OCEAN TERRAIN ANALYSIS

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ABSTRACT

A method to compute terrain parameters at regular intervals along depth profiles is described. This system of numerical analysis uses series of discrete data to extract quantitative geometrical properties; the system is easily programmed for digital computers.

Introduction

A method of quantitative analysis of submarine topography and its classification by geometric factors is presented herein; the eventual objective is to develop a working system to predict terrain factors of unsurveyed areas of the ocean floor.

Only an extremely small percentage of the ocean has been surveyed by detailed or precise bathymetric methods. All the major ocean basins, however, have been crossed by ships obtaining lines of soundings on a non-survey, non-detailed, port-to-port basis.

Bottom contour charts constructed from these random lines of data represent an attempt to predict the topography of the unsounded areas between these lines. The terrain parameter shown by these charts is averaged, interpolated depth.

Only the general outline of major ocean features, such as mountain ranges and basins, can be reliably outlined on these charts. The contour chart does *not* indicate the probable density, spacing, steepness, and type of terrain features such as seamounts, minor ridges, canyons, etc., expected to occur *between* sounding tracks. Thus, the terrain is "smoothed".

Physiographic diagrams surmount many of these difficulties, but a more quantitative, numerical technique is needed.

Many of the terrain parameters and some of the concepts of terrain analysis were derived from studies of the U.S. Army Quartermaster Corps (THOMPSON, 1964; WOOD and SNELL, 1960) and the U.S. Army Corps of Engineers (TURNER and BOSSERT, 1964).

DESCRIPTION OF THE METHOD

Data input

Data analysed were random lines of evenly-spaced, discrete soundings extracted from continuous depth profiles. These sequences of soundings were divided into segments containing 15 to 20 soundings and each segment was analyzed.

Terrain parameters

Terrain parameters to be considered in this paper are listed and defined below :

1. Depth-Relief Ratio, DRR, ranging from .0 to 1.0, is the ratio of upland to lowland (figure 1). A basin studded with seamounts would have a small DRR near .0. A plateau cut by canyons would have a large DRR near 1.0.

2. Grain, G, is the average horizontal peak-to-peak or valley-to-valley spacing between major peaks or valleys respectively.

3. Relief, R, is the average vertical distance between tops of major peaks and bottoms of adjacent valleys.

4. Average Slope Tangent, ST, is the average total peak-to-valley slope of major peaks and valleys.

5. Typical Slope Tangent, STT, is the average slope of peaks and valleys excluding intervening areas of relatively flatter topography.

6. Minor Peak Spacing, L_m, is the peak-to-peak spacing between minor features superimposed on the major features.

7. Minor Relief, *r*, is the average relief of the minor features.

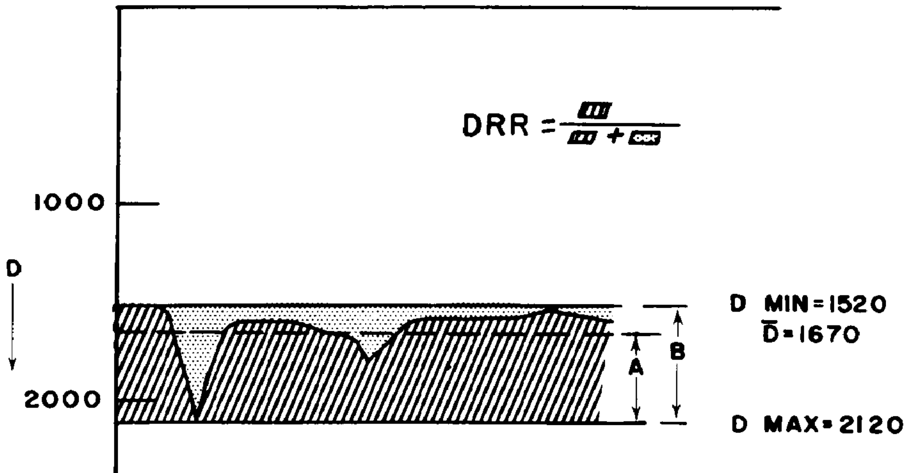
8. Minor Slope Tangent, *st*, is the slope of the minor features as they are superimposed on the major features.

9. Roughness Index, *r.i.*, is a function of the number and magnitude of slope direction changes.

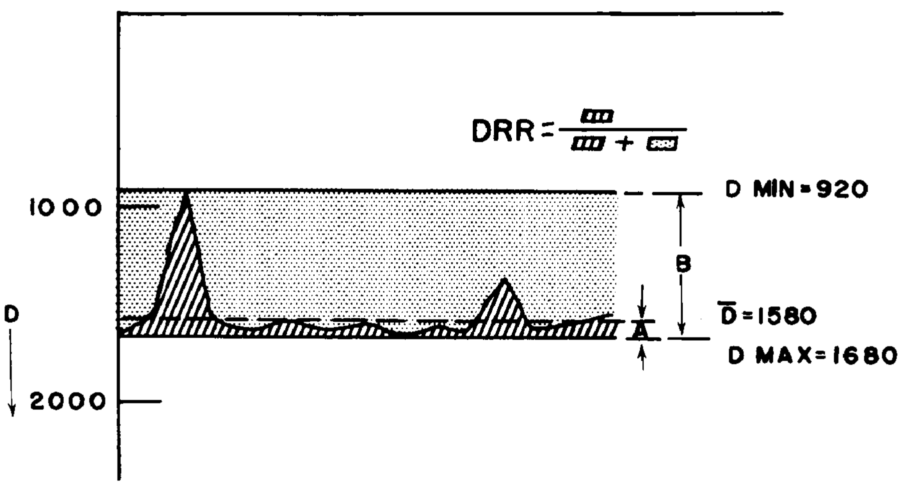
Theory and procedure of extraction of the terrain parameters

1. The random lines of uniformly spaced soundings are first sorted into individual lines; these lines are in turn subdivided into segments of a maxi-

mum length and containing a minimum of soundings, depending on the type and precision of input data. These segments are then analyzed individually.



$$DRR = \frac{A}{B} = \frac{2\,120 - 1\,670}{2\,120 - 1\,520} = .78$$



$$DRR = \frac{A}{B} = \frac{1\,680 - 1\,580}{1\,680 - \ \ 920} = .13$$

FIG. 1. — *Depth-relief ratio.*

2. The regional slope of the segment is next removed in order to get a true value of the Depth Relief Ratio.

Figure 2 shows a typical depth profile segment 48 miles long with dots representing a sequence of 17 soundings spaced three miles apart (three miles is a typical spacing of available random data).

Figure 3 shows the graph, ACB, made from this sequence to approximate the profile of the real ocean bottom. Point C is the center point of the segment.

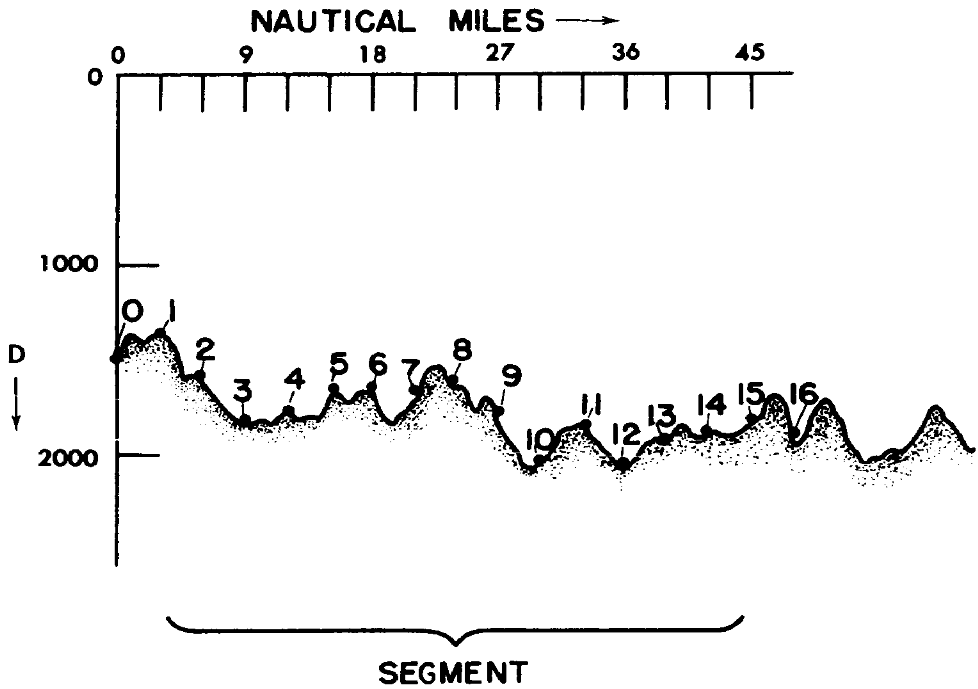


FIG. 2. — *Sample depth profile.*

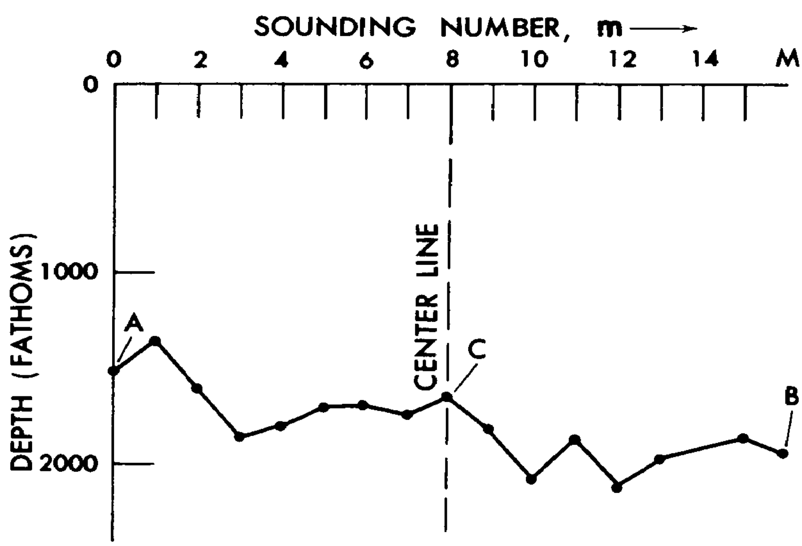


FIG. 3. — *Graph of soundings used to approximate the real profile.*

The same profile is shown as ACB in figure 4 (a). Profile A_1CB_1 having a regional gradient of 0° is the profile to be derived, and is defined as that profile which has equal areas about C; in other words, it is "balanced".

Such a balance is shown by following equality :

$$\int_0^{M/2} D dm = \int_{M/2}^{M} D dm$$

for a continuous curve,

where m is the distance, M is the total distance, and D is a function of m.

The amount of "inbalance" of the original profile ACB can be visualized as the difference between the left half, AC, and the mirror image of the right half, B_2C.

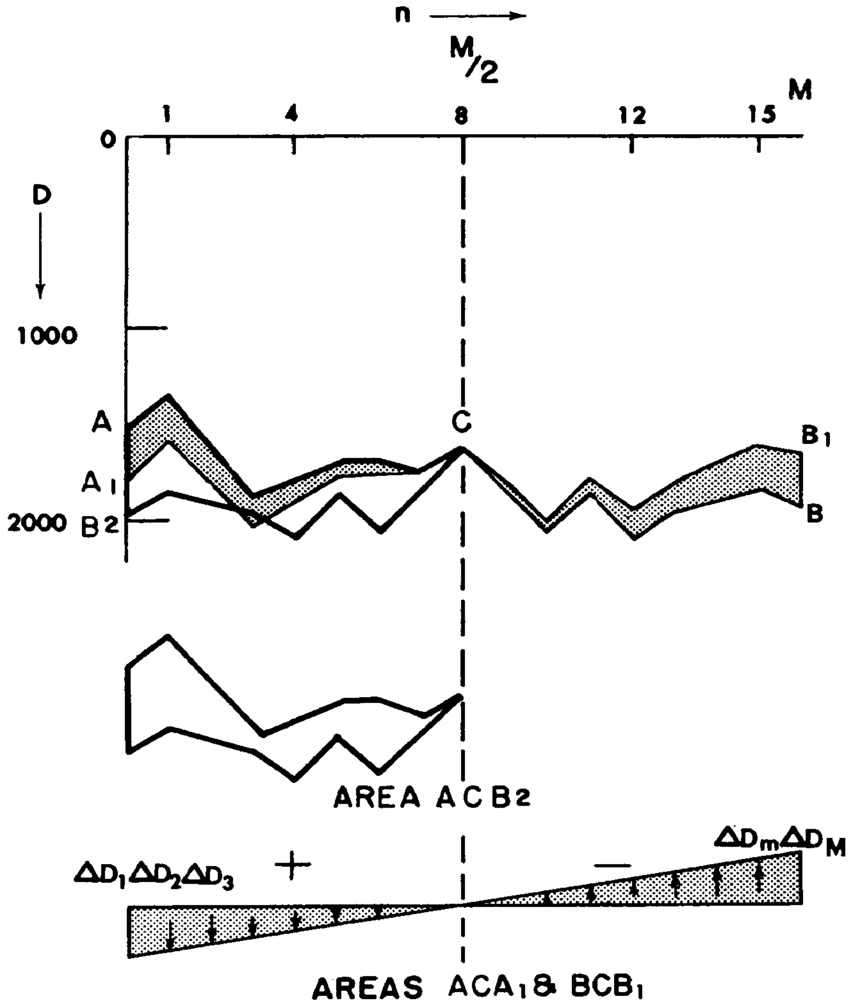


FIG. 4. — *Removal of regional gradient.*
4(*a*) Original profile ACB to be adjusted to " balanced " profile A_1CB_1 · B_2C is mirror image of BC.
4(*b*) Area representing the difference between profiles AC and B_2C.
4(*c*) Wedges of depth corrections providing necessary amount of " tilt ".

This difference is represented by the area ACB_2, also shown separately in figure 4 (b).

The area of ACB_2 is

$$\int_{M/2}^{M} D dm - \int_{0}^{M/2} D dm \simeq \sum_{m=M/2}^{M} D_m - \sum_{m=0}^{M/2} D_m$$

as a practical approximation.

This area also is the same amount as that represented by the difference between the original profile ACB and the "desired" profile A_1CB_1.

Thus, area ACB_2 = area $BCB_1 + ACA_1$.

To preserve all other terrain factors, the profile ACB must be "tilted" to A_1CB_1. Areas ACA_1 and BCB_1 can be represented by two equal wedges (figure 4 (c)), each having a length of M/2 and a height of

$$\Delta D_1 = \Delta D_M = \text{area } ACB_2 \,/\, (M/2)$$

$$= 2/M \left(\sum_{m=M/2}^{M} D_m - \sum_{m=0}^{M/2} D_m \right)$$

These wedges represent a sequence of correction factors,

$$\Delta D_1,\ \Delta D_2,\ \Delta D_3,\ \ldots\ \Delta D_m,\ \ldots\ \Delta D_M$$

to be added to the original sequence of depths :

$$D_1,\ D_2,\ D_3,\ \ldots\ D_m,\ \ldots\ D_M$$

The value of ΔD_m is given by :

$$\Delta D_m = \Delta D_M\ (1 - 2\,(m/M)).$$

3. Depth Relief Ratio is a direct adaptation of WOOD and SNELL's (1960) Elevation Relief Ratio. DRR compares average depth to the maximum and minimum depths of a segment after regional gradient has been removed.

DRR may be visualized (figure 5) as the ratio of the Area A (between a given profile and a line describing a maximum depth) to the area B (between lines describing the minimum and maximum depths respectively) :

$$DRR = \frac{\left(MD_{max} - \int_0^M D\,dm \right)}{(MD_{max} - MD_{min})} = \frac{(D_{max} - \bar{D})}{(D_{max} - D_{min})}$$

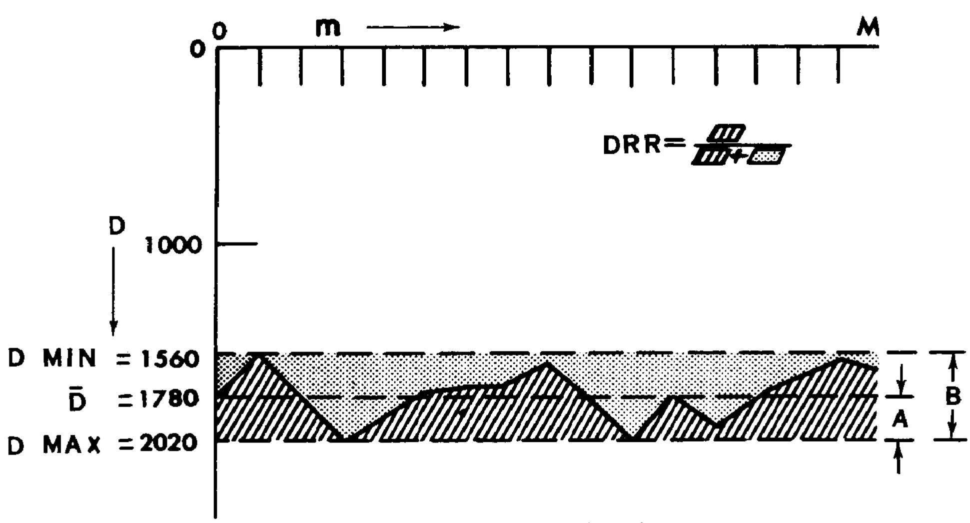


FIG. 5. — *Depth-relief ratio.*

$$DRR = \frac{A}{B} = \frac{D_{max} - \bar{D}}{D_{max} - D_{min}} = .52$$

4. Grain is the average spacing between prominent peaks or between major valleys. The concept of the "knickpoint" is used to define the Grain and Relief of these major peaks and valleys.

If, from a given arbitrary point, a traverse is made and relief (difference between maximum and minimum depths encountered up to the given point on the traverse) is plotted versus distance traversed, an ever increasing curve will result (figure 6). At some point on the curve, a "plateau" will be reached and a sharp bend of the curve will be evident at that point. This point of maximum downward curvature is called the "knickpoint". This concept of knickpoint, developed by GUTERSOHN, is discussed by THOMPSON (1964).

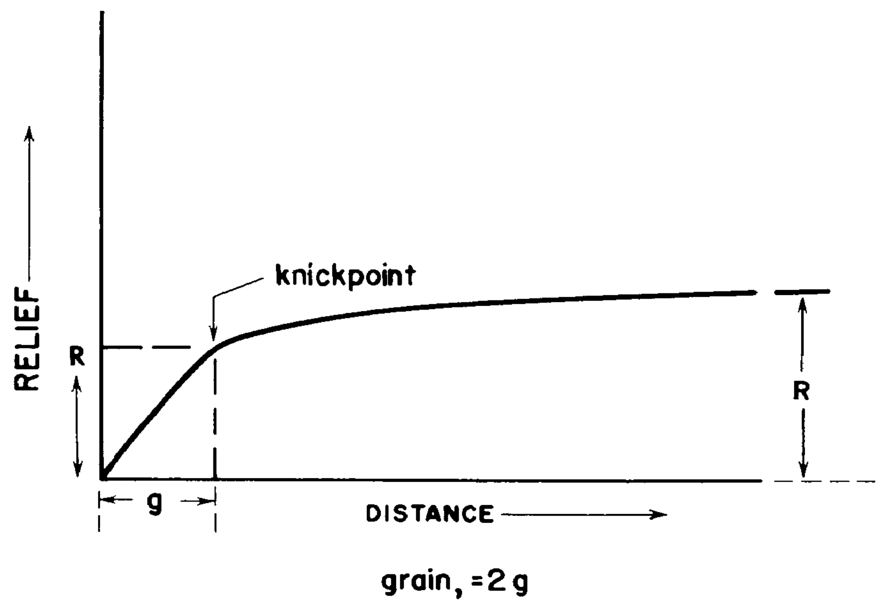


FIG. 6. — *Grain.*
$G = 2g$

Distance traversed, g, to the knickpoint is defined as the average peak-to-valley spacing, g, and the Grain, $G = 2g$.

Relief, R, is defined as the relief at the knickpoint.

Figures 7 (a) and 7 (b) show the derivation of a relief profile from the sample depth profile. As the knickpoint is defined at that point where the bend in the curve is steepest, then the knickpoint is that point on figure 8 (a) where the angle α is maximum or where the positive tangent of that angle is largest. These tangents can be represented by the vertical distances :

$$d_1, d_2, \ldots d_n$$

(figure 8 (b)) where

$$d_n = -R_{n-1} + 2R_n - R_{n+1}$$

Thus,

$$d_n \sim \frac{\partial^2 R}{\partial n^2}$$

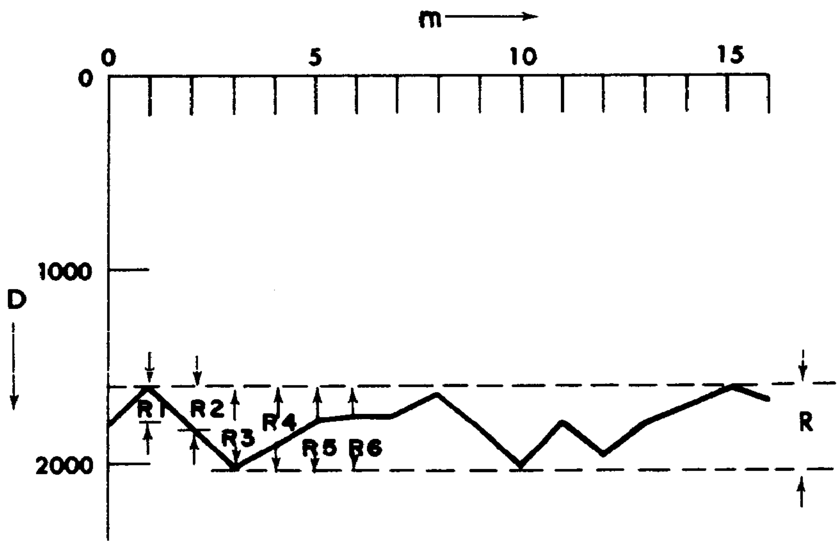


FIG. 7(*a*). — *Relief.*

$R_0 = 0$
$R_1 = | D_0 - D_1 |$
$R_2 = | D_1 - D_2 |$
$R_3 = | D_1 - D_3 |$
$R_4 = | D_1 - D_3 | = R_5 = R_6$

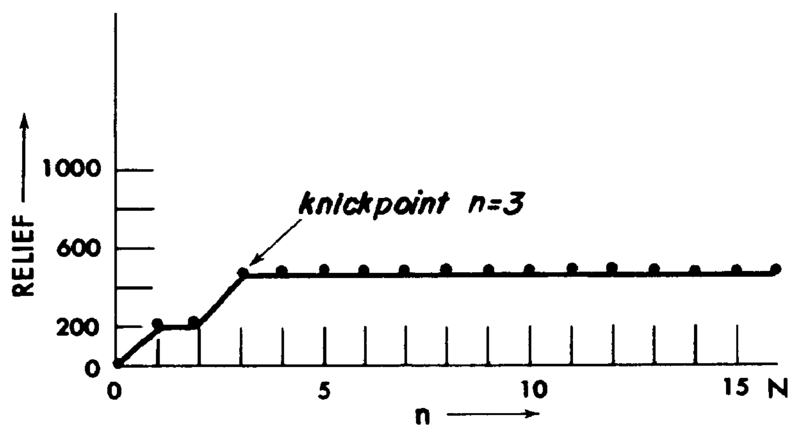


FIG. 7(*b*). — *Relief v.s. distance.*

(where the second derivative exists) and the knickpoint is at that point (n, R) where d_n is maximum, or where

$$\frac{\partial^3 R}{\partial n^3} = 0$$

(where the third derivative exists).

Solving for the value of n and the corresponding R,

$g = n \times$ spacing between soundings
Grain $= 2 \times n \times$ spacing between soundings
$G = 2 \times 3 \times 3 = 18$ miles for the sample segment and
$R = 457$ fathoms.

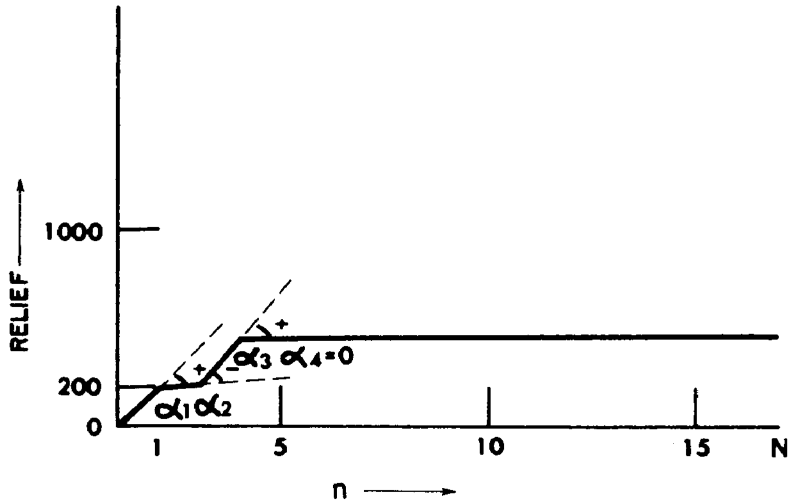


Fig. 8(*a*). — *Relief v.s. distance, showing deflection angles of the graph.*

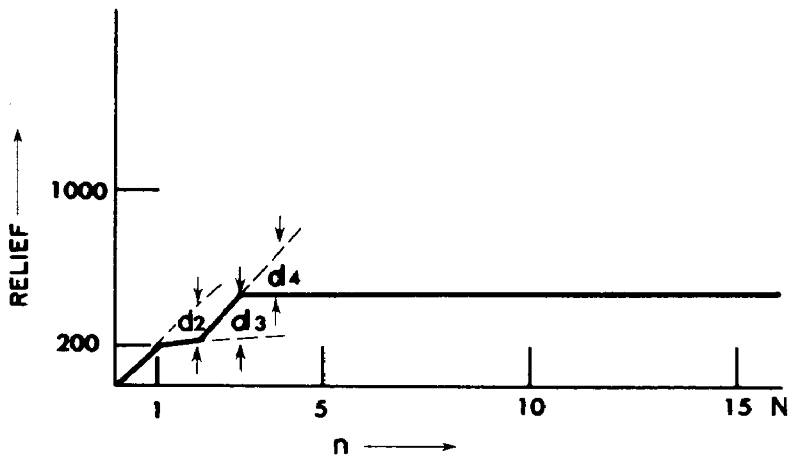


Fig. 8(*b*). — *Relief v.s. distance, showing tangents of the deflection angles.*

5. The Average Slope Tangent is defined simply as

$$ST = \frac{R}{g} = \frac{2R}{G}$$

6. Typical Slope Tangent, STT, takes into account instances where flatter areas intervening between steeper sides of peaks and valleys cause ST to indicate a gentler slope than is "typical" of the major peaks and valleys.

Figure 9 shows a hypothetical profile with a DRR of .2, illustrating this effect. The slope of the sides of the peaks, STT, is derived from ST and DRR by the relation :

$$STT = ST / (1 - 2\ |0.5 - DRR|)$$

as DRR is also an indicator of steepness of peaks or valleys with a given relief and grain.

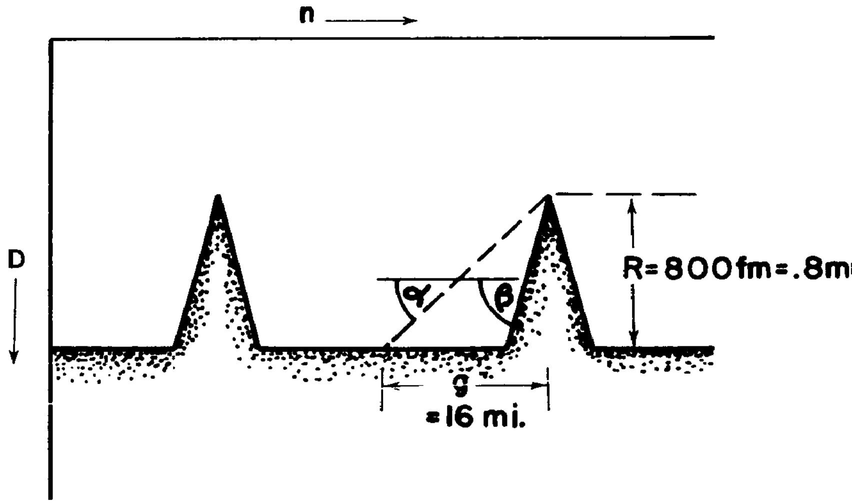


FIG. 9. — *Slope tangent,* ST *and typical slope tangent* STT, *of hypothetical profile with* DRR = .2

$$ST = \tan \alpha = .8/16 = .05$$
$$\alpha = 2.9°$$
$$STT = \tan \beta = .05 \,/\, (1-2\,|\,.5-DRR\,|) = .125$$
$$\beta = 7.1°$$

7. Minor Relief, r, and Minor Peak Spacing, L_m, are derived by comparing adjacent soundings. Minor Peak Spacing is computed simply by counting changes in slope direction. Half of this number, j, is the number, $j/2$, of Minor Peaks in the segment.

Thus, average peak spacing is the length of the segment divided by the number of peaks in the segment.

L_m = segment length/(j/2)

Average relief of these minor peaks, r, is computed by adding up the relief between all adjacent soundings (first differences) and dividing by the number of slope changes, j :

$$\Sigma\,(\text{1st difference}) =$$
$$= |D_1 - D_2| + |D_2 - D_3| + \ldots |D_n - D_{n+1}| + \ldots |D_{M-1} - D_M|$$
$$r = \Sigma\,(\text{1st difference}) \,/\, j$$

The computed L_m value is only a maximum value of minor peak spacing and the sensitivity of this indicator is inversely proportional to the spacing between soundings. Owing to the effect of "aliasing", the computed L_m is usually greater than measured L_m. For example, the hypothetical profile of figure 10 (a) and the profile based on 17 soundings from that same profile (figure 10 (b)) show the effect of aliasing. Thirteen changes in slope direction shown on figure 10 (a) can be detected as only 10 changes in figure 10 (b); thus, the computed (apparent) L_m is here 33 % larger than the real L_m.

8. Minor Slope Tangents, st_1 and st_2, are the slopes of the above minor features as they are superimposed on the major features. They are computed by the relation :

$$st = 2r / L_m$$
$$st_1 = st - ST$$
$$st_2 = st + ST$$

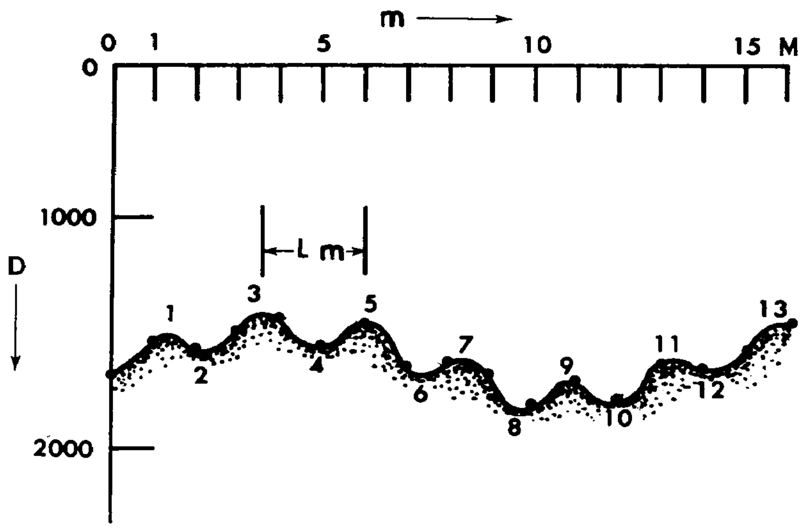


FIG. 10(*a*). — *Aliasing.*
Real L_m = length of segment ÷ number of peaks

$$= \frac{16}{(13/2)} = 2.4$$

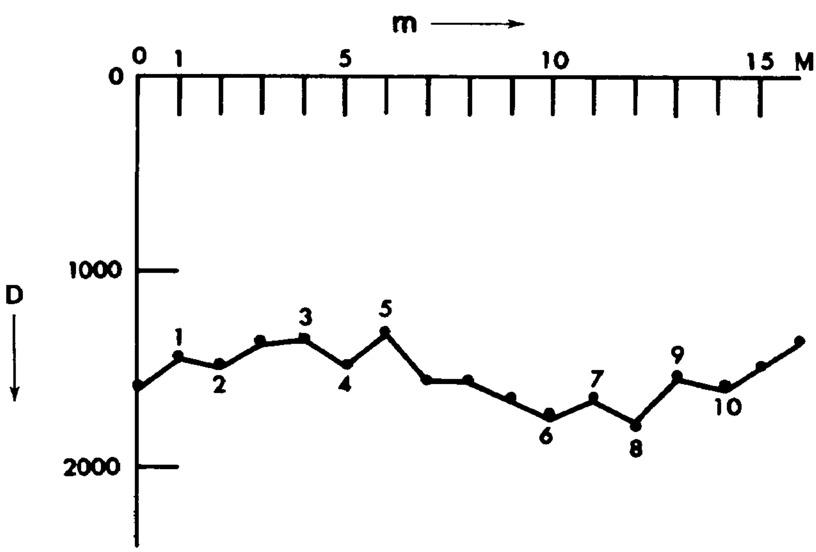


FIG. 10(*b*). — *Aliasing.*
Computed L_m = length of segment ÷ number of peaks

$$= \frac{16}{(10/2)} = 3.2$$

a 33 % increase over the real L_m

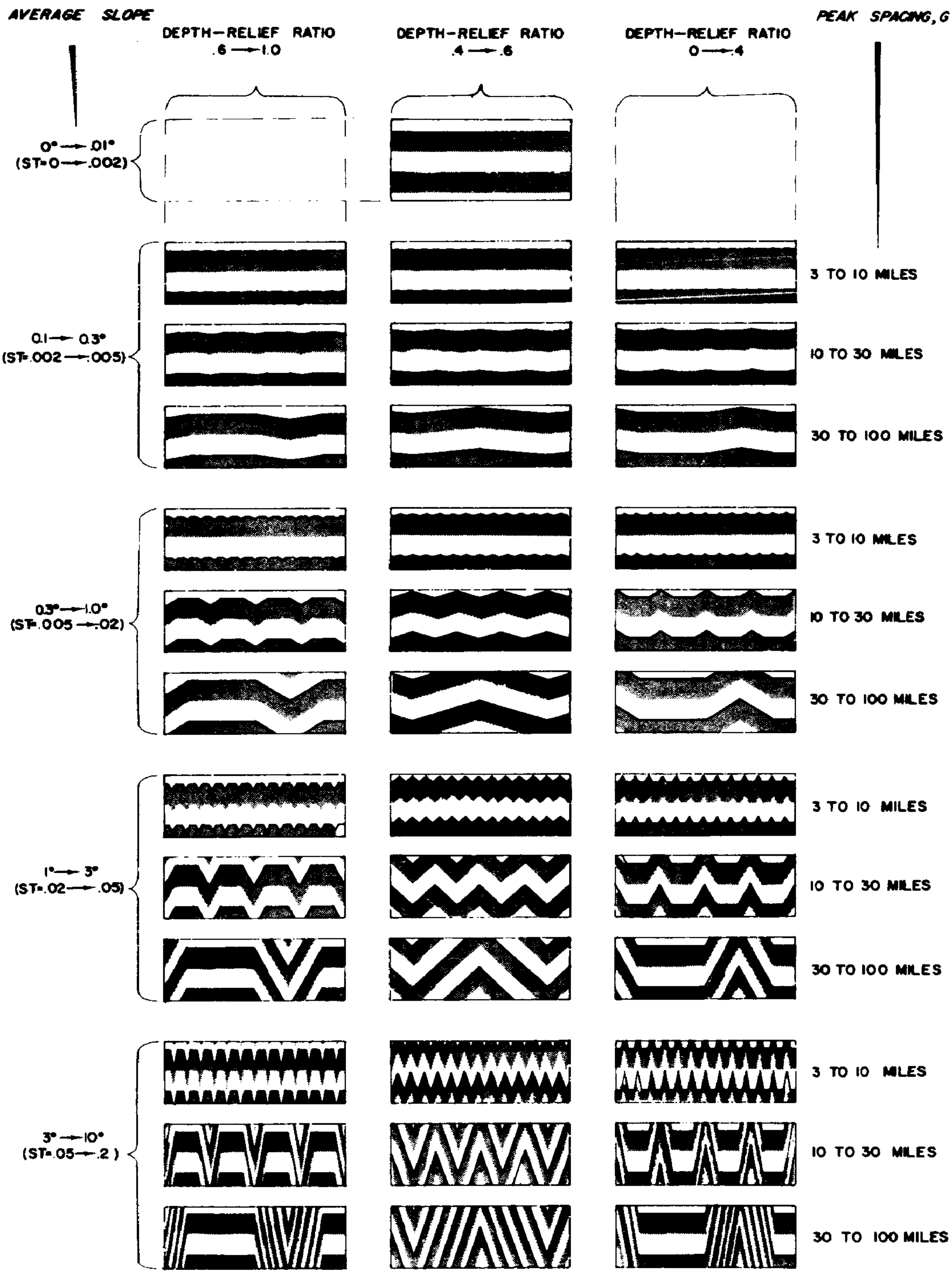


FIG. 11. — Legend of ocean terrain geometry factors.

9. Roughness Index, *r.i.*, is computed by summing the second differences and dividing by the number of second differences.

Σ (2nd diff) $=$

$$[|| D_1 - D_2 | - | D_2 - D_3 || + || D_2 - D_3 | - | D_3 - D_4 || + \dots | D_{M-1} - D_M ||]$$

$$r.i. = \Sigma \text{(2nd diff)} / (M - 1)$$

CHARTING TERRAIN PARAMETERS

A graphic display of terrain parameters derived by the above procedures might be a chart which delineates the different terrain provinces by various patterns of symbols keyed to a legend (after Van Lopick and Kolb, 1959). Each pattern would represent a combination of parameters whose numerical values fall within specified ranges. An example of a terrain legend is shown on figure 11. Three parameters are used, DRR, Grain, and Average Slope; symbols would be drawn to the same horizontal scale as accompanying chart and to a 20 : 1 vertical exaggeration. Thus these symbols, when printed on a chart, are a schematic representation of predicted topography. Slopes and shapes of these symbols represent, in a schematic way, slopes and shapes of real topography as would be seen on a series of fathograms taken in the same respective provinces.

These charts can be constructed as follows : Parameters (slope tangent, grain, depth-relief ratio, etc.) are plotted at the center point of the respective segments and a contour chart is made separately for each of these parameters. All of these contour charts are combined to yield blocks or provinces of terrain types which are then printed with the appropriate symbols.

Conclusion

The method has been programmed for automatic computation of terrain types by an IBM 7070 computer. A program is under development for automatic display of terrain charts.

This study is intended to meet the need for a system of rapid, quantitative analysis and display of ocean terrain. The resulting classification and mapping of terrain can be applied to problems requiring statistical averages or predictions of submarine topography such as :

1. Angles of incidence for bottom-bounce sonar.
2. Terrain requirements of bottom-mounted sonar arrays.
3. Utilization of topography by submarines.
4. Delineation of geomorphic provinces in poorly-sounded oceans.

This study is incomplete and more objective methods for charting terrain are now under development by this author.

TABULAR SOLUTIONS

	D	m	$D_o \longrightarrow D_{M/2}$	$D_{M/2} \longrightarrow D_M$
D_1	1 540	0	1 540	1 640
D_2	1 360	1	1 360	1 800
D_3	1 600	2	1 600	2 060
D_4	1 850	3	1 850	1 870
D_5	1 790	4	1 790	2 090
D_6	1 690	5	1 690	1 960
D_7	1 680	6	1 680	1 930
D_8	1 720	7	1 720	1 860
D_9	1 640	8	1 640	1 940
D_{10}	1 800	9		
D_{11}	2 060	10	$\sum_{m=o}^{M/2} D_m = 14\,870$	$\sum_{m=M/2}^{M} D_m = 17\,150$
D_{12}	1 870	11		
D_{13}	2 090	12		
D_{14}	1 960	13		
D_{15}	1 930	14		
D_{16}	1 860	15		
D_{17}	1 940	16 = M		

$$\sum_{m=o}^{M/2} D_m \;-\; \sum_{m=M/2}^{M} D_m = 14\,870 - 17\,150 = -2\,280$$

$\sum D = 30\,380$

$$\Delta D_m = \Delta D_1 = -2\,280\ (2/M) = -2\,280 \times 8.5$$
$$= -268$$

$$\Delta D_m = 2\ [-268\ (1/2 - m/M)] = -268\ (m/M)$$

D_m	m	m/M	$\Delta D_M \times (m/M)$
1 540	0	0	0
1 360	1	1/16	- 17
1 600	2	1/8	- 33
1 850	3	3/16	- 50
1 790	4	1/4	- 67
1 690	5	5/16	- 84
1 680	6	3/8	- 100
1 720	7	7/16	- 117
1 640	8	1/2	- 134
1 800	9	9/16	- 151
2 060	10	5/8	- 167
1 870	11	11/16	- 184
2 090	12	3/4	- 201
1 960	13	13/16	- 218
1 930	14	7/8	- 234
1 860	15	15/16	- 251
1 940	16	1	- 268

$\Delta D_m = 2\,[\Delta D_M\,(1/2 - m/(M))]$	$D_{mc} = D_m + \Delta D_m$	
+ 268	1 808	
+ 234	1 594	
+ 201	1 801	
+ 167	2 017	
+ 134	1 924	
+ 100	1 790	
+ 67	1 747	Profile
+ 33	1 753	With
0	1 640	Regional
- 33	1 767	Slope
- 67	1 993	Removed
- 100	1 770	
- 134	1 956	
- 167	1 793	
- 201	1 729	
- 234	1 626	
- 268	1 672	

Σ = 30 381, check

m	D_{mc}	Accum. Max., D_{max}	Accum. Min., D_{min}	$D_{max} - D_{min} = R_n$
0	1 808	1 808	1 808	0
1	1 594	1 808	1 594	214
2	1 801	1 808	1 594	214
3	2 017	2 017	1 594	423
4	1 924	2 017	1 594	423
5	1 790	2 017	1 594	423
6	1 747	2 017	1 594	423
7	1 753	2 017	1 594	423
8	1 640	2 017	1 594	423
9	1 767	2 017	1 594	423
10	1 993	2 017	1 594	423
11	1 770	2 017	1 594	423
12	1 956	2 017	1 594	423
13	1 793	2 017	1 594	423
14	1 729	2 017	1 594	423
15	1 626	2 017	1 594	423
16	1 672	2 017	1 594	423

n	$-R_{n-1}$	$2R_n$	$-R_{n+1}$	$d_n = -R_{n-1} + 2R_n - R_{n+1}$
0		+ 0	- 214	- 214
1	- 0	+ 428	- 214	+ 214
2	- 214	+ 428	- 423	- 209
3	- 214	+ 846	- 423	+ 209
4	- 423	+ 846	- 423	0
5	- 423	+ 846	- 423	0
6	- 423	+ 846	- 423	0
7	- 423	+ 846	- 423	0
8	- 423	+ 846	- 423	0
9	- 423	+ 846	- 423	0
10	- 423	+ 846	- 423	0
11	- 423	+ 846	- 423	0
12	- 423	+ 846	- 423	0
13	- 423	+ 846	- 423	0
14	- 423	+ 846	- 423	0
15	- 423	+ 846	- 423	0
16	- 423	+ 846		

max d_n = 209 at n = 3

g = (n) (3 mi) = 9 miles

G = (2) (g) = 18 miles

R_3 = 423 fms

ST = R/g = 423/(9 × 1 013) = .053

Average crest-to-depression slope = Arctan .053 = 3°

		1st. Diff.	Change in Sign	2nd. Diff.
D_1	1 808	+ 214		
D_2	1 594	- 207	X	7
D_3	1 801	- 216		9
D_4	2 017	+ 93	X	123
D_5	1 924	+ 134		41
D_6	1 790	+ 43		91
D_7	1 747	- 06	X	37
D_8	1 753	+ 113	X	107
D_9	1 640	- 127	X	14
D_{10}	1 767	- 226		99
D_{11}	1 993	+ 223	X	3
D_{12}	1 770	- 186	X	37
D_{13}	1 956	+ 163	X	23
D_{14}	1 793	+ 64		99
D_{15}	1 729	+ 103		39
D_{16}	1 626	- 46	X	57
D_{17}	1 672		X	
		$\sum$ (1st diff.) = 2 164	j = 10	$\sum$ (2nd diff.) = 786

r = $\sum$ 1st diff / j = 2 164/10 = 216 fms

r.i. = $\sum$ 2nd diff / (M-1) + 786/15 = 52

Lm = segment length / j/2 = 48/5 ≃ 10 miles

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