEN FROM GROUPS OF 30 ADJACENT SOUNDINGS (ABOUT 5 MILES OF TRACK)
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Contangents
Track Codes
Schematic Distribution
<3 ▲
3-4 ●
5-7 ▲
8-10 ●
11-15 x
<5
5-15
15-100
>100

Geographic Distribution of Bottom Roughness in the North Atlantic — December 1965



RISE
CORNER
RISE
ATLANTIC
ZONE
SCARP
BERMUDA
Abyssal
Hills
NARES A.P.
OUTER RIDGE
MID
OF MID
FLANK OF
CREST
FLANK
F.
60°
50°
40°


SMTS
MADEIRA A.P.
KRYLOV RISE
Abyssal Hills
CAPE VERDE A.P.
GAMBIA A.P.
CAPE VERDE PLATEAU
FLANK OF MID ATLANTIC
40°
30°
20°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BOTTOM SLOPE — 90TH PERCENTILE
TAKEN FROM GROUPS OF 30 ADJACENT SOUNDINGS (ABOUT 5 MILES OF TRACK)
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Contangents
Track Codes
<3
3-4
5-7
8-10
11-15
16-30
31-50
51-100
>100
Schematic Distribution
<5
5-15
15-100
>100
Mercator Projection
Scale: 1:10,000,000 @ 14°N
1:8,000,000 @ 40°N
MADEIRA A.P.
CONTINENTAL RISE
CONTINENTAL SHELF
SMTS
A.P.
CAPE VERDE PLATEAU
GAMBIA A.P.
DAVID C. JOHNSON
30°
20°
10°
20°
10°

CHART 3

A.

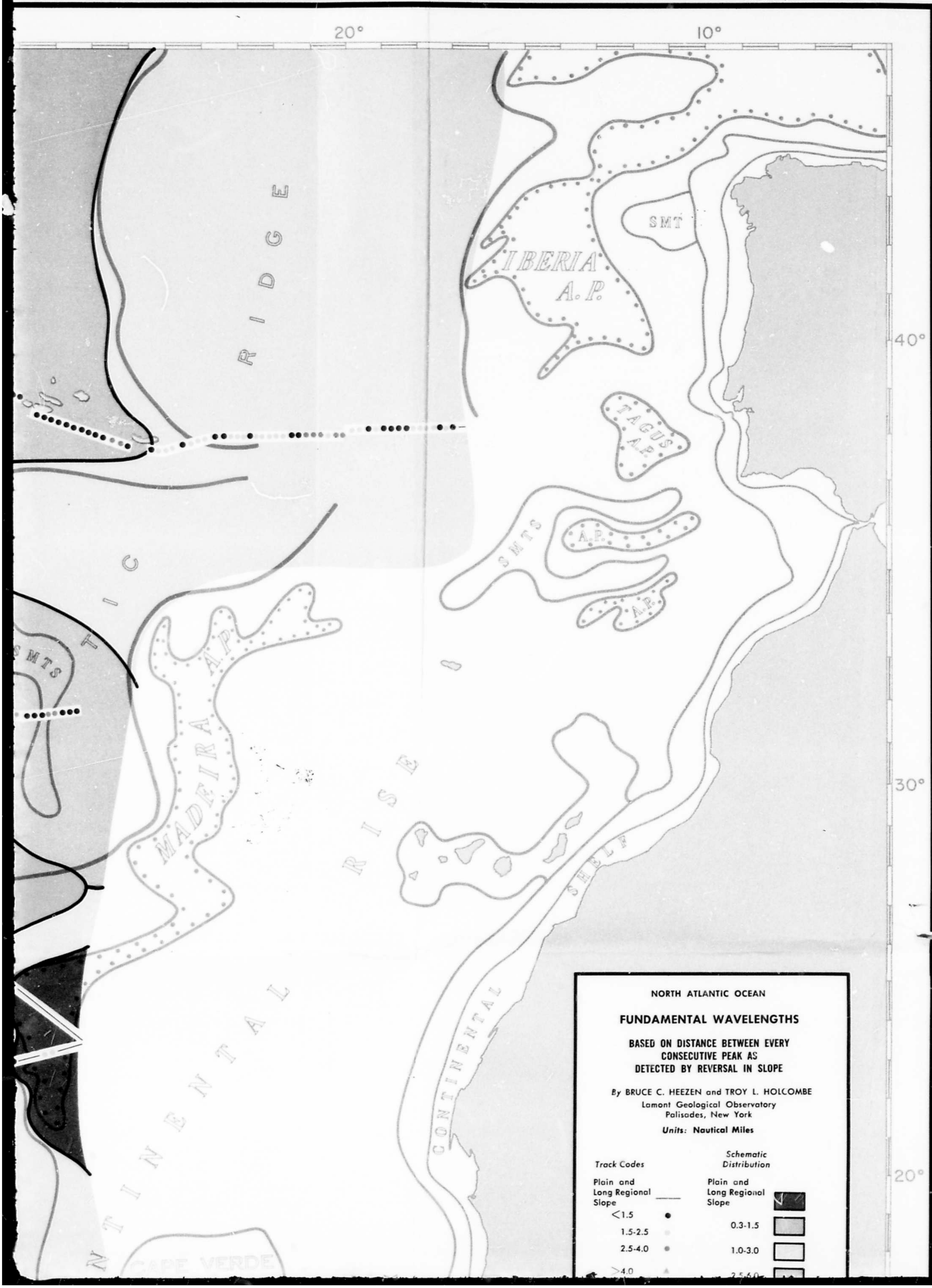

80°
70°
40°
30°
20°
CONTINENTAL SHELF
CONTINENTAL
BLAKE PLATEAU
CREST OF BLAKE-BAHAMA OUTER RIDGE
HATTERAS ABYSSAL PLAIN
BERMUDA PLATEAU
BERMUDA
BERMUDA SCARP
ANTILLES OUTER RIDGE

B


60°
50°
40°
ELF
R I S E
NEWFOUNDLAND RIDGE
A B Y S S A L P L A I N
Abyssal Hills
Abyssal Hills
CORNER
RISE
RISE
M I D A T L A N T I C
M I D A T L A N T I C
ZONE
SCARP
BERMUDA
BERMUDA
Abyssal
Hills
OF
RIDGE
OF
OF
LANK
LANK
REST


40°
30°
20°
Abyssal
Hills
RIDGE
RIDGE
RIDGE
NTIC
ATLANTIC
ATLANTIC
SMTS
MID
ATLAN
TIC
MADEIRA AP
RISE
RISE
Hills
OF
LANK
KRYLOV
RISE
TINENTAL
CONTINENTAL

D.


20°
10°
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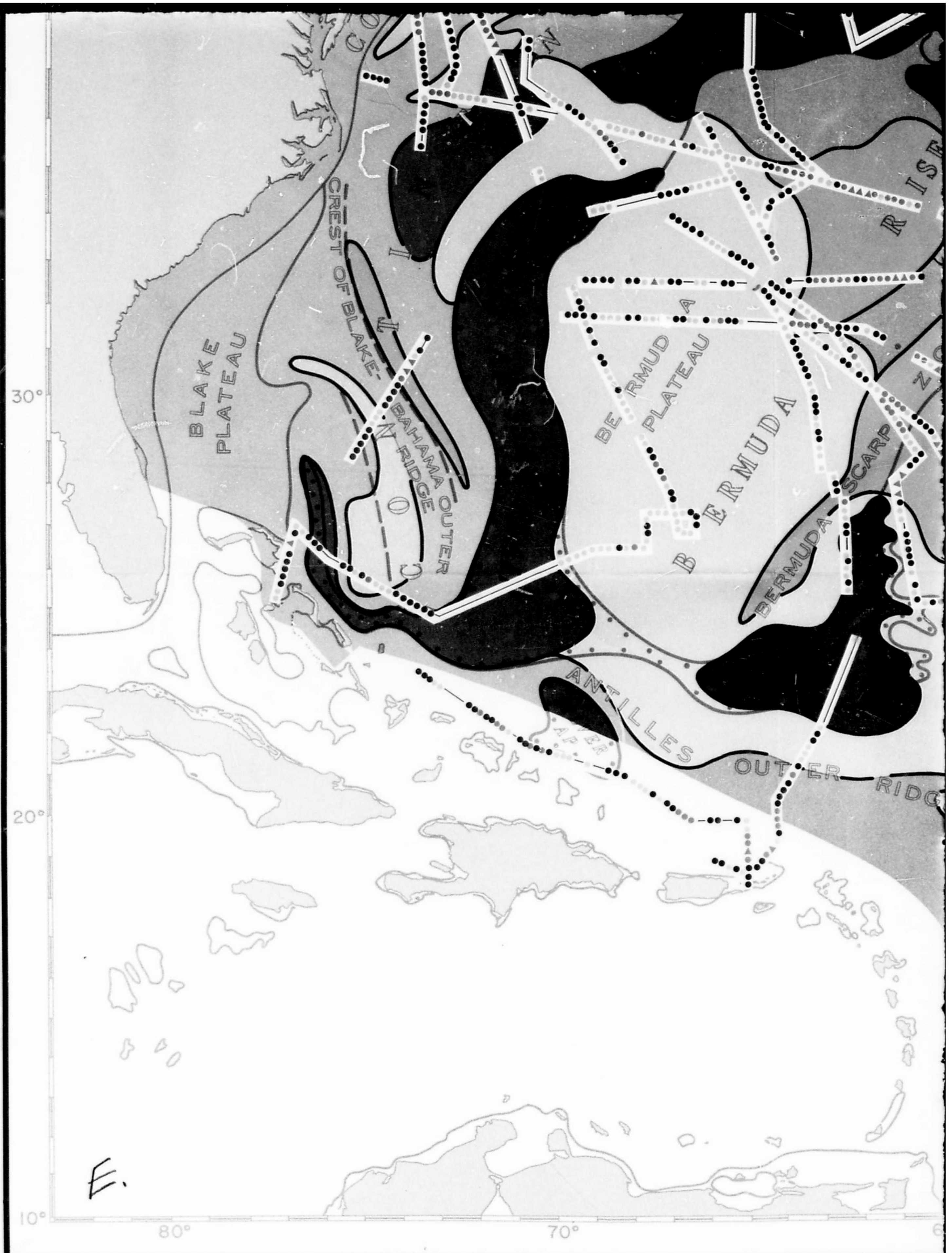
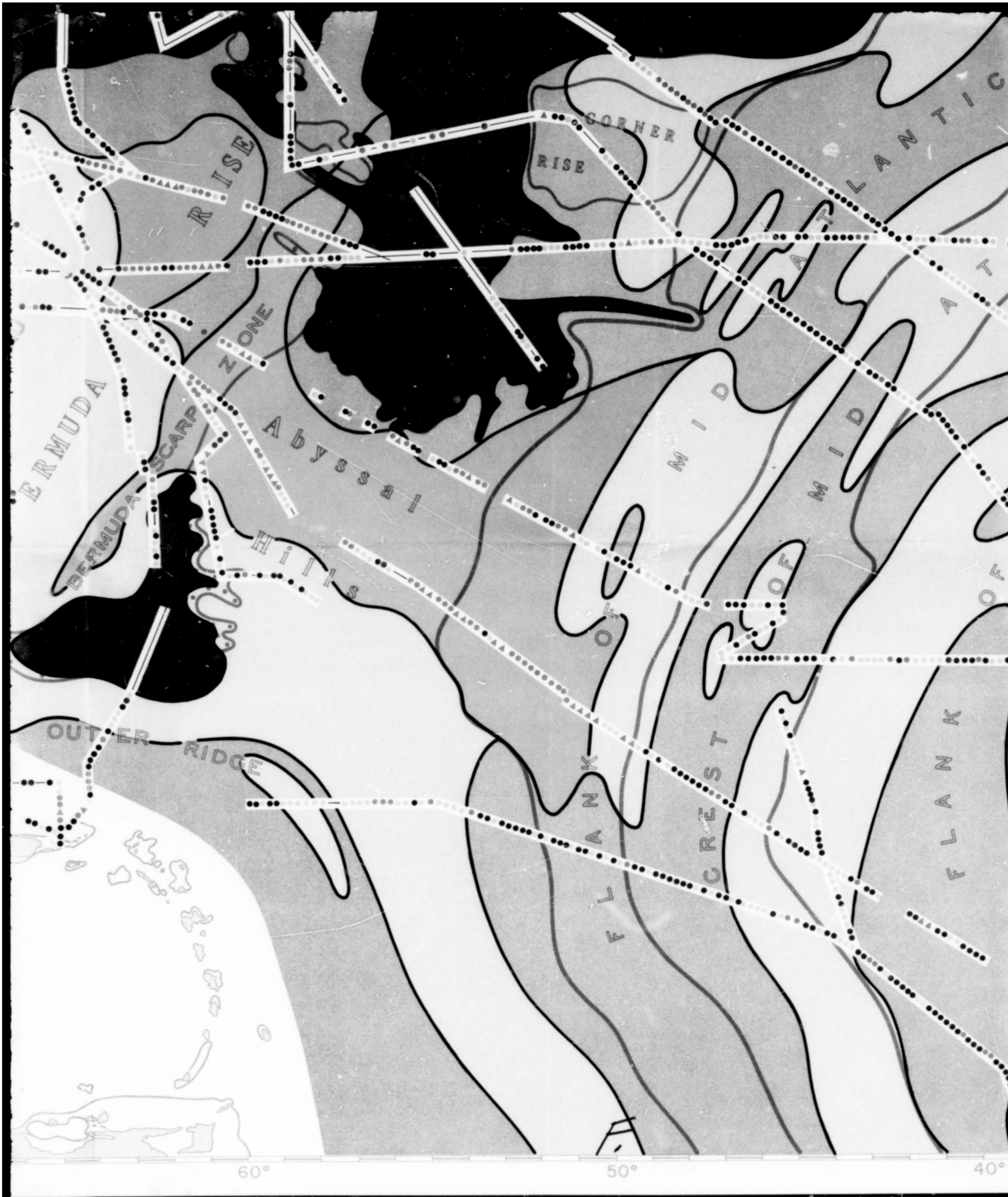
RIDGE
TIC
SMTS
SMT
IBERIA A.P.
TAGUS A.P.
SMTS
A.P.
A.P.
MADEIRA A.P.
RISE
CONTINENTAL SHELF
CONTINENTAL
NTINENTAL
CAPE VERDE
NORTH ATLANTIC OCEAN
FUNDAMENTAL WAVELENGTHS
BASED ON DISTANCE BETWEEN EVERY CONSECUTIVE PEAK AS DETECTED BY REVERSAL IN SLOPE
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Nautical Miles
Track Codes
Plain and Long Regional Slope
<1.5
1.5-2.5
2.5-4.0
>4.0
Schematic Distribution
Plain and Long Regional Slope
0.3-1.5
1.0-3.0
2.5-6.0



Geographic Distribution of Bottom Roughness in the North Atlantic — December 1965



RISE
CORNER
RISE
ATLANTIC
BERMUDA
ZONE
SCARP
Abyssal
Hills
BERMUDA
OUTER RIDGE
MID
OF
CREST
OF
MID
ATLANTIC
FLANK
FLANK
MID
OF
FLANK
60°
50°
40°

ATLANTIC
MID ATLANTIC
FLANK OF MID ATLANTIC
SMTS
ATLANTIC
Abyssal Hills
KRYLOV RISE
CONTINENTAL RISE
MADEIRA A.P.
CAPE VERDE PLATEAU
CAPE VERDE A.P.
GAMBIA A.P.
G.
40°
30°
20°

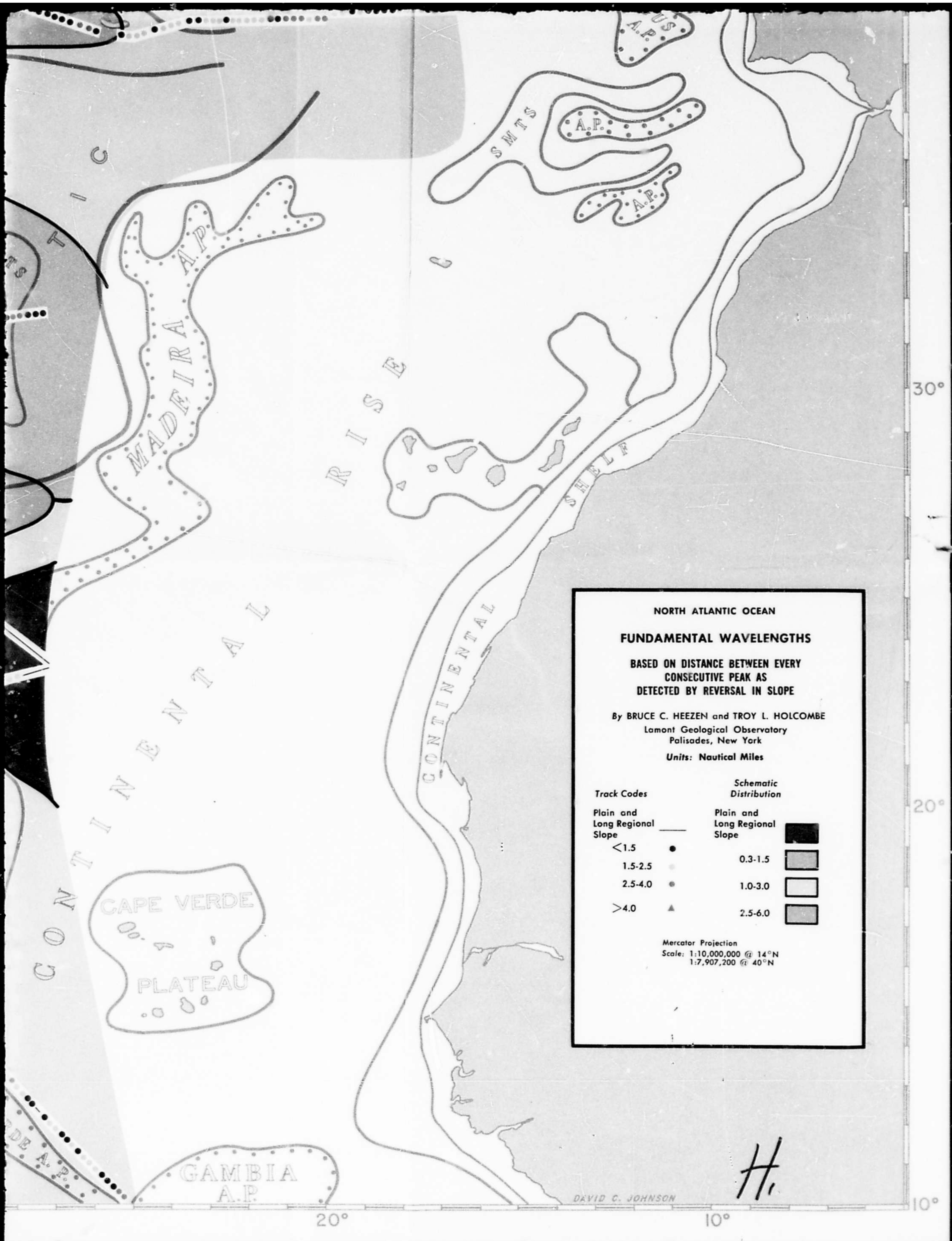
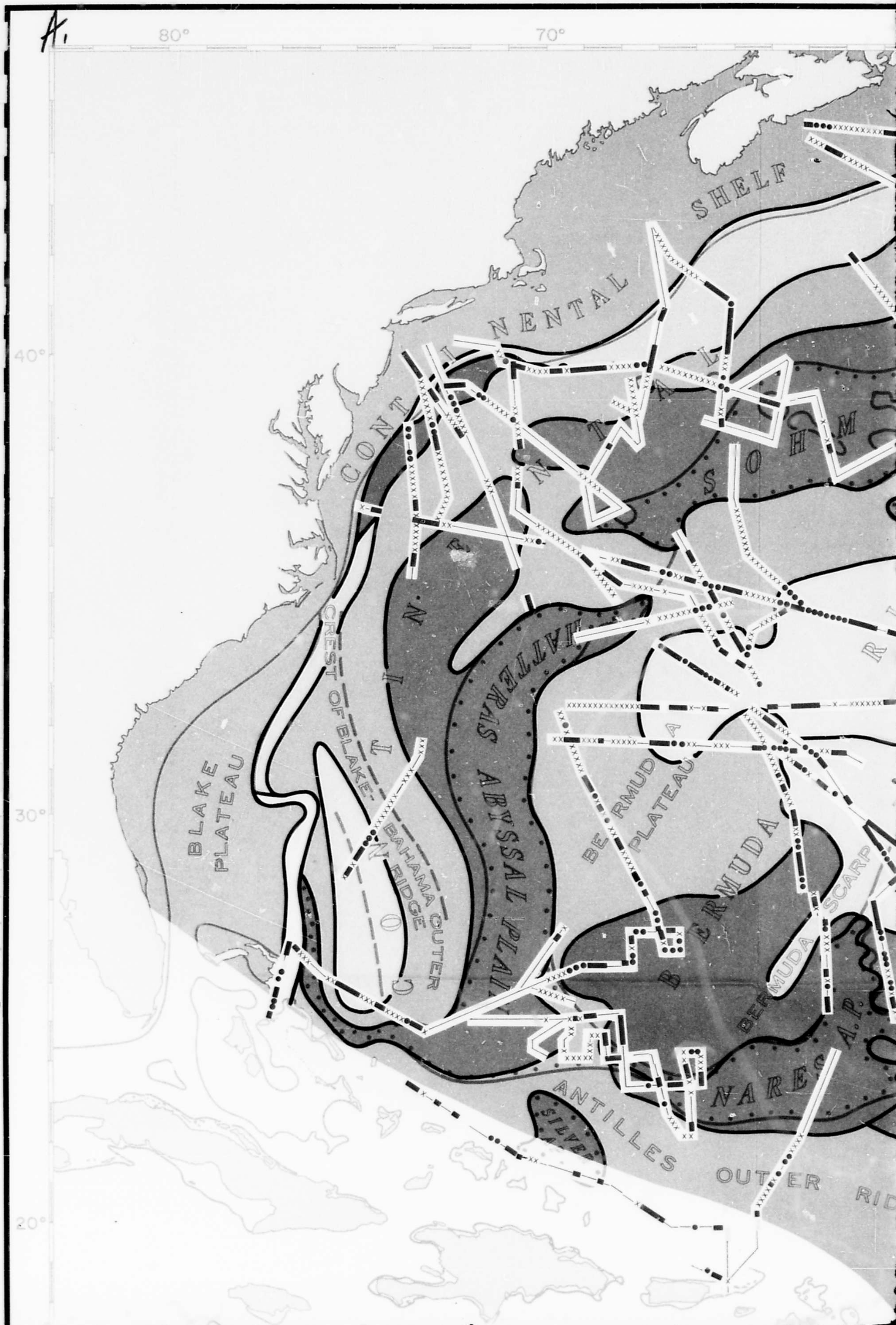

NORTH ATLANTIC OCEAN
FUNDAMENTAL WAVELENGTHS
BASED ON DISTANCE BETWEEN EVERY CONSECUTIVE PEAK AS DETECTED BY REVERSAL IN SLOPE
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Nautical Miles
Track Codes
Plain and Long Regional Slope
<1.5
1.5-2.5
2.5-4.0
>4.0
Schematic Distribution
Plain and Long Regional Slope
0.3-1.5
1.0-3.0
2.5-6.0
Mercator Projection
Scale: 1:10,000,000 @ 14°N
1:7,907,200 @ 40°N
CONTINENTAL RISE
MADEIRA A.P.
SMTS
A.P.
CONTINENTAL SHELF
CONTINENTAL
SHELF
CAPE VERDE
PLATEAU
GAMBIA
A.P.
A.P.
30°
20°
10°
20°
10°
DAVID C. JOHNSON

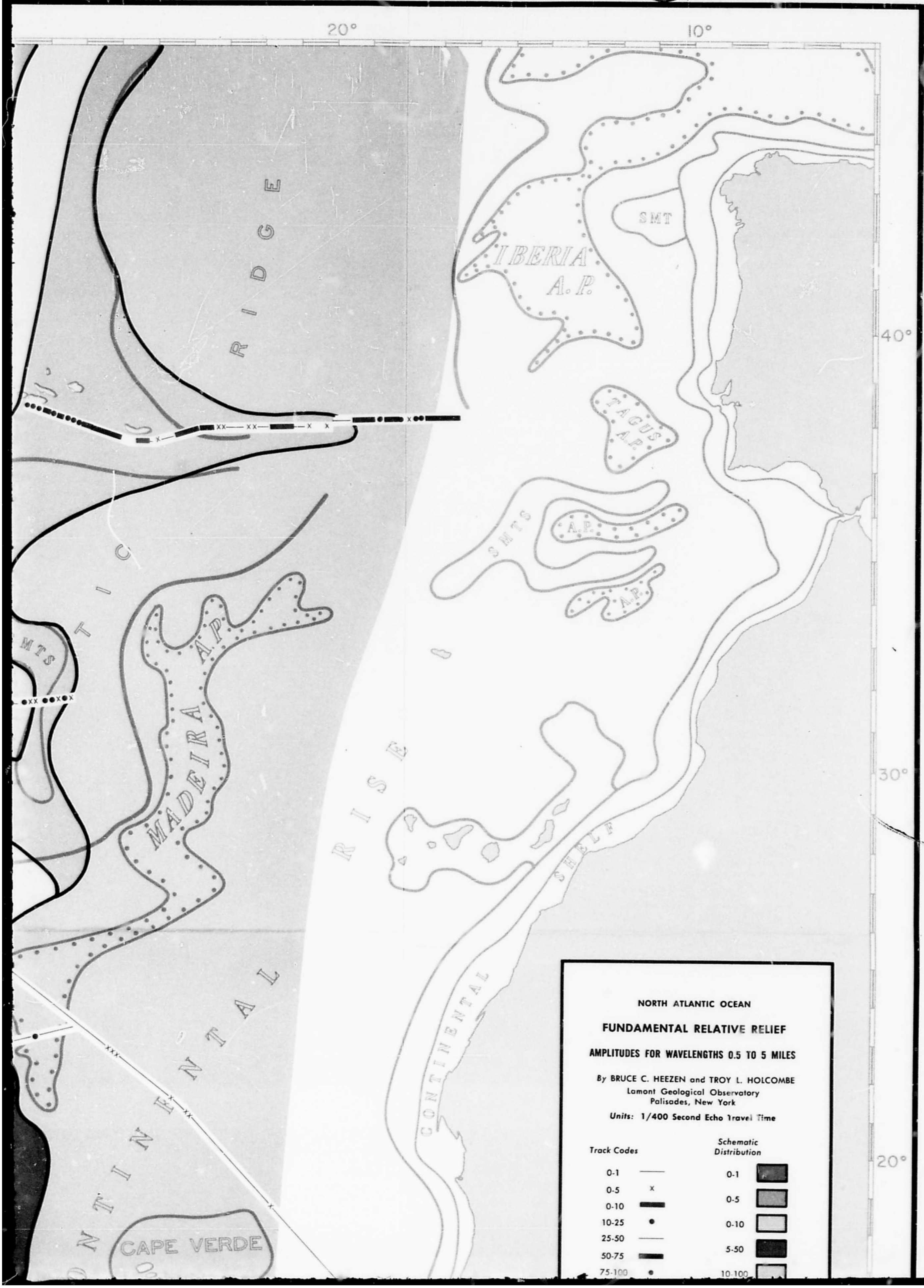
CHART 4


A,
80°
70°
40°
30°
20°
CONT
NENTAL
SHELF
BLAKE PLATEAU
CREST OF BLAKE-BAHAMA OUTER RIDGE
HATTERAS ABYSSAL PLAI
BERMUDA PLATEAU
BERMUDA
BERMUDA SCARP
BERMUDA A.P.
NARES A.P.
ANTILLES OUTER RID

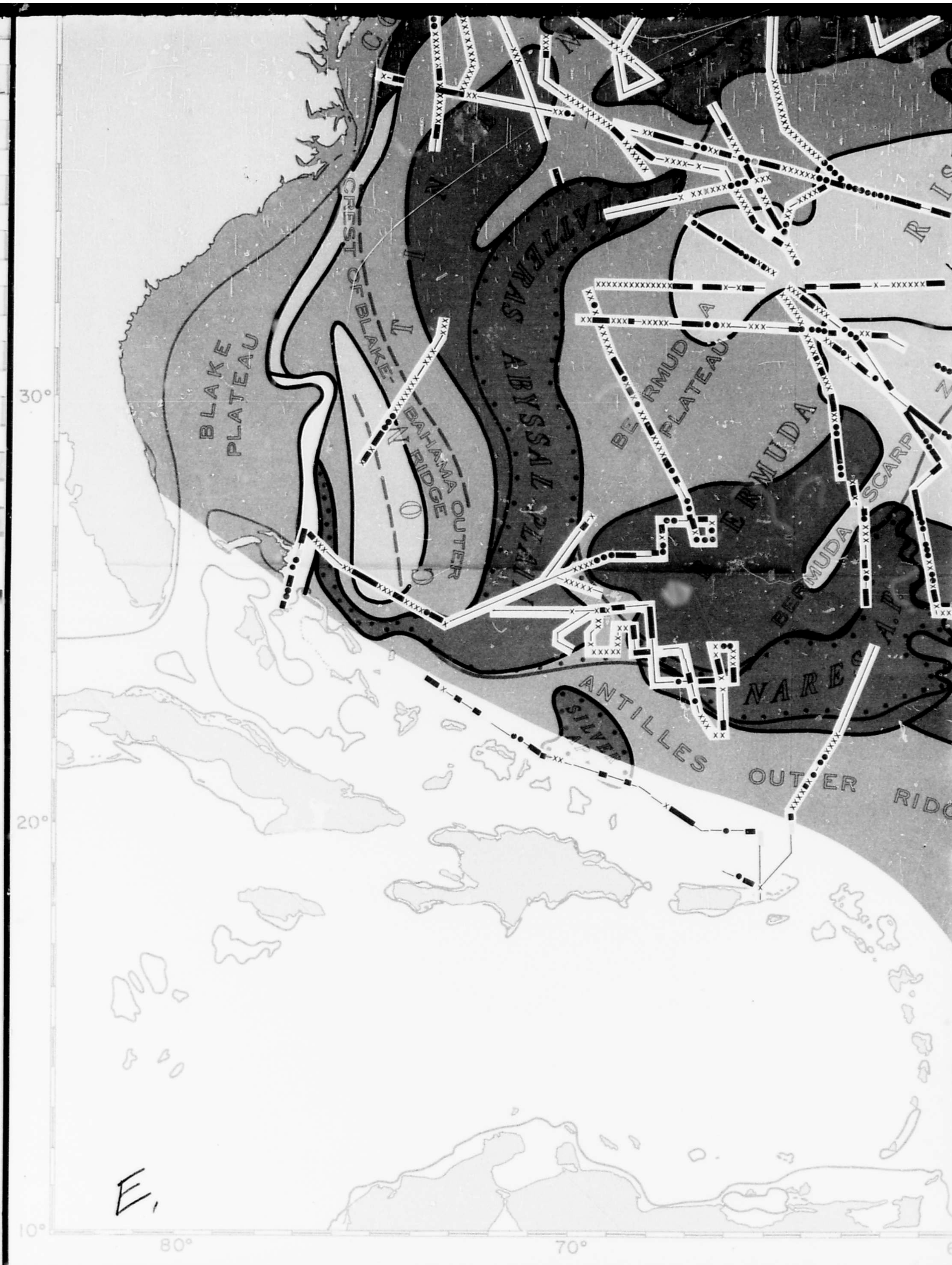
B

60°
50°
40°
SHELF
R I S E
NEWFOUNDLAND RIDGE
NEWFOUNDLAND ABYSSAL PLAIN
Aby ssal Hills
O H M A B Y S S A L P L A I N
CORNER
RISE
R I S E
A T L A N T I C
Abys sal Hills
BERMUDA
ZONE
SCARP
BERMUDA
NARES A.P.
OUTER RIDGE
M I D
O F M I D
C R E S T O F

C'
40°
30°
20°
ABYSSAL PLAIN
Abyssal Hills
RIDGE
RIDGE
MID ATLANTIC RIDGE
MID ATLANTIC RIDGE
ATLANTIC
SMTS
MADEIRA AP
FLANK OF MID ATLANTIC RIDGE
Hills
KRYLOV RISE
CONTINENTAL RISE
CAPE VERDE



20°
10°
40°
30°
20°
RIDGE
IBERIA A.P.
SMT
TAGUS A.P.
SMTS
A.P.
A.P.
MTS
MADEIRA A.P.
TIC
RISE
CONTINENTAL
CONTINENTAL SHELF
CONTINENTAL
CAPE VERDE
NORTH ATLANTIC OCEAN
FUNDAMENTAL RELATIVE RELIEF
AMPLITUDES FOR WAVELENGTHS 0.5 TO 5 MILES
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: 1/400 Second Echo Travel Time
Track Codes
Schematic Distribution
0-1
0-5
0-10
10-25
25-50
50-75
75-100
0-1
0-5
0-10
5-50
10-100


BLAKE PLATEAU
CREST OF BLAKE
BAHAMA OUTER RIDGE
HATTERAS ABYSSAL PLAIN
BERMUDA PLATEAU
BERMUDA
BERMUDA SCARP
BERMUDA
NARES A.P.
ANTILLES OUTER RIDGE
SILVER
30°
20°
10°
80°
70°
E,


CORNER
RISE
RISE
BERMUDA
PLATEAU
BERMUDA
BERMUDA
SCARP
ZONE
Abyssal
Hills
NARES A.P.
OUTER RIDGE
MID
MID
OF
OF
CREST
FLANK
FLANK
F.
60°
50°

MID ATLANTIC
CREST OF MID ATLANTIC R
FLANK OF MID ATLANTIC
ATLANTIC
SMTS
MADEIRA A.P.
CONTINENTAL
Hills
KRYLOV RISE
Abyss
CAPE VERDE PLATEAU
CAPE VERDE A.P.
GAMB A.P.
40°
30°

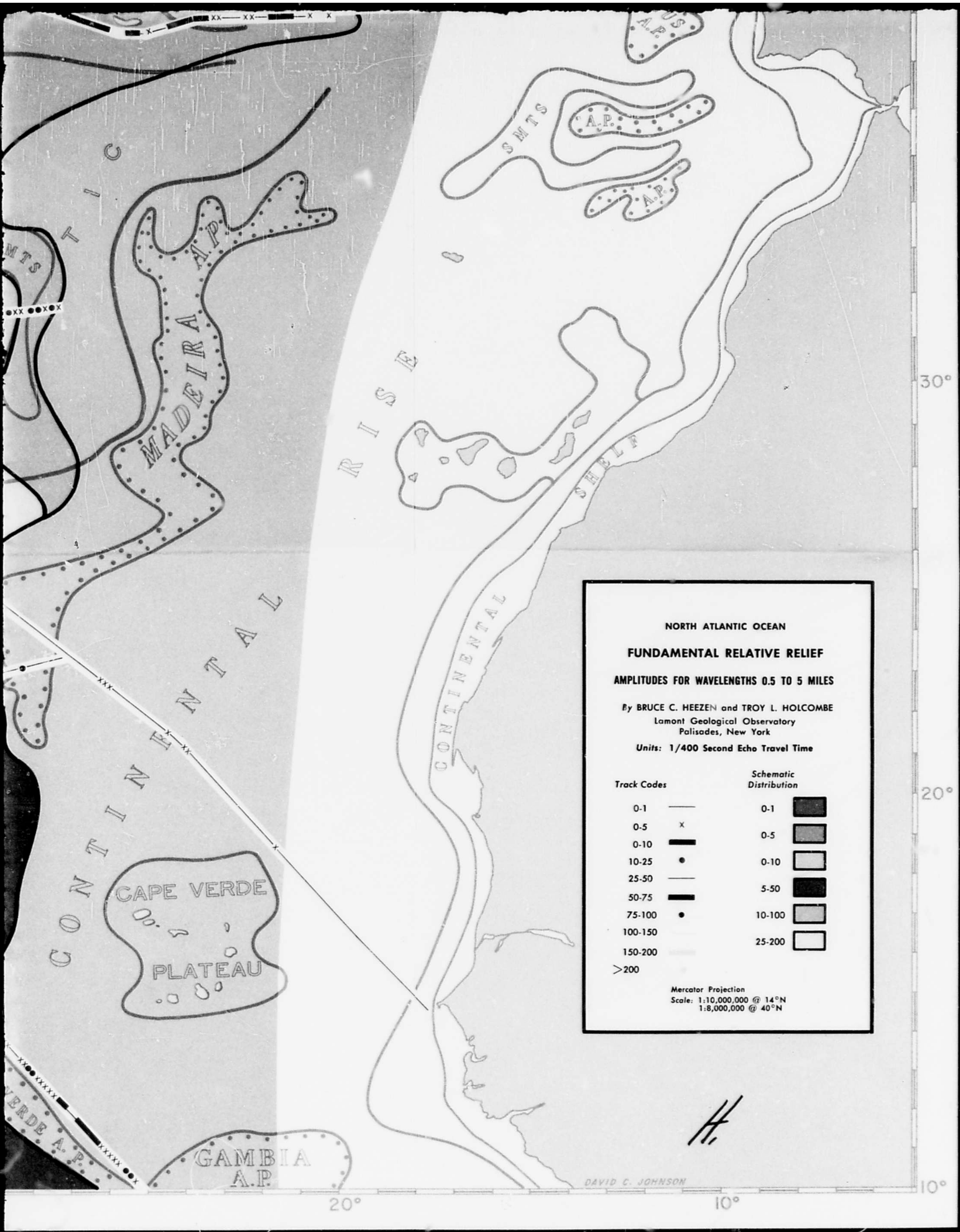

NORTH ATLANTIC OCEAN
FUNDAMENTAL RELATIVE RELIEF
AMPLITUDES FOR WAVELENGTHS 0.5 TO 5 MILES
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: 1/400 Second Echo Travel Time
Track Codes
0-1
0-5
0-10
10-25
25-50
50-75
75-100
100-150
150-200
>200
Schematic Distribution
0-1
0-5
0-10
5-50
10-100
25-200
Mercator Projection
Scale: 1:10,000,000 @ 14°N
1:8,000,000 @ 40°N
MADEIRA A.P.
SMTS
A.P.
CONTINENTAL RISE
CONTINENTAL SHELF
CAPE VERDE PLATEAU
GAMBIA A.P.
VERDE A.P.
30°
20°
10°
20°
10°
DAVID C. JOHNSON

CHART 5

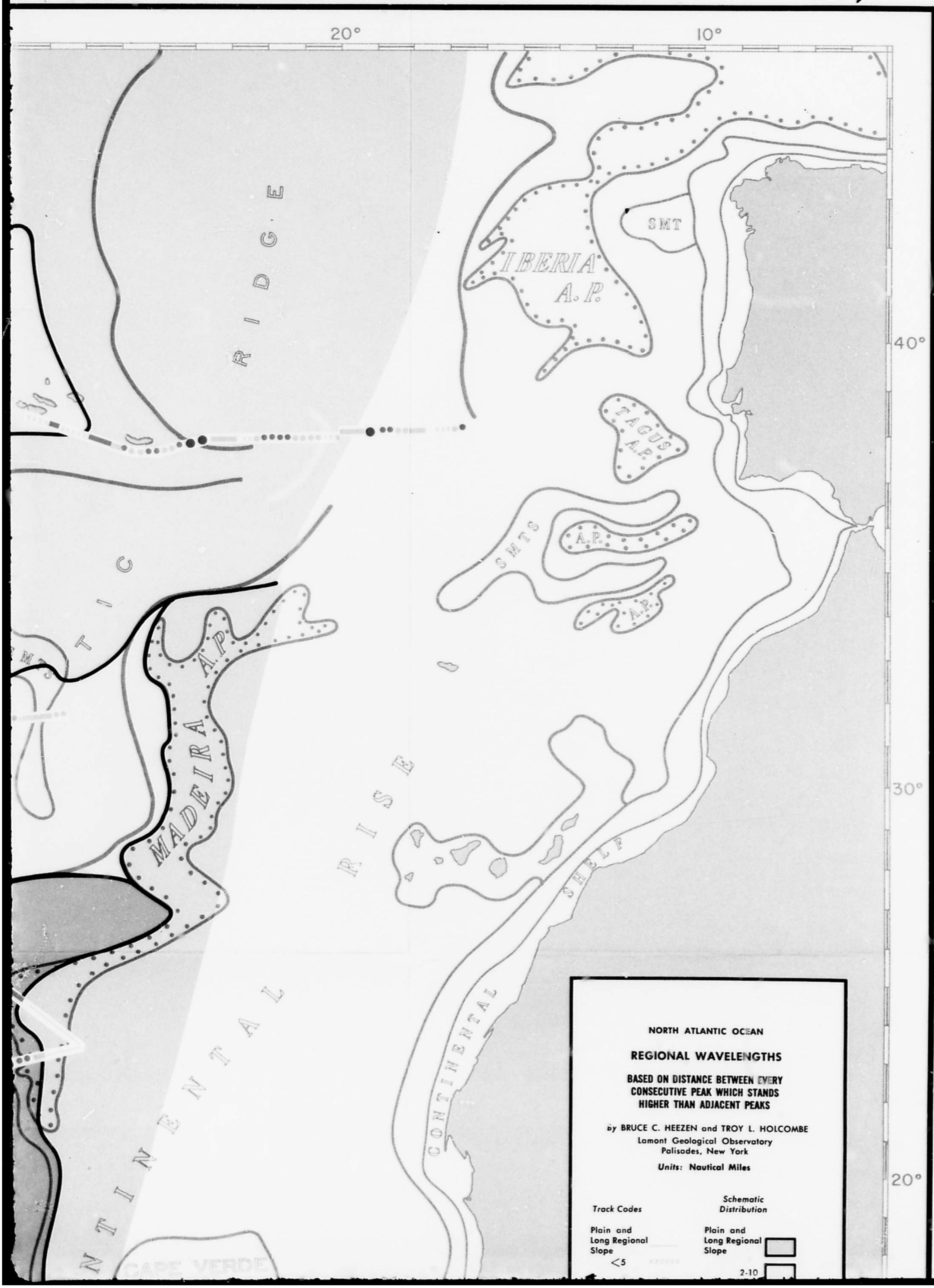
A.

80°
70°
40°
30°
20°
CONTINENTAL SHELF
CONTINENTAL RISE
BLAKE PLATEAU
CREST OF BLAKE BAHAMA OUTER RIDGE
HATTERAS ABYSSAL PLAIN
BERMUDA PLATEAU
BERMUDA RISE
BERMUDA SCARP
BERMUDA A.P.
NARES A.P.
SILVER A.P.
ANTILLES OUTER RIDGE
SOHM

60°
50°
RISE
NEWFOUNDLAND RIDGE
NEWFOUNDLAND ABYSSAL PLAIN
ABYSSAL PLAIN
CORNER RISE
RISE
ZONE
SCARP
Abyssal Hills
BERMUDA
A.P.
RIDGE
ATLANTI
OF MID
CREST OF MID


40°
30°
20°
PLAIN
Abyssal Hills
Abyssal Hills
RIDGE
RIDGE
RIDGE
RIDGE
ATLANTIC
ATLANTIC
ATLANTIC
SMT
MID ATLANTIC
FLANK OF MID
Hills
MADEIRA AP
CONTINENTAL RISE
KRYLOV RISE
CAPE VERDE

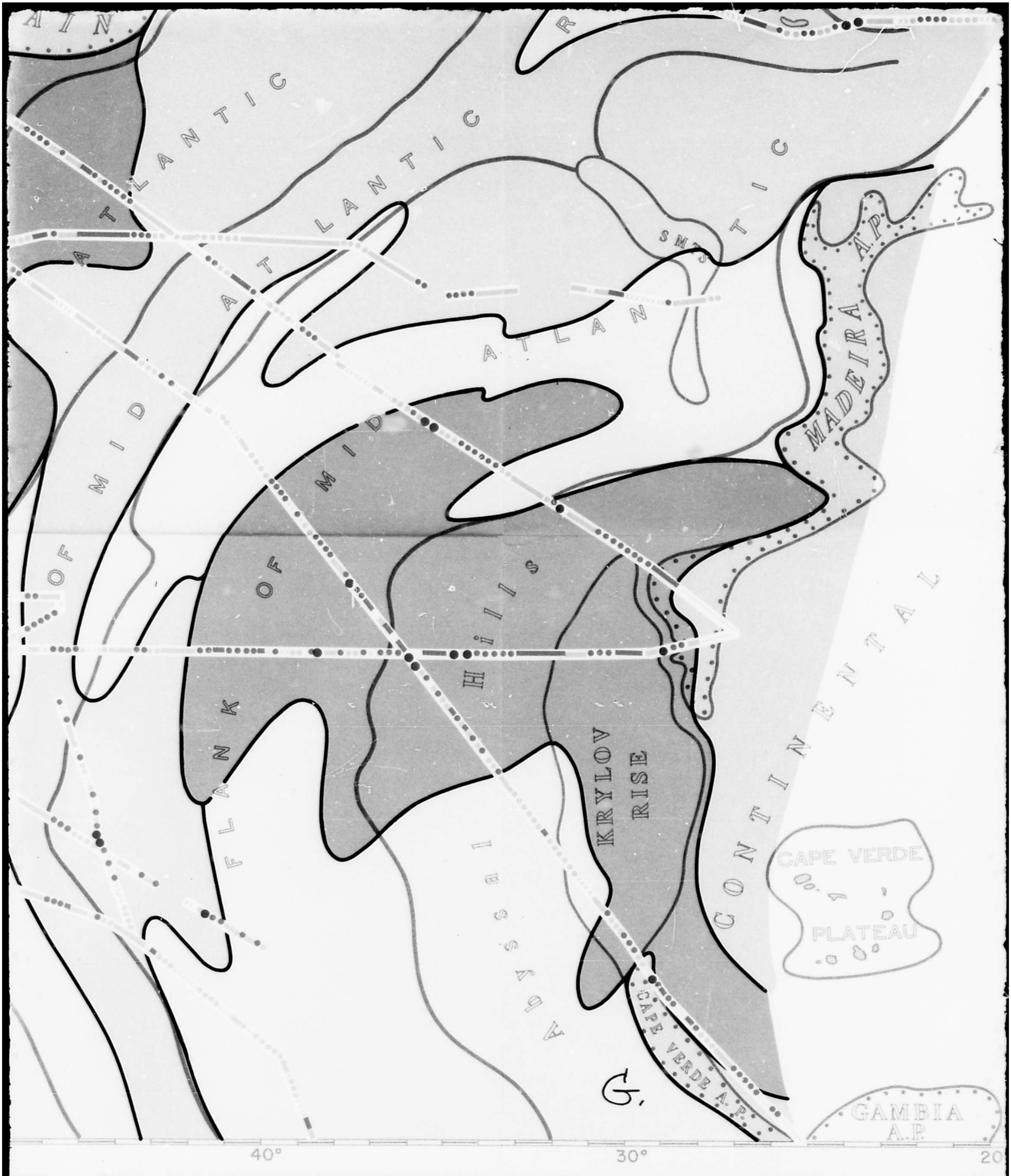
D,



20°
10°
40°
30°
20°
RIDGE
IBERIA A.P.
SMT
TAGUS A.P.
SMTS
A.P.
A.P.
MADEIRA A.P.
CONTINENTAL RISE
CONTINENTAL SHELF
CAPE VERDE
NORTH ATLANTIC OCEAN
REGIONAL WAVELENGTHS
BASED ON DISTANCE BETWEEN EVERY CONSECUTIVE PEAK WHICH STANDS HIGHER THAN ADJACENT PEAKS
by BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Nautical Miles
Track Codes
Schematic Distribution
Plain and Long Regional Slope
Plain and Long Regional Slope
<5
2-10

Geographic Distribution of Bottom Roughness in the North Atlantic — December 1965


PLAIN
CORNER
RISE
RISE
ATLANTIC
BERMUDA
ZONE
SCARP
Abyssal
Hills
BERMUDA
A.P.
NARES
MID
OF MID
OF
OUTER RIDGE
FLANK
CREST
FLANK OF
F.
60°
50°
40°



MID ATLANTIC
FLANK OF MID ATLANTIC
FLANK OF MID
SM
Abyssal Hills
KRYLOV RISE
MADEIRA A.P.
CONTINENTAL
CAPE VERDE PLATEAU
CAPE VERDE A.P.
GAMBIA A.P.
G.
40°
30°

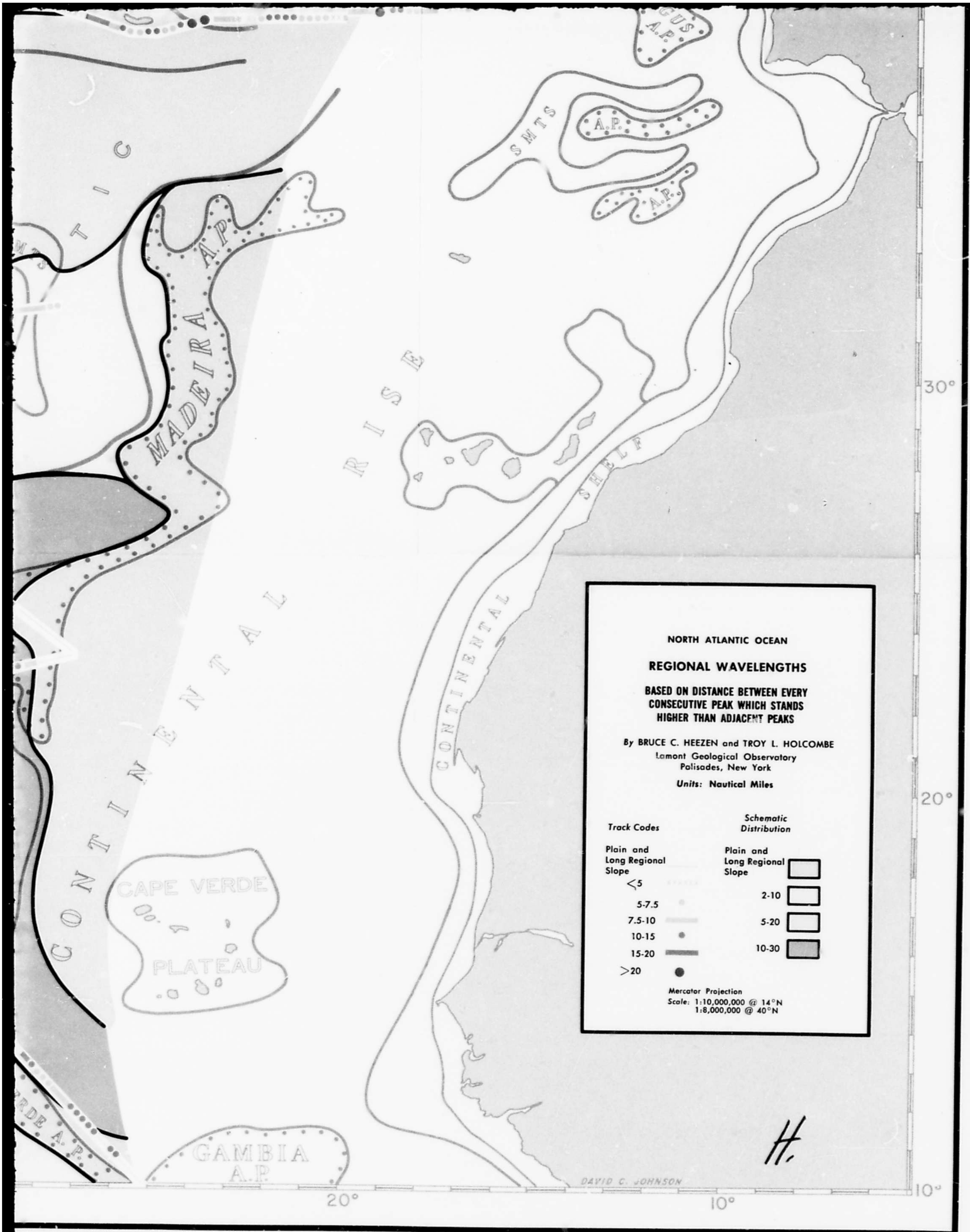

NORTH ATLANTIC OCEAN
REGIONAL WAVELENGTHS
BASED ON DISTANCE BETWEEN EVERY CONSECUTIVE PEAK WHICH STANDS HIGHER THAN ADJACENT PEAKS
By BRUCE C. HEEZEN and TROY L. HOLCOMBE
Lamont Geological Observatory
Palisades, New York
Units: Nautical Miles
Track Codes
Plain and Long Regional Slope
<5
5-7.5
7.5-10
10-15
15-20
>20
Schematic Distribution
Plain and Long Regional Slope
2-10
5-20
10-30
Mercator Projection
Scale: 1:10,000,000 @ 14°N
1:8,000,000 @ 40°N
MADEIRA A.P.
CONTINENTAL RISE
CONTINENTAL SHELF
SMTS
A.P.
CAPE VERDE PLATEAU
GAMBIA A.P.
30°
20°
10°
DAVID C. JOHNSON
H.

CHART 6