THE RELATIVE ACCURACY OF SOME MAGNETIC DEPTH-DETERMINATION TECHNIQUES

by

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ABSTRACT

The determination of the depth to an anomaly-causing body is an important part in the interpretation of magnetic anomalies, and various methods can be used to accomplish this goal. In this study the relative accuracy of some of these depth-determination techniques is investigated and conclusions are drawn as to their applicability.

Total-intensity magnetic profiles were calculated over three basic models. The dimensions of these vertical-sided, rectangular bodies were varied to approximate various geological models, such as a horizontal pipe, a vertical dike, a thin horizontal plate, a vertical pipe, and an equidimensional body. In addition to these changes in model dimensions, variations in the strike and dip of the body, as well as in the regional applied to the anomaly, and the declination of the magnetic field, were then applied to a few specific models.

Four amplitude-measuring techniques, which use the width of the anomaly at some amplitude level, and two slope-measuring methods, which use the steepness of the flanks of the anomaly, were then applied to each profile, and the calculated depths compared with each other and the known model depth.

Overall results indicate that the slope-measuring techniques are decidedly inferior in most of the above-mentioned aspects to the amplitude-measuring methods, and could not be repeated to within an accuracy of 12 percent of the calculated depth.

The depth extent of the body is an important factor. When a thin, horizontal plate was extended into a vertical pipe, differences in depths as much as 35 to 63 percent were obtained for the amplitude-measuring techniques and slope-measuring methods respectively. The effect of depth extent decreases with increasing two-dimensionality of the model.

The range of depth variation for a change in horizontal extent of the models varied between 5 and 18 percent for the amplitude-measuring methods and 5 and 35 percent for the slope-measuring techniques. The effects of changes in declination (up to 20 degrees), strike of the body (within 20 degrees from perpendicular to the profile), and profile position relative to the center of the body are very small and can generally be ignored. A 40-degree change in dip from the vertical gave rise to a variation in determined depths of up to 40 and 28 percent for the slope-measuring and amplitude-measuring techniques respectively.

The source of the largest error introduced in the process of depth-determination, as studied in this thesis, is found in the incomplete or erroneous removal of the regional of the anomaly. Relatively small changes in the base level of the anomaly led to a variation in determined depths of 72 and 58 percent for the slope-measuring methods and amplitude-measuring techniques respectively.

In conclusion it is stated that the slope-measuring methods were found to be very unsatisfactory for any measure of accuracy in magnetic depth determinations. Slightly better results were obtained with the amplitude-measuring methods. The inherent ambiguity of all potential-field methods cannot be overcome in magnetic depth determinations without additional information regarding the geological and geophysical parameters of the anomalous body. A use for magnetic depth determinations can, however, be found in the determination of relative depths of similar bodies in a similar environment.

INTRODUCTION

One of the primary uses of magnetic anomaly maps and profiles is the determination of the depth to the top, or some other point, of the body causing an anomaly in the observed field. This process can usually not be undertaken without a series of preceding steps, such as the removal of the regional gradient of the profile or map, and the separation of the disturbing effects of adjoining anomalies. Any errors in these processes are the cause of uncertainties in the finally interpreted depths. In addition, a large number of other factors influence the accuracy of the depth-determination techniques, such as the shape of the body, the dip and strike of an anomalous mass, and many others. This thesis is primarily concerned with the relative accuracy of some of the depth-determination techniques and the extent to which they are sensitive to a number of disturbing factors.

Some depth-determination techniques have a mathematical basis, while others are purely empirical or have been derived from model studies. For the purpose of this thesis, the techniques can generally be classified as follows:

a) direct profile observations,

b) curve matching techniques,

c) model building techniques.

All of these techniques require some assumptions or previous knowledge of the geological setting or parameters of the disturbing body, particularly the last two, which can be considered more sophisticated than the first. Direct profile observations, however, are important because they can be applied in the early stages of the interpretation process, generally require little or no additional knowledge, and can be done with the information contained in the profile or map without consuming a large amount of time or money. This study is therefore concerned only with depth-determination techniques using direct profile observations and with the validity and accuracy of these techniques under different conditions and assumptions. This restriction does not imply that the author considers any other technique inferior to direct profile observations, but it does mean that he considers the application of a fast and inexpensive technique to be a matter that warrants investigation.

The following method was used in the investigation of the problem. A number of model bodies were designed, and a total-intensity magnetic profile was calculated for each of these bodies under varying conditions and with different depths. Depth-determination techniques were then applied to each of these profiles. A total of 672 depths was determined and compared with each other and the known model depth. The results are presented in various graphs and tables from which a number of conclusions can be drawn.

SELECTION OF THE MODELS

Geological bodies occur in nature in a large variety of shapes and sizes. A virtually unlimited number of models can therefore be selected to represent geological structures and bodies. Meaningful and comparable results will be obtained only if regularly shaped models are chosen. Three basic structural types were used as models in the generation of the total-field magnetic profiles and are shown in Fig. 1. The depth extent of these vertical-sided, rectangular bodies was varied so that different geological structures could be approximated.

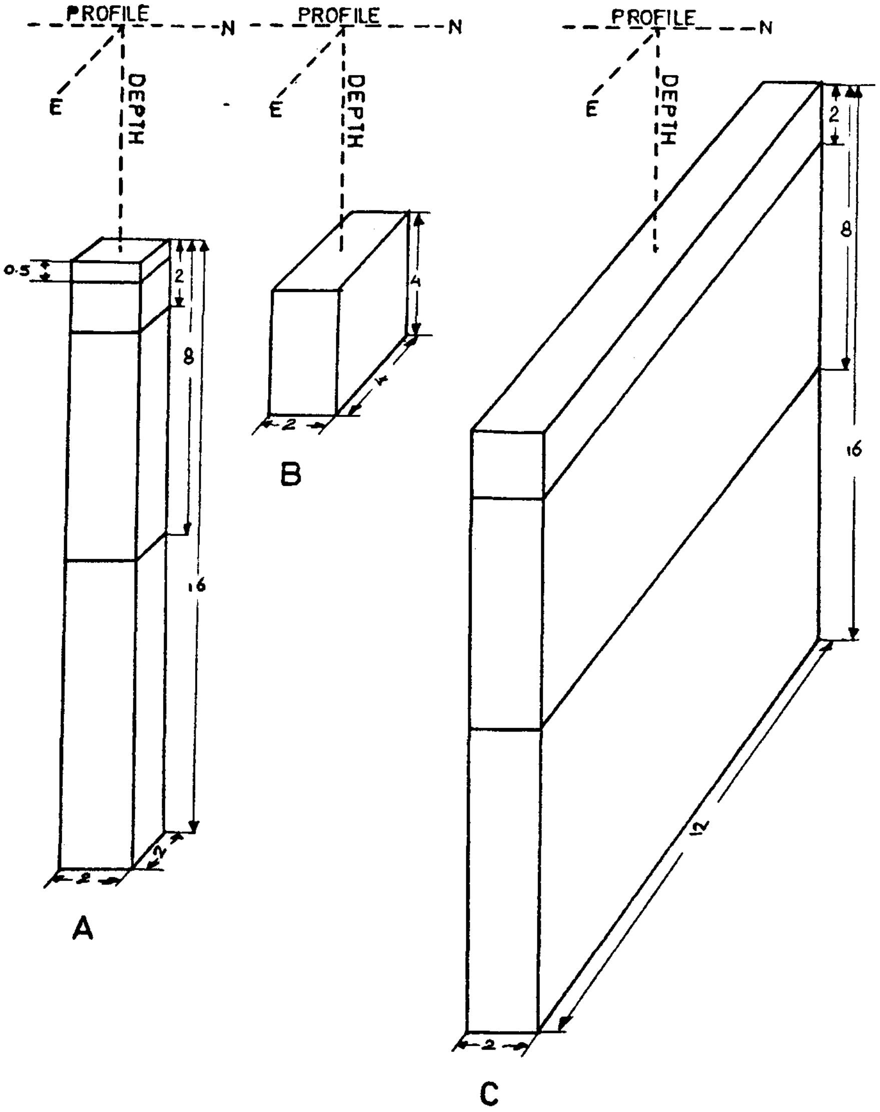
Model Dimensions

The width-length-depth extent ratio of the models is expressed in dimensionless station-spacing units.

Model 1 (Fig. 1A) This model varies in shape from a thin plate to a deep, vertical pipe. The dimensions of the models in this series are the following:

2 x 2 x 0.5 units (plate),
2 x 2 x 2 units
2 x 2 x 8 units,
2 x 2 x 16 units (pipe).

A geological correlative for these models can be found in a thin, plate-like irregularity on a basement floor



A = HORIZONTAL-PLATE, VERTICAL-PIPE MODEL.

B = THREE-DIMENSIONAL MODEL

C = HORIZONTAL-PIPE, VERTICAL-DIKE MODEL

FIG. 1

(supra-basement structure), and a long, narrow, vertical intrusive or volcanic pipe.

Model 2 (Fig. 1B) A single body, dimensions 2 x 4 x 4 units, was chosen to represent a three-dimensional body, which was assumed to be a reasonable compromise between an uplifted block of basement floor, an intrusive, or a large, erosional subsurface irregularity.

Model 3 (Fig. 1C) This model was chosen to vary from a thin, horizontal pipe-like body to a vertical dike. The series of models have the following dimensions:

2 x 12 x 2 units (pipe),
2 x 12 x 8 units,
2 x 12 x 16units (dike).

The horizontal length extent of 12 units was taken to sufficiently represent two dimensionality for the profile (Daniels, 1970, p. 34). Geological correlatives can be found in a horizontal lava tube and a mineralized faultzone or dike.

The Magnetic Field

The magnetic anomaly generated by the model was assumed to be due to induced polarization only. The earth's magnetic field was assigned the following values:

Magnetic Field Strength - 50,000 gammas,
Declination - 0°,
Inclination - 60°.

The susceptibility contrast throughout the model was taken to be uniform, and a constant value of 0.01 c.g.s. units was assigned to it.

The Profile

The profile was chosen to cross the body at right angles over the center point of the body. The lateral extent of the profile was terminated at a distance of ten times the width of the body on either side of the model. It was assumed that at this distance the anomaly can no longer be regarded as interpretable due to interference from adjoining anomalies.

In all practical applications, finite coverage only of an anomaly is available. Forty points were taken on each profile, except in a few instances where the profile was terminated at ten points on either side of the body. The center of the profile was taken to coincide with the projection of the center of the body on the surface. (Fig. 1).

The Varying Parameters

Several parameters were varied in the generation of the profiles, or prior to the application of the depth-determination techniques. These variations will be discussed here. A summary of the variations is indicated in Table 1.

Depth So that an insight could be gained into the relative accuracy of the depth-determination techniques, the depth to the top of the body was varied for each of the models and each of the other varying parameters. Depths of 2, 4, and 8 station-spacing units were used. In one instance an additional depth of 6 units was used, as shown in Table 1.

Profile Position If the full extent of an anomaly is accurately known, most interpretation techniques can generally be applied with good results. When, however, a body is crossed by only one or two profiles, the size and shape of the causative body is not easily determined. It cannot always be assumed that a profile crosses the center of the body, and if only one or two profiles are available, they can be situated at any point on or off the body. To see whether the displacement of the profile from the center of the body would have any appreciable effect on the determined depths, three profile lines were chosen to cross the three-dimensional body, dimensions 2 x 4 x 4 units, at various positions (Fig. 2).

Strike The strike of the body in all the investigations was assumed to be perpendicular to the profile. In two instances, however, the strike was varied to investigate the behavior of the depth-determination techniques. This variation was applied to the three-dimensional body, dimensions 2 x 4 x 4 units, and to the dike-like structure, dimensions

Body parameter	Depth	Profile length	Regional variation	Profile position	Dip	Strike	Declination variation	Remarks
2x2x0.5	2,4,8	40	none	center	90°	0°	0°	plate ↓ pipe
2x2x2								
2x2x8								
2x2x16					90°,70°,50°			
2x4x4					90°	0°,10°,20°		3-D model
	2,4,6,8	20	yes	varied		0°	0°,10°,20°	
2x12x2	2,4,8	40	none	center			0°	pipe ↓ dike
2x12x8								
2x12x16					90°,70°,50°	0°,10°,20°		

TABLE 1. Variations in parameters.

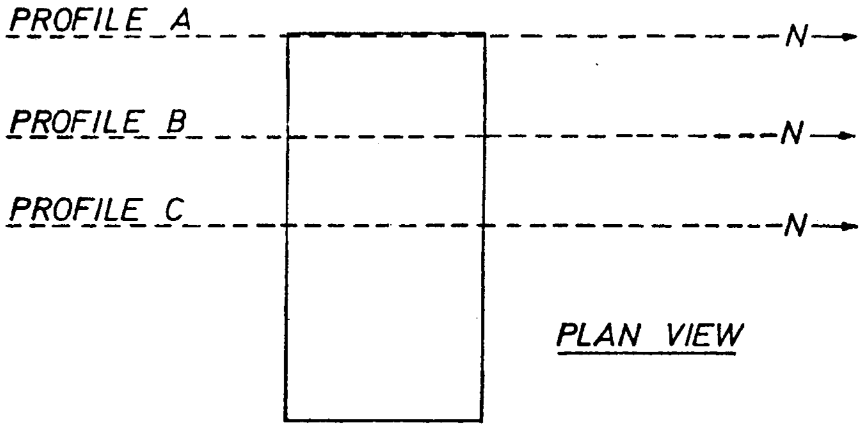

PROFILE A
N
PROFILE B
N
PROFILE C
N
PLAN VIEW

FIG. 2

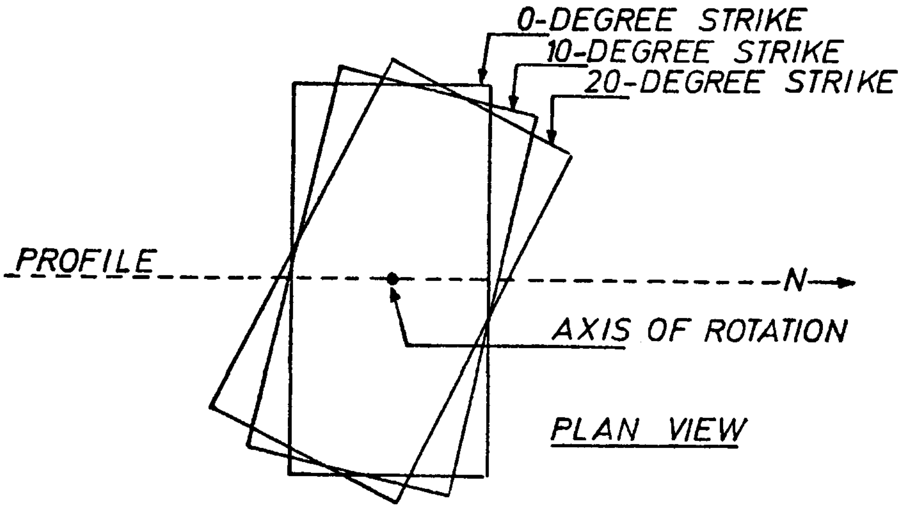

0-DEGREE STRIKE
10-DEGREE STRIKE
20-DEGREE STRIKE
PROFILE
N
AXIS OF ROTATION
PLAN VIEW

FIG. 3

2 x 12 x 16 units. A strike change of 10° and 20° was introduced and the depth determination repeated (Fig. 3). The body was rotated along an imaginary vertical axis through the center of the body.

Dip The variation in the results of depth-determination techniques was investigated for two bodies with large vertical extent. A deviation from the vertical of 20° and 40° was imposed upon the vertical pipe-like body, dimensions 2 x 2 x 16 units and the dike-like structure, dimensions 2 x 12 x 16 units (Fig. 4). The top surface of the body was held constant, as well as the vertical extent of the body.

Regional Inaccuracies in the final profile that is used for depth-determinations can be caused by either incomplete removal of the regional field or by remaining disturbing influences of adjoining anomalies. To investigate whether such a regional fluctuation would have an effect upon the determined depths, a variation of the regional was imposed upon the calculated profile. In Fig. 5 these fluctuations are indicated in which the level 0 - 0 is the original zero-level as calculated. A translation of the regional upward and downward through a distance of one-half the maximum negative anomaly (distance "A") was used for regionals I and II. Regionals III and IV have undergone rotation through half the width of the regional variation as indicated. These variations, both translation and rotation, were combined to give the maximum deviation effect. The combined effect of regionals I + III is indicated in Fig. 5. The effect of regional variations on the determined depths was investigated for the three-dimensional body, dimensions 2 x 4 x 4 units, only.

Declination (Remnant Magnetization) Another problem that, in the writer's opinion, warranted investigation was the effect of remnant magnetism of the body. This effect adds a vector field to the induced magnetization vector, and effectively changes its amplitude and direction. This effect was approximated in the model studies by changing the declination, and not the amplitude, of the induced magnetization vector, by amounts of

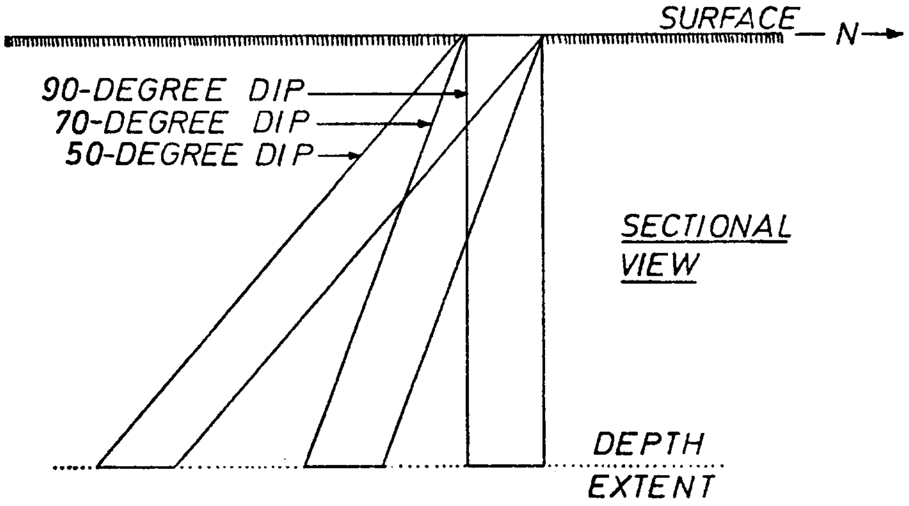

SURFACE
N
90-DEGREE DIP
70-DEGREE DIP
50-DEGREE DIP
SECTIONAL VIEW
DEPTH EXTENT

FIG. 4

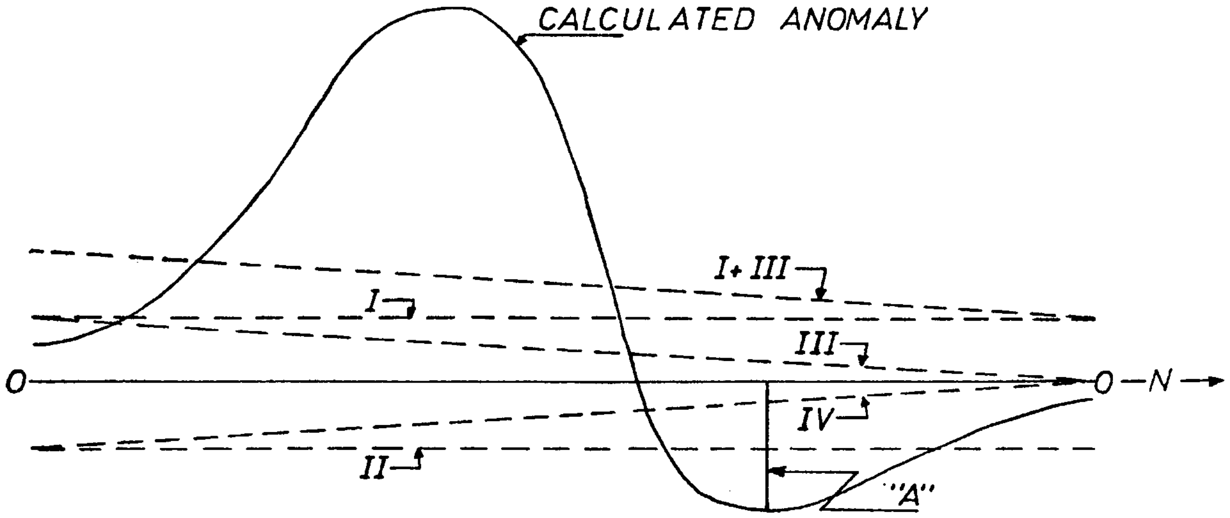

CALCULATED ANOMALY
I+III
I
III
O
O
N
IV
II
"A"

FIG. 5

10° and 20° in an easterly direction. A change of declination of 20° would be roughly equivalent to a remnant magnetization vector, strength 17500 gammas, in a ESE-direction. The effect of remnant magnetization (change in declination) was investigated for the three-dimensional body, dimensions 2 x 4 x 4 units, only. A summary of the varying parameters is given in Table 1.

Profile Calculation

The total-intensity magnetic profiles were calculated by use of a technique developed by Talwani (Talwani et al, 1965, p. 797), a technique that uses the volume integrals over the body along a set of contour lines. The program was adapted for use on the Colorado School of Mines PDP-10 computer. All profiles were plotted on the Calcomp plotter, using the computer-generated output. To check the accuracy of the program, a few examples of computed anomalies were taken from Vaquier (Vaquier et al, 1951) and recalculated by using the adapted Talwani technique and the results compared. Satisfactory results were obtained with models described with 5 and 9 contour lines. The number of contour lines was directly related to the depth extent of the models.

DEPTH DETERMINATION METHODS

Many methods make use of one or more characteristic properties of the observed anomaly. Most, if not all, of these techniques are inaccurate to some extent, as certain assumptions have to be made regarding the shape, depth extent, or magnetic pole or dipole configuration of these bodies. Heiland (1968, p. 380) states that the magnetic method lacks depth control. This inherent problem cannot easily be overcome without the necessary assumptions. Some information regarding the depth extent, strike, and dip of the anomalous body can usually be obtained from a study of magnetic maps (Parasnis, 1966, p. 42-43), but this advantage disappears to a large extent in the interpretation of magnetic profiles.

A number of publications are devoted to the study of depth-determination techniques. Gay (1963), McGrath and Hood (1970), and Hutchinson (1958) investigated curve-matching techniques to derive an approximation to the depth to the body. Model studies have been undertaken by Henderson and Zietz (1948, 1967) and Cook (1950). Jakosky (1957, p. 215) discusses the subject of depth determination by magnetic triangulation; Vaquier and others (1951) have published an extensive summary of magnetic anomalies over a series of three-dimensional bodies and derived relationships between the depth to the body and the distances between points of maximum, minumum, and zero curvature of the anomalies.

As this study is primarily concerned with the relative accuracy of depth-determination techniques as applied to profiles under the assumption that little or nothing is known about the geometry or other properties of the anomaly-causing body, only the relatively simple techniques were selected for investigation. Two publications exist, however, that warrant a discussion, although the methods proposed in them were not used in this study.

Henderson and Zietz (1967) used amplitude measurements of the anomaly over a magnetic doublet to derive a series of coefficients for depth-determination calculations. The distances from the maximum value of the anomaly to the points of inflection, minimum-, 0.8-, and 0.1-amplitude value, are determined in this process. The author's main objection to the technique is that the value of 0.1-maximum amplitude would be very sensitive to disturbing influences of adjoining anomalies. The dipole extent, stated by Henderson and Zietz (1967) to be 0.01 depth units, is in the writer's opinion not sufficiently flexible to cover a variety of geological models, and the method was therefore not considered in this study.

Peters (1949) discusses his half-slope technique, in which the horizontal distance between the points of tangency of one-half the maximum slope of the anomaly is used as a depth indicator. Dobrin (1960, p. 330) states that this method gives very satisfactory results and can also be used in the interpretation of aeromagnetic (i. e. presumably total-field) data as well. Peters (1949) restricts his method as applicable only to vertical-sided prisms with the following parameters:

length: width ratio >3,
length: thickness ratio >6.

The body must be symmetrically magnetized. The width-depth ratio of this body is used to derive a set of coefficients as a multiplicator with the depth indicator. These coefficients vary between 0.5 and 2.0 for width-depth ratios of 0 and ∞ respectively. The limitations placed on the shape of the body seem to limit the application of this technique to a large extent, and it was therefore not considered in this study.

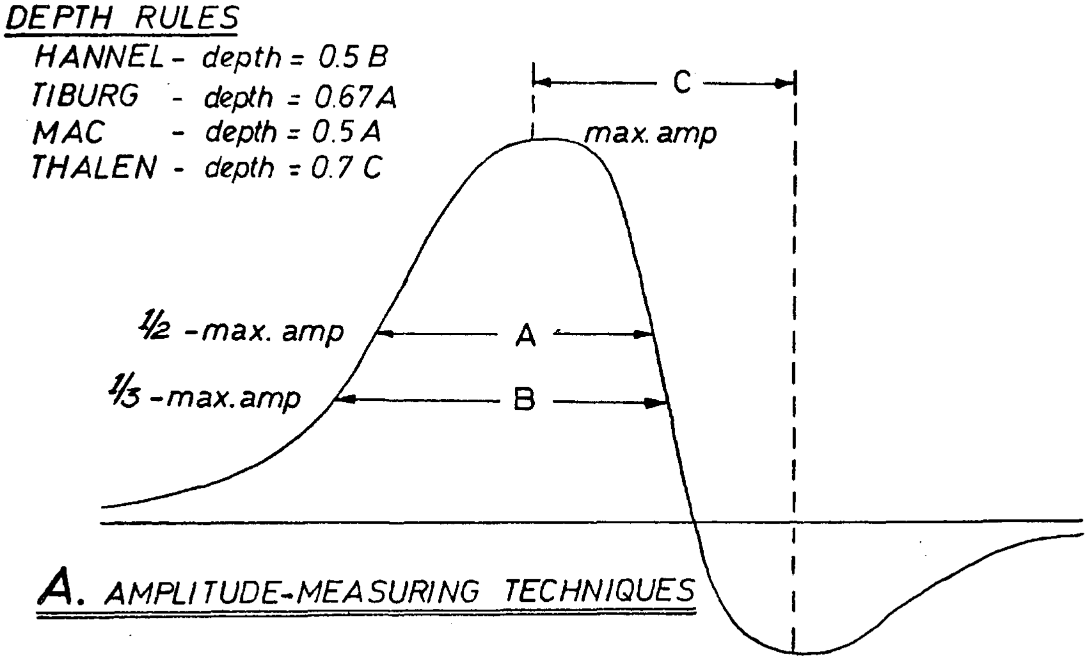
Amplitude-measuring Techniques

These techniques are based on the use of the width of the anomaly at a certain amplitude level as a depth indicator

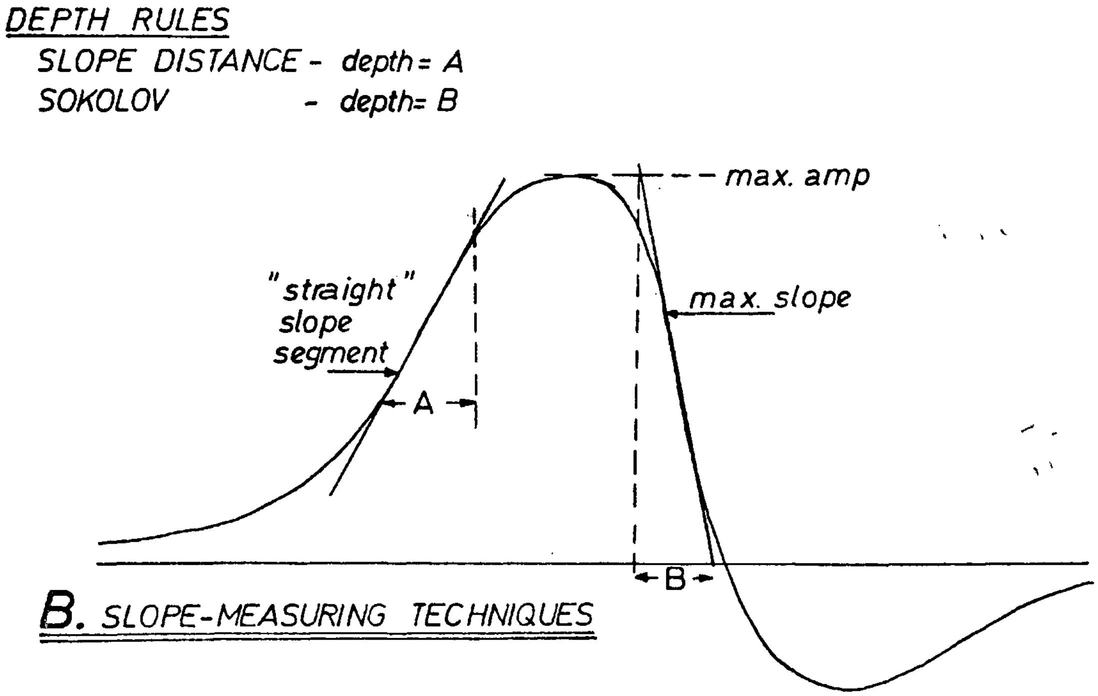
(Fig. 6A). The basis of these methods is found in the development of the theory of the magnetic field due to a single pole, a single dipole, or a series of poles and dipoles (Smellie, 1956). The use of these methods was primarily restricted to the vertical-intensity anomaly, although the use was also advocated for high-latitude total-intensity anomalies (Dobrin, 1960, p. 311). The methods are known by various names. The use of these names by the author of this thesis does not imply any proprietary aspects, nor that these names are necessarily the only or correct names under which a technique is known, but it provided an easy way to distinguish between the methods.

Mac Rule

This is one of the simplest rules. It relates the depth to a single pole, or the upper pole of a doublet of infinite length to the horizontal distance between the points of maximum and half-maximum amplitude on the anomaly (Heiland, 1968, p. 387). Two depth indices can be measured this way, one in either direction from the point of maximum amplitude of the anomaly. Jakosky (1957, p. 189), who uses the mean of these two values, states that the depth to a dike of infinite depth extent equals half the horizontal distance between points of half-maximum amplitude. Daniels (1970, p. 32) uses the same relationship but applies it to a vertical body of infinite strike length and depth extent, under vertical magnetization. Smellie (1956) has considerably refined this technique by deriving depth-indices coefficients for poles, dipoles, and lines of poles and dipoles for different amounts of inclination and strike of the body. The depth indices of Smellie are applicable to the distance between the maximum and half-maximum parts of the anomaly only and Smellie defines two coefficients for each anomaly. For example for a single pole, inclination 60°, Smellie's coefficients are approximately 1.52 and 1.15 for the northern and southern half of the anomaly respectively (Smellie, 1956, p. 1026).



A. AMPLITUDE-MEASURING TECHNIQUES



B. SLOPE-MEASURING TECHNIQUES

FIG. 6

Smellie (1956) does not differentiate between coefficients for different depths to the body and seems to assume that the relationship between the width of the anomaly and the depth to the body is strictly linear. He does, however, mention that the determined depths can either be the depth to the top or the center of the body, depending on its geometric shape. The estimated depth will be a maximum value (Smellie, 1966, p. 1022).

Dobrin (1960, p. 311) states that all half-width techniques lack precision because of interference from adjoining anomalies and states that the half-width techniques can be applied only to bodies of known shape; for example, the depth to the center of a sphere is given as 2 times the half-width, while for a horizontal cylinder the depth to the center is 2.05 times the half-width at half-amplitude points of the anomaly.

According to Parasnis (1966, p. 41-42.) the half-width of the anomaly at half-amplitude values for a profile perpendicular to the strike of the body and on or near the anomaly center can be used only as a first approximation to the depth to the body. He has derived a set of coefficients (Parasnis, 1966, p. 42) varying between 1.0 and 1.7 for bodies of different depth extent and strike length. Once again the relationship between depth to the body and width of the anomaly is assumed to be linear, as no mention is made of any difference in coefficients for different depths to the body.

A summary of the preceding paragraphs in tabular form is given as follows:

Mac Rule - (depth to the body - 0.5 width of anomaly at half-amplitude points.)

Heiland - no coefficients, magnetic doublets of infinite length only.

Jakosky - no coefficients, for dike-like bodies only.

Smellie - coefficients for poles, dipoles, lines of poles and dipoles for different inclination and strike of body.

Dobrin -	no coefficients, applicable to bodies of known shape only, such as spheres and horizontal cylinders.
Parasnis -	coefficients vary with strike-length and depth-extent of body.

Tiburg Rule

This rule, which is closely associated with Mac's rule, states that the depth to the top of the body equals two-thirds of the distance between points of half-maximum amplitude of an anomaly. In the author's opinion this rule is the same as Mac's rule, but for a difference in coefficients only.

Heiland (1968, p. 382) states that the depth to a single pole is two-thirds times the distance between the maximum and half maximum points of the vertical-field anomaly over that pole. Jakosky (1957, p. 212, 213, and 186) uses the total width of the vertical-field anomaly at the half-maximum points and states that the depth to a single pole is two-thirds of this width. Dobrin (1960, p. 311) uses a slightly different figure and says that the half-width of the anomaly over a single pole at half-maximum amplitude equals 0.768 times the depth to the pole.

No further restrictions by any of these authors are placed on the body, other than that it must be approximated by a single pole only. The only geological correlative would be thin, vertical pipe of infinite depth extent, and the application of this technique would thus be highly limited. This depth-determination technique would not give the depth to the top of the body, but instead the depth to the pole.

Hannel Rule

This technique uses the halfwidth of the anomaly at one-third amplitude values, which equals the depth to the body. Few literature references could be found for this method, and it does not seem to be very popular or widely used.

Heiland (1968, p. 382) applies the rule to the vertical-field anomaly over a single pole. Jakosky (1957, p. 213) derives the depth to a single pole as 0.962 times the half-width of the anomaly at one-third amplitude points.

In general this technique would seem to measure the depth to the pole and not the depth to the top of the body.

Thalen Rule

This rather simple rule states that the depth to the top of vertical dipole of limited extent is 0.7 times the distance between the maximum and zero values of the vertical-field anomaly (Jakosky, 1957, p. 187). Heiland (1968, p. 381) mentions that the distance between the maximum- and minumum-amplitude values of the vertical-field anomaly over a magnetic doublet equals the depth to the center of the doublet, provided that the length of the dipole is greater than 1.5 times the depth to the upper pole. Dobrin (1960, p. 311) limits this technique further and states that it can be applied only to determine the depth to a fault, which equals the distance from the center to the edge of the anomaly. No further information is given.

In the application of this rule an approximation of Thalen's method as stated by Heiland (1968, p. 381) was used by the writer, in which the depth to the upper pole was taken as approximately 0.7 times the distance between maximum and minumum points of the anomaly. Once again the depth to the upper pole, and not to the top of the body, is determined in this technique.

Slope-measuring Techniques

The use of these techniques is widely accepted in industry. Apart from the previously mentioned half-slope method (Peters, 1949) and the Vaquier technique (Vaquier et al, 1951), the straight slope method and the Sokolov technique were found to be relatively simple and accordingly included in this study.

All slope-measuring techniques are based on the principle that the slope of the steepest part of an anomaly will decrease as the depth to the basement or disturbing body increases (Dobrin, 1960, p. 329). In practical applications the north or steep-slope side of the anomaly is generally used for depth determinations. (Daniels, 1970, p. 32). Both sides of the anomaly with different depths to the disturbing body were investigated (Fig. 6B).

Slope-distance Rule

In this technique, also known as the "straight-slope method," the depth to the body equals the horizontal distance between the upper and lower points of the apparent straight segment of the flank of the anomaly times a variable coefficient (Daniels, 1970, p. 33). There is no theoretical basis for the technique, although Daniels (1970, p. 33) reports that Vaquier and others (1951) have achieved excellent results with this technique. A literature search did not reveal any evidence of different coefficients for different parameters of the body and few references to the applicability of the technique could be found (Steenland, 1965). The coefficients in this study for both sides of the anomaly were therefore taken as unity. Daniels (1970, p. 35) investigated the accuracy of this technique and found the deviations in the determined depths to be generally greater than 10 percent.

Sokolov's Method

This little-known method equates the depth to the top of an anomaly with the product of a coefficient and the horizontal distance between the intersection of the maximum slope of the anomaly with the regional and the intersection of the maximum slope with a line parallel to the regional drawn through the maximum-amplitude point (Fig. 6B) (Sokolov, 1956). The coefficient as mentioned by Sokolov varies between 1.54 and 1.14, depending upon the width-depth (to top of body) ratio of the anomalous mass. Two disadvantages are present in this technique. One has to know the depth to the body before a coefficient can be determined, and the relative amplitude of the regional or zero level of the anomaly has to be accurately known.

It is rather remarkable that this is the only technique encountered in the literature which recognizes that the relationship between the width of the anomaly and the depth to the body is not linear. This relationship will be further discussed in later chapters in this thesis.

For the purpose of this study the coefficients of the Sokolov depth rule were in all cases taken to be equal to unity.

RESULTS

The results of the depth determinations are shown in Table 2 for each of the varying parameters as discussed earlier. The calculated depth to the top of the body is shown, as well as a depth index, which was calculated as follows.

True depth = Depth index times Calculated depth.

The depths were determined by graphical methods from the computer-plotted profiles as shown in Fig. 6. Three depth values for each model were determined as a linear relationship between the depth to the body and the anomaly width or slope was assumed.

Errors in the Results

Three types of errors can be distinguished to play a role in the accuracy of the depth determinations.

1. Errors due to inaccuracies in the profile. These errors tend to be constant for each subsequent depth determination.

2. Errors due to the actual measuring technique that was used. This error varies for each depth determination and can be considered to be the repeatability of the method.

3. Errors inherent in the technique itself due to variations in the body parameters and/or other factors. These errors are the subject of investigation in this thesis and as such will be discussed in detail in a later chapter.

Errors Due to Inaccuracies in the Profile

These errors are not due to any computational procedure, but are primarily a result of the station spacing in the pro-

PARAMETERS				DETERMINED DEPTHS & COEFFICIENTS							
Body shape	Variable parameter	Amount of variation	DEPTH	Hannel Rule	Mac Rule	Tiburg Rule	Thalén Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
2x2x0.5	none		2	1.11	1.43	1.05	0.95	1.05	1.33	0.71	1.18
				1.8	1.4	1.9	2.1	1.9	1.5	2.8	1.7
			4	1.33	1.73	1.29	1.17	1.74	1.90	0.93	1.60
				3.0	2.3	3.1	3.4	2.3	2.1	4.3	2.5
			8	1.43	1.90	1.43	1.19	1.90	2.50	1.01	1.74
				5.6	4.2	5.6	6.7	4.2	3.2	7.9	4.6
2x2x2	none		2	0.95	1.25	0.95	0.87	0.91	1.33	0.71	1.11
				2.1	1.6	2.1	2.3	2.2	1.5	2.8	1.8
			4	1.18	1.54	1.18	1.00	1.33	1.82	0.85	1.43
				3.4	2.6	3.4	4.0	3.0	2.2	4.7	2.8
			8	1.33	1.70	1.29	1.08	1.82	2.42	0.93	1.67
				6.0	4.7	6.2	7.4	4.4	3.3	8.6	4.8
2x2x8	none		2	0.83	1.05	0.83	0.74	0.91	1.43	0.54	1.11
				2.4	1.9	2.4	2.7	2.2	1.4	3.7	1.8
			4	0.95	1.29	0.95	0.83	1.25	1.67	0.63	1.25
				4.2	3.1	4.2	4.8	3.2	2.4	6.3	3.2
			8	1.13	1.48	1.11	0.95	1.74	2.10	0.78	1.40
				7.1	5.4	7.2	8.4	4.6	3.8	10.3	5.7
2x2x16	none		2	0.87	1.18	0.91	0.83	0.83	1.18	0.52	1.18
				2.3	1.7	2.2	2.4	2.4	1.7	3.8	1.7
			4	0.93	1.21	0.91	0.75	1.33	1.73	0.62	1.25
				4.3	3.3	4.4	5.3	3.0	2.3	6.5	3.2
			8	1.03	1.36	1.01	0.88	1.57	2.16	0.67	1.33
				7.8	5.9	7.9	9.1	5.1	3.7	11.9	6.0
2x4x4	none		2	0.87	1.18	0.83	0.74	1.25	1.33	0.61	1.05
				2.3	1.7	2.4	2.7	1.6	1.5	3.3	1.9
			4	1.08	1.38	1.08	0.87	1.54	1.74	0.77	1.25
				3.7	2.9	3.7	4.6	2.6	2.3	5.2	3.2
			8	1.21	1.60	1.21	1.01	2.00	2.16	0.84	1.48
				6.6	5.0	6.6	7.9	4.0	3.7	9.5	5.4

TABLE 2.

Upper value = depth coefficient.
Lower value = calculated depth.

PARAMETERS				DETERMINED DEPTHS & COEFFICIENTS							
Body shape	Variable parameter	Amount of variation	DEPTH	Hannel Rule	Mac Rule	Tiburg Rule	Thalén Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
2x12x2	none		2	0.91	1.18	0.91	0.74	1.54	1.67	0.63	1.33
				2.2	1.7	2.2	2.7	1.3	1.2	3.2	1.5
			4	1.11	1.43	1.08	0.95	1.73	1.82	0.75	1.54
				3.6	2.8	3.7	4.2	2.3	2.2	5.3	2.6
			8	1.27	1.70	1.29	1.05	2.05	2.35	0.91	1.67
				6.3	4.7	6.2	7.6	3.9	3.4	8.8	4.8
2x12x8	none		2	0.67	0.91	0.67	0.67	0.91	1.18	0.43	1.18
				3.0	2.2	3.0	3.0	2.2	1.7	4.6	1.7
			4	0.87	1.17	0.87	0.80	1.38	1.60	0.58	1.38
				4.6	3.4	4.6	5.0	2.9	2.5	6.9	2.9
			8	1.08	1.40	1.07	0.91	1.90	2.29	0.75	1.43
				7.4	5.7	7.5	8.8	4.2	3.5	10.7	5.6
2x12x16	none		2	0.61	0.87	0.65	0.69	0.95	1.25	0.38	1.11
				3.3	2.3	3.1	2.9	2.1	1.6	5.3	1.8
			4	0.78	1.08	0.82	0.71	1.29	1.60	0.52	1.21
				5.1	3.7	4.9	5.6	3.1	2.5	7.7	3.3
			8	0.95	1.25	0.94	0.82	1.90	2.42	0.66	1.33
				8.4	6.4	8.5	9.8	4.2	3.3	12.2	6.0
2x4x4	strike	10°	2	0.83	1.11	0.83	0.74	1.00	1.54	0.59	1.11
				2.4	1.8	2.4	2.7	2.0	1.3	3.4	1.8
			4	1.08	1.38	1.03	0.89	1.38	1.82	0.71	1.48
				3.7	2.9	3.9	4.5	2.9	2.2	5.6	2.7
			8	1.23	1.60	1.21	1.03	1.67	2.16	0.83	1.60
				6.5	5.0	6.6	7.8	4.8	3.7	9.6	5.0
2x4x4	strike	20°	2	0.83	1.11	0.83	0.71	1.18	1.54	0.61	1.00
				2.4	1.8	2.4	2.8	1.7	1.3	3.3	2.0
			4	1.11	1.38	1.05	0.89	1.54	1.82	0.71	1.33
				3.6	2.9	3.8	4.5	2.6	2.2	5.6	3.0
			8	1.25	1.60	1.21	1.04	2.00	2.50	0.87	1.57
				6.4	5.0	6.6	7.7	4.0	3.2	9.2	5.1

TABLE 2. (CONT'D)

PARAMETERS				DETERMINED DEPTHS & COEFFICIENTS							
Body shape	Variable parameter	Amount of variation	DEPTH	Hannel Rule	Mac Rule	Tiburg Rule	Thalén Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
2x12x16	strike	10°	2	0.61	0.83	0.65	0.63	1.00	1.43	0.43	1.00
				3.3	2.4	3.1	3.2	2.0	1.4	4.7	2.0
			4	0.78	1.05	0.80	0.73	1.33	1.67	0.49	1.21
				5.1	3.8	5.0	5.5	3.0	2.4	8.1	3.3
			8	0.95	1.25	0.94	0.81	2.00	1.90	0.65	1.29
				8.4	6.4	8.5	9.9	4.0	4.2	12.3	6.2
2x12x16	strike	20°	2	0.59	0.83	0.63	0.59	0.83	1.43	0.41	1.11
				3.4	2.4	3.2	3.4	2.4	1.4	4.9	1.8
			4	0.69	1.03	0.78	0.71	1.25	1.67	0.49	1.08
				5.8	3.9	5.1	5.6	3.2	2.4	8.1	3.7
			8	0.95	1.25	0.94	0.81	1.70	2.29	0.63	1.29
				8.4	6.4	8.5	9.9	4.7	3.5	12.6	6.2
2x4x4	regional	I	2	0.95	1.25	0.95	0.74	1.25	1.11	0.67	1.18
				2.1	1.6	2.1	2.7	1.6	1.8	3.0	1.7
			4	1.18	1.54	1.11	0.87	1.74	1.74	0.87	1.48
				3.4	2.6	3.6	4.6	2.3	2.3	4.6	2.7
			8	1.32	1.74	1.31	1.13	2.00	2.16	0.96	1.60
				6.0	4.6	6.1	7.1	4.0	3.7	8.3	5.0
2x4x4	regional	II	2	0.95	1.05	0.80	0.74	1.25	1.11	0.54	0.91
				2.1	1.9	2.5	2.7	1.6	1.8	3.7	2.2
			4	0.95	1.29	0.98	0.87	1.74	1.74	0.71	1.21
				4.2	3.1	4.1	4.6	2.3	2.3	5.6	3.3
			8	1.05	1.51	1.14	1.13	2.00	2.16	0.80	1.36
				7.6	5.3	7.0	7.1	4.0	3.7	10.0	5.9
2x4x4	regional	III	2	0.77	1.11	0.80	0.74	1.25	1.11	0.54	0.91
				2.6	1.8	2.5	2.7	1.6	1.8	3.7	2.2
			4	0.95	1.33	0.98	0.87	2.00	1.54	0.71	1.25
				4.2	3.0	4.1	4.6	2.0	2.6	5.6	3.2
			8	1.05	1.54	1.14	1.13	2.22	2.05	0.79	1.40
				7.6	5.2	7.0	7.1	3.6	3.9	10.1	5.7

TABLE 2. (CONT'D)

PARAMETERS				DETERMINED DEPTHS & COEFFICIENTS							
Body shape	Variable parameter	Amount of variation	DEPTH	Hannel Rule	Mac Rule	Tiburg Rule	Thalén Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
2x4x4	regional	IV	2	0.95	1.25	0.91	0.74	1.25	1.11	0.65	1.11
				2.1	1.6	2.2	2.7	1.6	1.8	3.1	1.8
			4	1.18	1.54	1.11	0.87	1.54	1.90	0.85	1.38
				3.4	2.6	3.6	4.6	2.6	2.1	4.7	2.9
			8	1.36	1.67	1.25	1.13	1.63	2.50	0.94	1.54
				5.9	4.8	6.4	7.1	4.9	3.2	8.5	5.2
2x4x4	regional	I+III	2	0.87	1.18	0.87	0.74	1.25	1.11	0.61	1.05
				2.3	1.7	2.3	2.7	1.6	1.8	3.3	1.9
			4	1.11	1.43	1.05	0.87	2.00	1.54	0.77	1.38
				3.6	2.8	3.8	4.6	2.0	2.6	5.2	2.9
			8	1.19	1.63	1.23	1.13	2.22	2.05	0.88	1.54
				6.7	4.9	6.5	7.1	3.6	3.9	9.1	5.2
2x4x4	regional	I+IV	2	1.05	1.33	1.00	0.74	1.25	1.11	0.74	1.25
				1.9	1.5	2.0	2.7	1.6	1.8	2.7	1.6
			4	1.29	1.67	1.25	0.87	1.54	1.90	0.93	1.54
				3.1	2.4	3.2	4.6	2.6	2.1	4.3	2.6
			8	1.48	1.82	1.36	1.13	1.63	2.50	1.04	1.70
				5.4	4.4	5.9	7.1	4.9	3.2	7.7	4.7
2x4x4	regional	II+III	2	0.69	1.00	0.74	0.74	1.25	1.11	0.49	0.87
				2.9	2.0	2.7	2.7	1.6	1.8	4.1	2.3
			4	0.85	1.21	0.91	0.87	2.00	1.54	0.66	1.18
				4.7	3.3	4.4	4.6	2.0	2.6	6.1	3.4
			8	0.96	1.38	1.05	1.13	2.22	2.11	0.74	1.31
				8.3	5.8	7.6	7.1	3.6	3.8	10.8	6.1
2x4x4	regional	II+IV	2	0.87	1.11	0.83	0.74	1.25	1.11	0.59	0.95
				2.3	1.8	2.4	2.7	1.6	1.8	3.4	2.1
			4	1.08	1.43	1.05	0.87	1.54	1.90	0.75	1.25
				3.7	2.8	3.8	4.6	2.6	2.1	5.3	3.2
			8	1.21	1.60	1.21	1.13	1.60	2.35	0.86	1.43
				6.6	5.0	6.6	7.1	5.0	3.4	9.3	5.6

TABLE 2. (CONT'D)

PARAMETERS				DETERMINED DEPTHS & COEFFICIENTS							
Body shape	Variable parameter	Amount of variation	DEPTH	Hannel Rule	Mac Rule	Tiburg Rule	Thalén Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
2x4x4	declination	10°	2	0.87	1.18	0.87	0.83	1.05	1.25	0.59	1.18
				2.3	1.7	2.3	2.4	1.9	1.6	3.4	1.7
			4	1.08	1.38	1.05	0.95	1.48	1.74	0.71	1.33
				3.7	2.9	3.8	4.2	2.7	2.3	5.6	3.0
			8	1.19	1.63	1.19	1.10	2.00	2.22	0.85	1.48
				6.7	4.9	6.7	7.3	4.0	3.6	9.4	5.4
2x4x4	declination	20°	2	0.87	1.18	0.91	0.83	1.11	1.18	0.63	0.95
				2.3	1.7	2.2	2.4	1.8	1.7	3.2	2.1
			4	1.08	1.38	1.05	1.03	1.67	1.54	0.75	1.29
				3.7	2.9	3.8	3.9	2.4	2.6	5.3	3.1
			8	1.19	1.60	1.18	1.07	1.90	2.22	0.86	1.48
				6.7	5.0	6.8	7.5	4.2	3.6	9.3	5.4
2x4x4	profile	"A"	2	0.80	1.11	0.83	0.74	1.43	1.33	0.54	1.17
				2.5	1.8	2.4	2.7	1.4	1.5	3.7	1.7
			4	1.03	1.38	1.05	0.87	1.67	1.74	0.69	1.29
				3.9	2.9	3.8	4.6	2.4	2.3	5.8	3.1
			8	1.19	1.60	1.21	1.13	2.00	2.11	0.80	1.54
				6.7	5.0	6.6	7.1	4.0	3.8	10.0	5.2
2x4x4	profile	"B"	2	0.83	1.19	1.00	0.74	1.43	1.08	0.63	1.05
				2.4	1.7	2.0	2.7	1.4	1.9	3.2	1.9
			4	1.08	1.38	1.08	0.87	1.67	1.74	0.77	1.25
				3.7	2.9	3.7	4.6	2.4	2.3	5.2	3.2
			8	1.21	1.60	1.21	1.13	1.95	2.16	0.83	1.51
				6.6	5.0	6.6	7.1	4.1	3.7	9.6	5.3
2x2x16	dip	20°	2	0.83	1.11	0.83	0.83	0.91	1.25	0.53	1.18
				2.4	1.8	2.4	2.4	2.2	1.6	3.8	1.7
			4	0.91	1.21	0.91	0.83	1.29	1.82	0.57	1.29
				4.4	3.3	4.4	4.8	3.1	2.2	7.0	3.1
			8	0.99	1.29	0.97	0.88	1.78	2.50	0.66	1.43
				8.1	6.2	8.2	9.1	4.5	3.2	12.2	5.6

TABLE 2. (CONT'D)

PARAMETERS				DETERMINED DEPTHS & COEFFICIENTS							
Body shape	Variable parameter	Amount of variation	DEPTH	Hannel Rule	Mac Rule	Tiburg Rule	Thalen Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
2x2x16	dip	40°	2	0.77	1.05	0.77	0.91	0.87	1.33	0.49	1.25
				2.6	1.9	2.6	2.2	2.3	1.5	4.1	1.6
			4	0.82	1.11	0.83	0.87	1.17	1.82	0.51	1.54
				4.9	3.6	4.8	4.6	3.4	2.2	7.8	2.6
			8	0.93	1.23	0.93	0.91	1.54	2.50	0.59	1.51
				8.6	6.5	8.6	8.8	5.2	3.2	13.6	5.3
2x12x16	dip	20°	2	0.56	0.80	0.59	0.67	0.80	1.18	0.34	1.18
				3.6	2.5	3.4	3.0	2.5	1.7	5.9	1.7
			4	0.74	1.00	0.75	0.82	1.17	1.43	0.45	1.33
				5.4	4.0	5.3	4.9	3.4	2.8	8.9	3.0
			8	0.93	1.25	0.93	0.82	1.74	2.42	0.60	1.40
				8.6	6.4	8.6	9.8	4.6	3.3	13.6	5.7
2x12x16	dip	40°	2	0.48	0.67	0.50	0.71	0.63	1.00	0.26	1.25
				4.2	3.0	4.0	2.8	3.2	2.0	7.8	1.6
			4	0.65	0.91	0.69	0.75	1.00	1.54	0.40	1.38
				5.9	4.4	5.8	5.3	4.0	2.6	9.9	2.9
			8	0 87	1 18	0 89	0 88	1 43	2 16	0 56	1 43
				9.2	6.8	9.0	9.1	5.6	3.7	14.4	5.6

TABLE 2. (CONT'D)

file. The relative position of the maximum and minimum amplitude may not always be correctly determined to within a station-spacing unit. The absolute value of the maximum and minimum amplitude points, if they fall between two stations, may be uncertain, and the maximum slope between two stations does not necessarily have to be the maximum slope of the anomaly when its values are known everywhere.

These effects could have been overcome by using a smaller station spacing in the calculation of the profiles. To minimize this error the profile was smoothly drawn between the calculated values. This approximation to the profile is not expected to vary greatly from the real values in between stations. Another consideration is that this problem is also present in actual data, which in most cases is measured only at discrete points. No attempt was made in this study to evaluate the errors thus caused. It will be shown below that the repeatability of most techniques is sufficiently good, so that any errors due to this effect seem to be small enough to be disregarded.

Repeatability of the Methods

The depth measurements on a number of profiles were repeated to gain an insight into the repeatability of the various methods. The differences between subsequent measurements were taken as an indication of this repeatability and the average values of these differences are shown in Table 3 below. This table shows the average values of four measured differences for each of the methods, with the exception of the Slope-distance Rule, for which 16 values for each side of the anomaly and for each of the three depths were determined.

DEPTH	Average variation (in depth units)							
	Hannel Rule	Mac Rule	Tiburg Rule	Thalén Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
2	0.0	0.1	0.0	0.2	0.3	0.2	0.1	0,1
4	0.0	0.0	0.0	0,1	0.4	0.2	0.2	0.1
8	0.1	0.0	0.0	0.4	0,4	0.3	0.2	0.3

TABLE 3. AVERAGE VARIATION IN DEPTH-DETERMINATION TECHNIQUES

As can be expected the slope-measurement techniques exhibit poor repeatability, with the Slope-distance Rule being the worst offender in this respect. The maximum differences measured for the Slope-distance Rule exceeded the maximum differences for any of the other methods by a factor of at least two, being measured as 0.8-, 0.8-, and 1.0-depth units for depths of 2, 4, and 8 units at the southern part of the anomaly respectively, and 0.5 depth units for all three depths on the northern part of the profile.

The best response is given by the amplitude-measurement techniques, with the Thalén Rule at greater depths showing a decreased amount of accuracy. It should be taken into account that on the scale of the profiles one depth unit is equal to 6 millimeters and that the distances involved were measured to an accuracy of approximately one millimeter.

In a later chapter on the discussion of the results the repeatability of the methods are recalculated as percentages and compared with the errors involved in the variation of the various parameters.

DISCUSSION OF THE RESULTS

The results tabulated in Table 2 are shown in Fig. 7 to Fig. 65 in graphical form as determined depths versus true depths for each of the different parameters that were varied in this study. Some inaccuracies are present in these figures, particularly in those concerning the Slope-distance Technique, due to the bad repeatability of this method. The following symbols were used throughout this thesis in the figures:

HN -Hannel Rule,
MC -Mac Rule,
TB -Tiburg Rule,
TH -Thalén Rule,
SDS-Slope-distance Rule South,
SDN-Slope-distance Rule North,
SKS-Sokolov Rule South,
SKN-Sokolov Rule North.

On each of the figures the 1:1 correlation between the calculated and true depths is indicated by a dotted line from the origin with a 45-degree slope.

Comparison of the Methods for Various Bodies

The responses of the various techniques to each of the different models are shown in Fig. 7 to 14. The difference in slope of the plotted results between the Slope-distance Technique and the others is noteworthy and seems to point to a basic difference between them. Another point of interest is the large difference in results for opposite sides of the anomaly using the Sokolov Rule. If we regard Fig. 7 to 10 as a series with increasing depth extent, we see that the

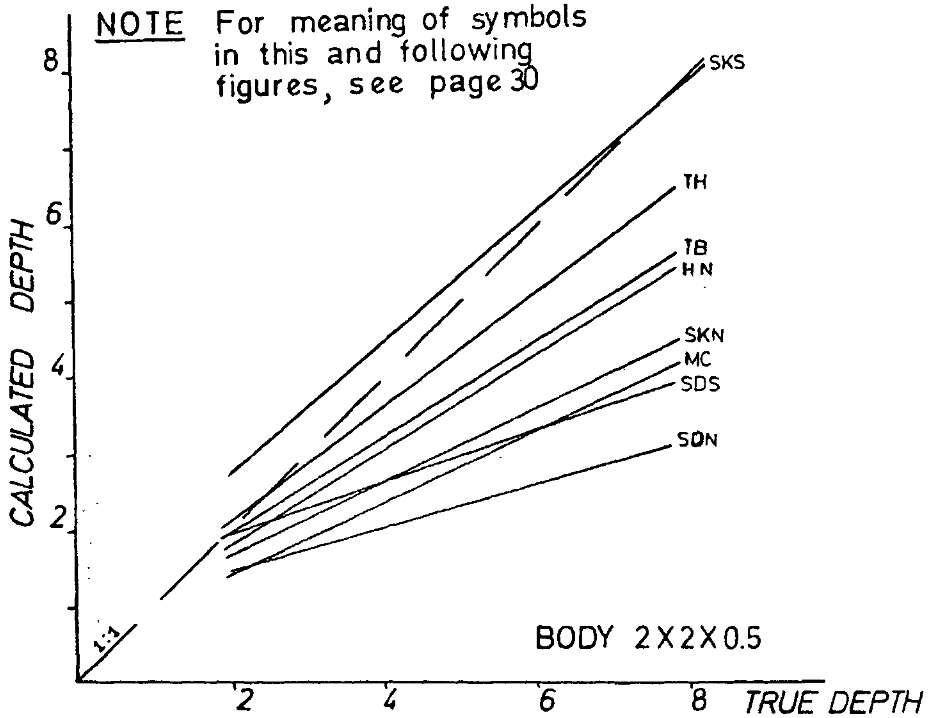

NOTE For meaning of symbols in this and following figures, see page 30

FIG. 7

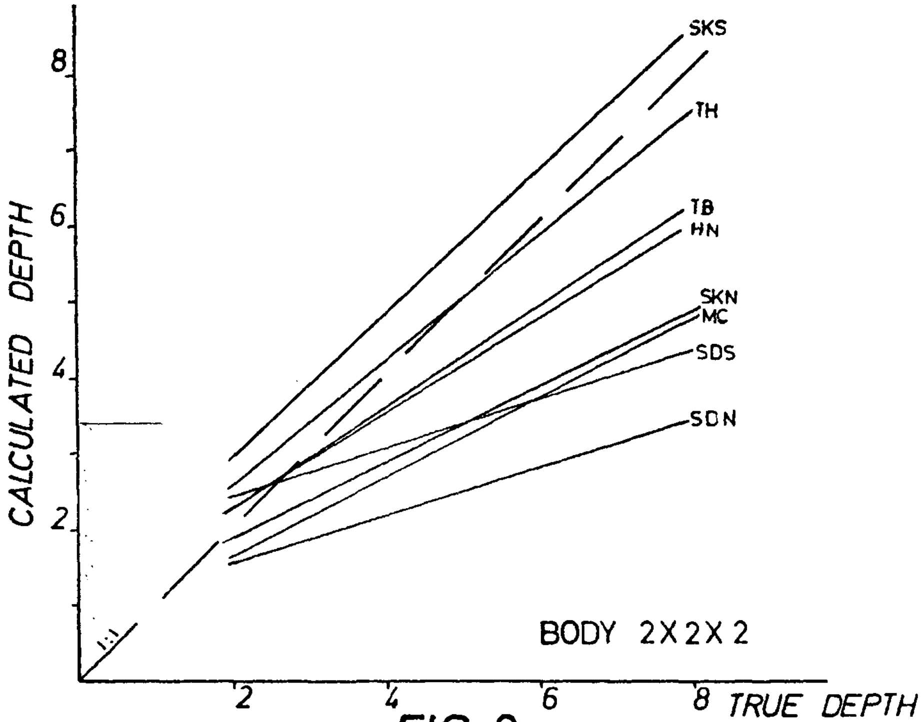


FIG. 8

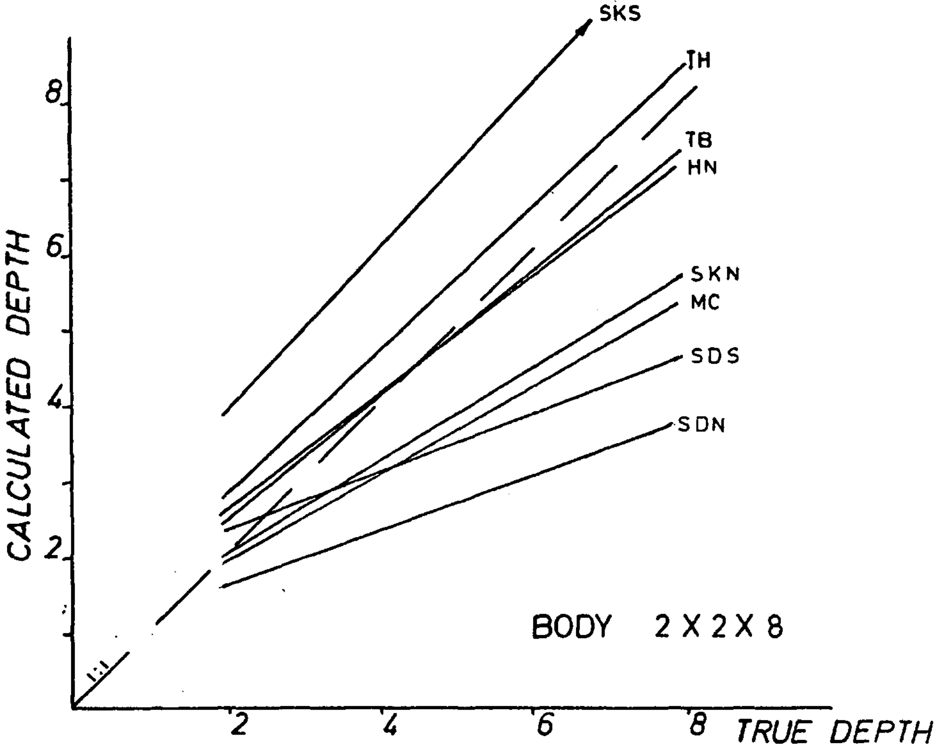

SKS
TH
TB
HN
SKN
MC
SDS
SDN
CALCULATED DEPTH
8
6
4
2
1:1
2
4
6
8
TRUE DEPTH
BODY 2 X 2 X 8

FIG. 9

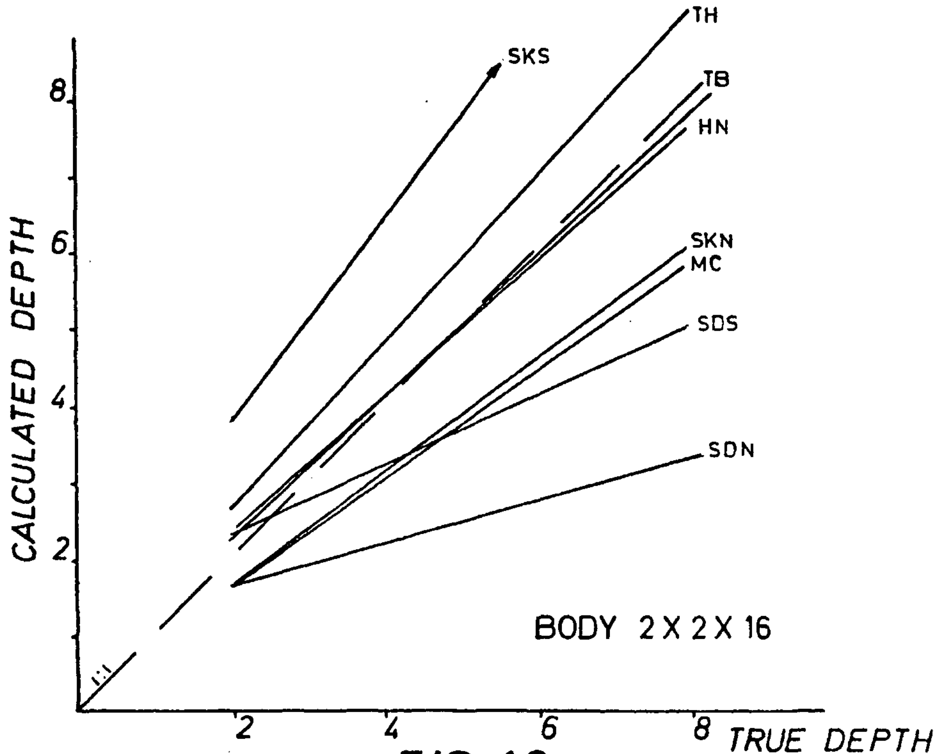

TH
SKS
TB
HN
SKN
MC
SDS
SDN
CALCULATED DEPTH
8
6
4
2
1:1
2
4
6
8
TRUE DEPTH
BODY 2 X 2 X 16

FIG. 10

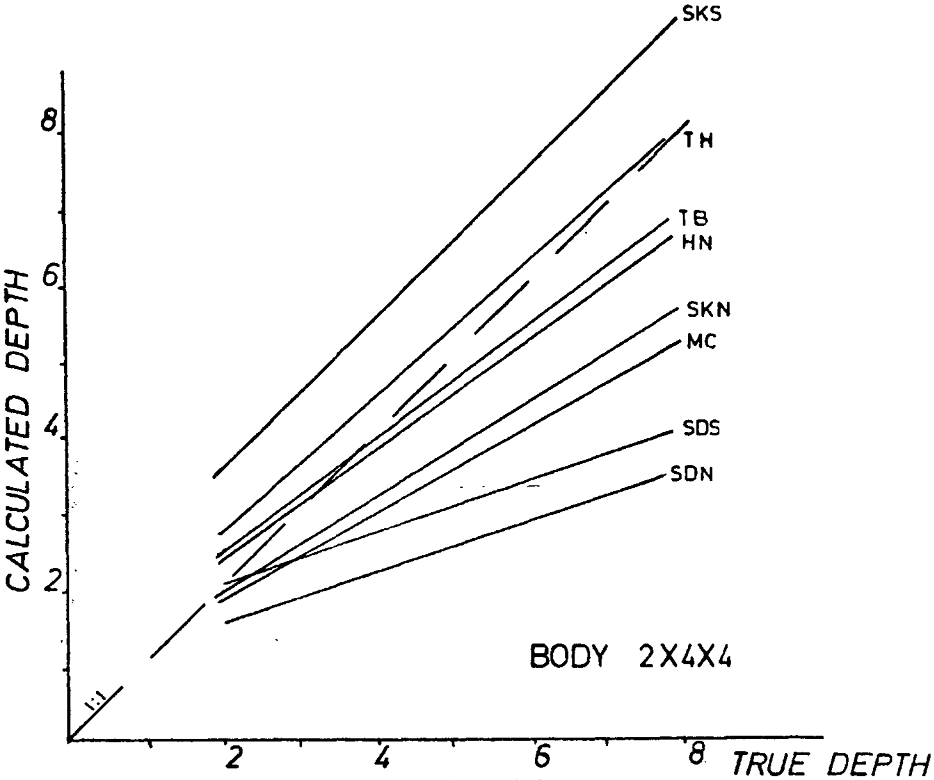

SKS
TH
TB
HN
SKN
MC
SDS
SDN
CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
1:1
BODY 2X4X4

FIG. 11

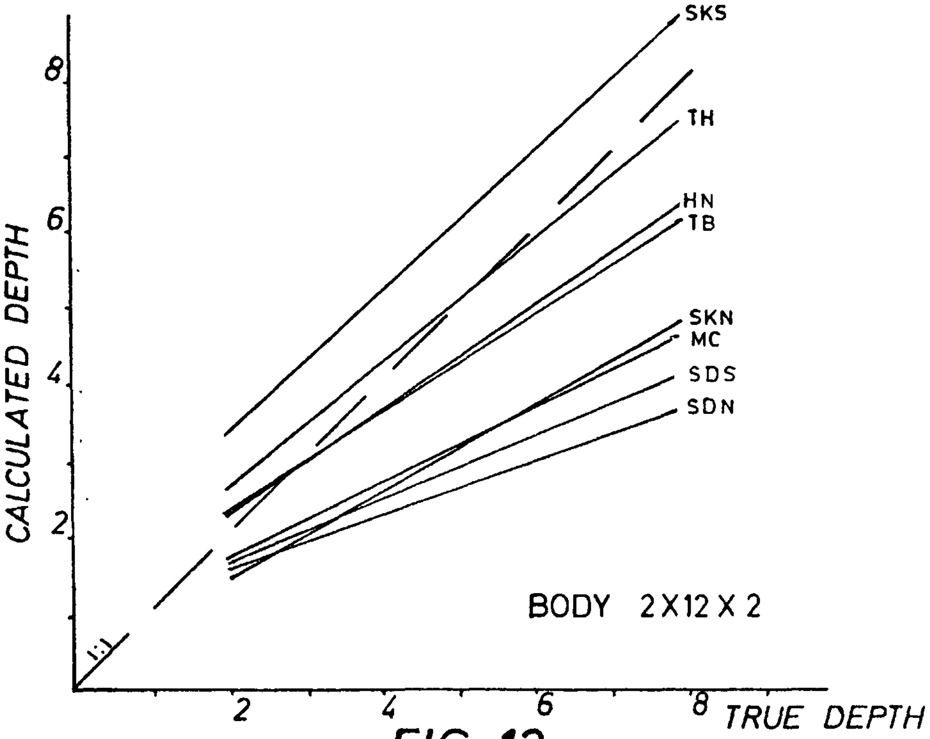

SKS
TH
HN
TB
SKN
MC
SDS
SDN
CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
1:1
BODY 2X12X2

FIG. 12

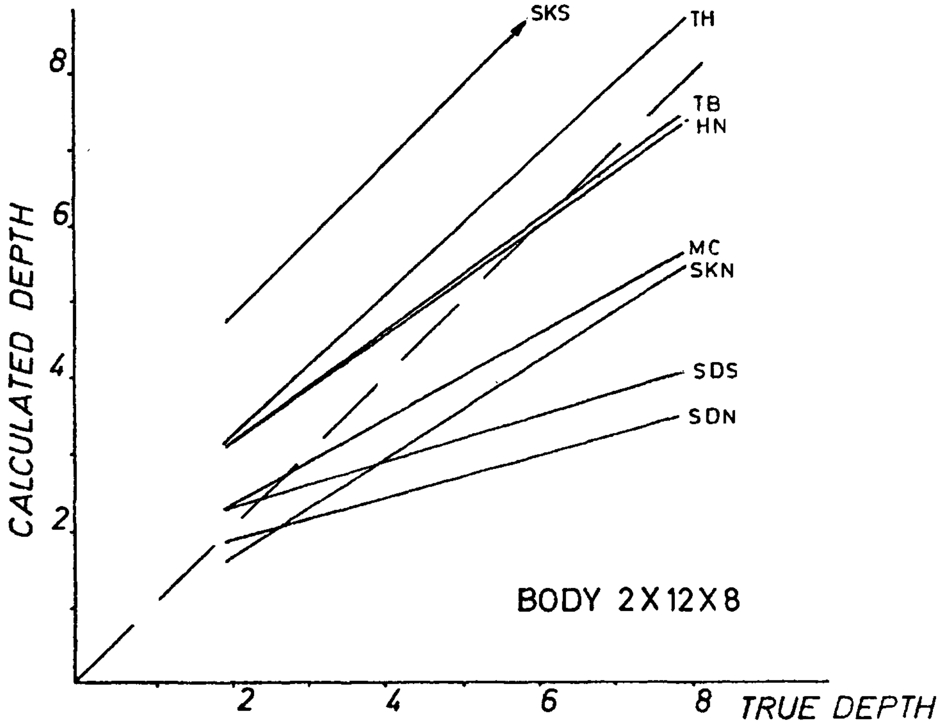

SKS
TH
TB
HN
MC
SKN
SDS
SDN
CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
BODY 2X12X8

FIG. 13

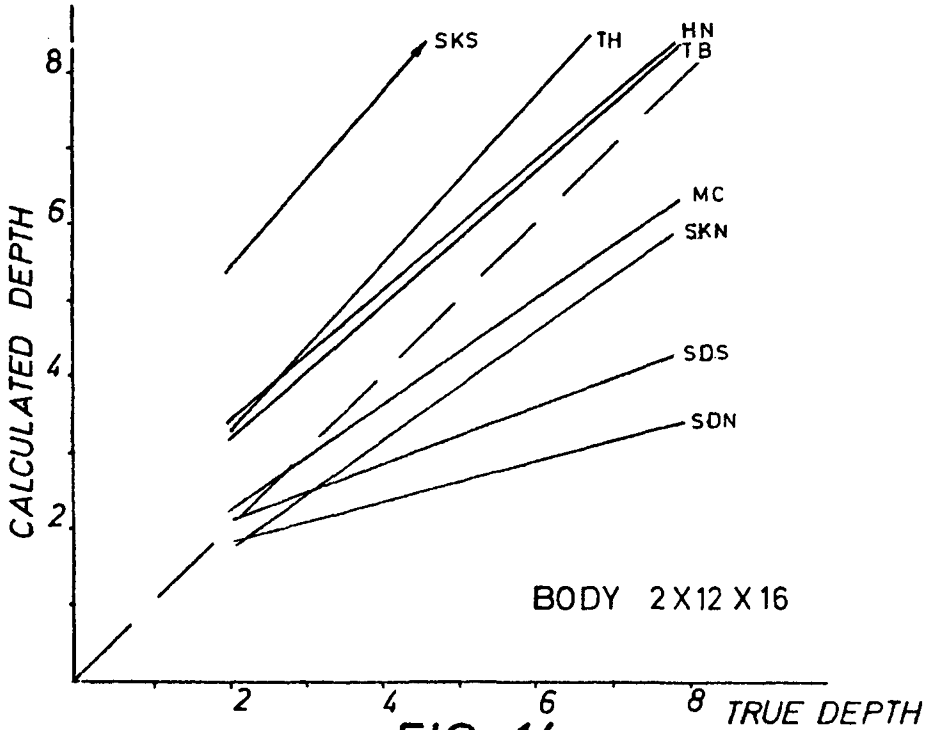

SKS
TH
HN
TB
MC
SKN
SDS
SDN
CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
BODY 2X12 X16

FIG. 14

spread of the results of the methods increases with increasing depth extent of the model. The calculated depths also increase with increasing depth extent of the model. For the case of a thin, horizontal plate (Fig. 7) all techniques show a calculated depth which is too shallow, with the exception of the Sokolov Rule South. For a vertical pipe (Fig. 10) the Tiburg and Hannel Rules show a very good correlation, while the Sokolov South and Thalén Rules result in too great a calculated depth, as opposed to other methods which give too small a value for the determined depth.

The horizontal pipe to vertical dike extension (Fig. 12, 13, and 14) shows a similar increase in spread of the results of the various techniques for increasing depth extent of the models. The results for the three-dimensional model (Fig. 11) seem to lie between the results for a 2x2x2 and a 2x2x8 model (Fig. 8 and 9), as well as between the results for the 2x12x2 and the 2x12x8 models (Fig. 12 and 13).

The varying response of the techniques to the factor of depth extent will be discussed in more detail in the next paragraphs. Note that the variation in response is not the same for different techniques. If the depth-response curves were dependent on depth extent only, a set of master curves for each model could be prepared.

Depth Extent

The response of each technique to the factor of depth extent is shown in detail in Fig. 15 to 20 (horizontal plate to vertical pipe). In the first case the slope of the depth-response curve increases with increasing depth extent of the model, and approaches the slope of the 1:1-correspondence curve due to the fact that most of the techniques have been developed for a dipole of infinite depth extent. This assumption is approximated more closely by a vertical pipe than a thin, horizontal plate.

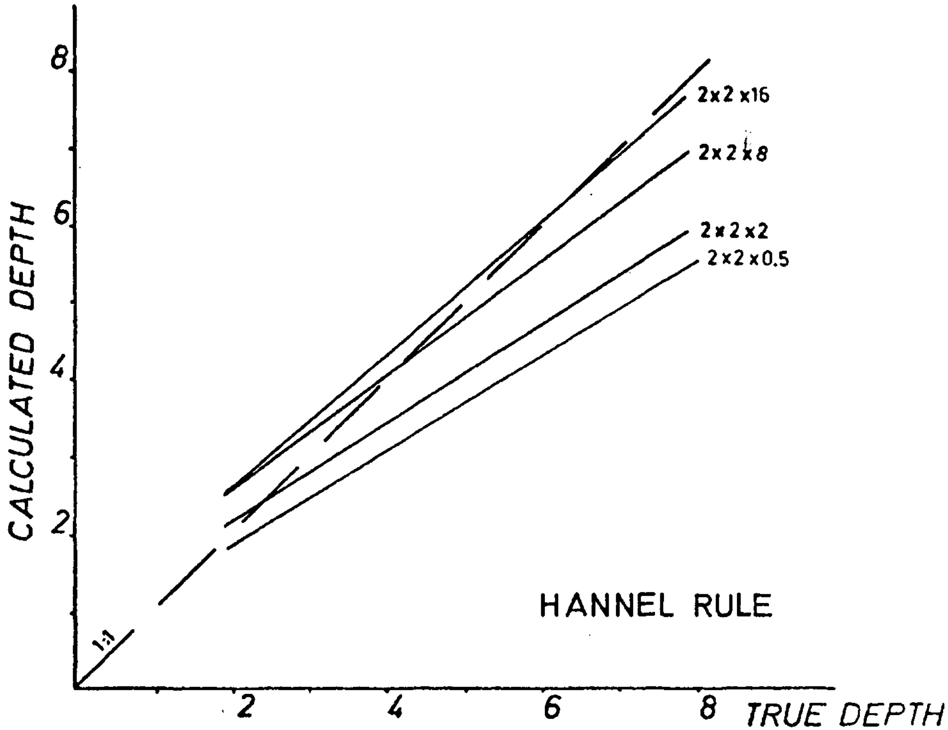

CALCULATED DEPTH
8
6
4
2
1:1
2x2x16
2x2x8
2x2x2
2x2x0.5
HANNEL RULE
2
4
6
8
TRUE DEPTH

FIG. 15

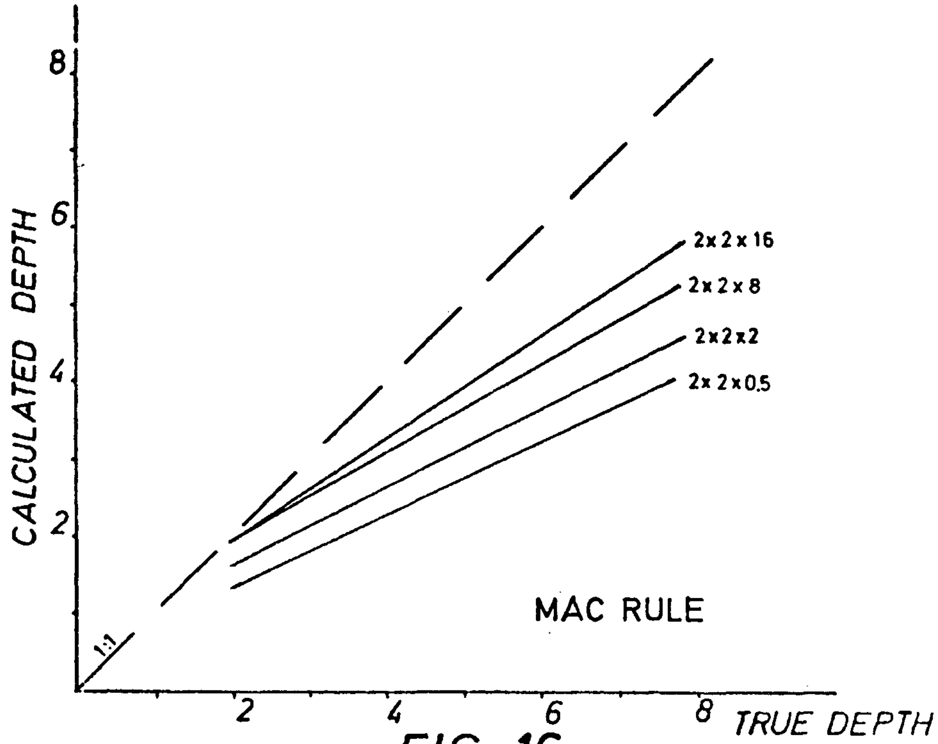

CALCULATED DEPTH
8
6
4
2
1:1
2x2x16
2x2x8
2x2x2
2x2x0.5
MAC RULE
2
4
6
8
TRUE DEPTH

FIG. 16

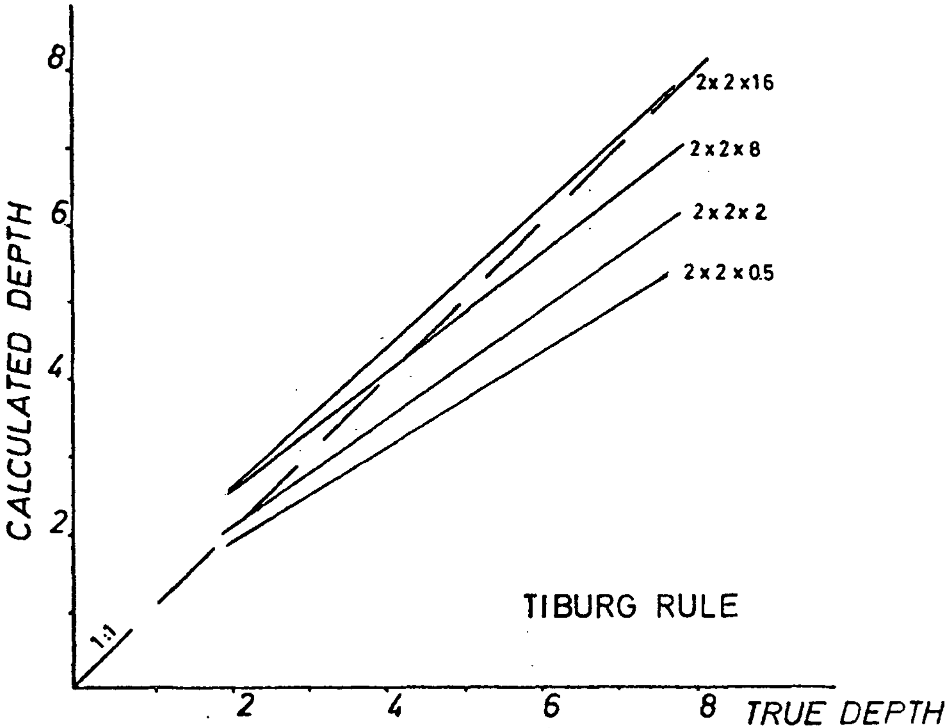

CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
1:1
2x2x16
2x2x8
2x2x2
2x2x0.5
TIBURG RULE

FIG. 17

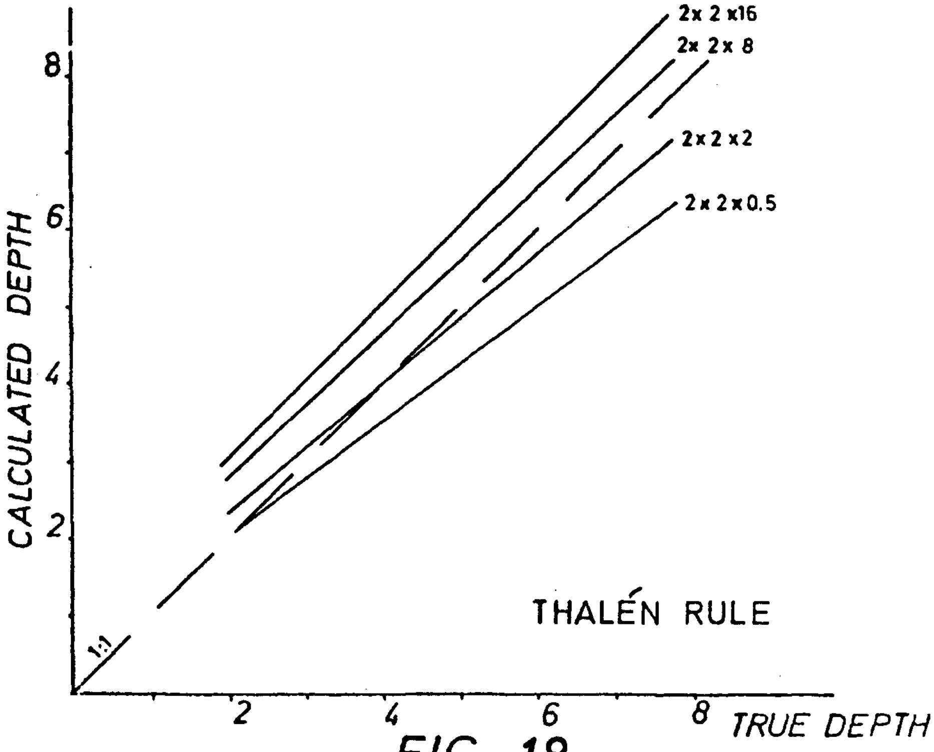

CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
1:1
2x2x16
2x2x8
2x2x2
2x2x0.5
THALÉN RULE

FIG. 18

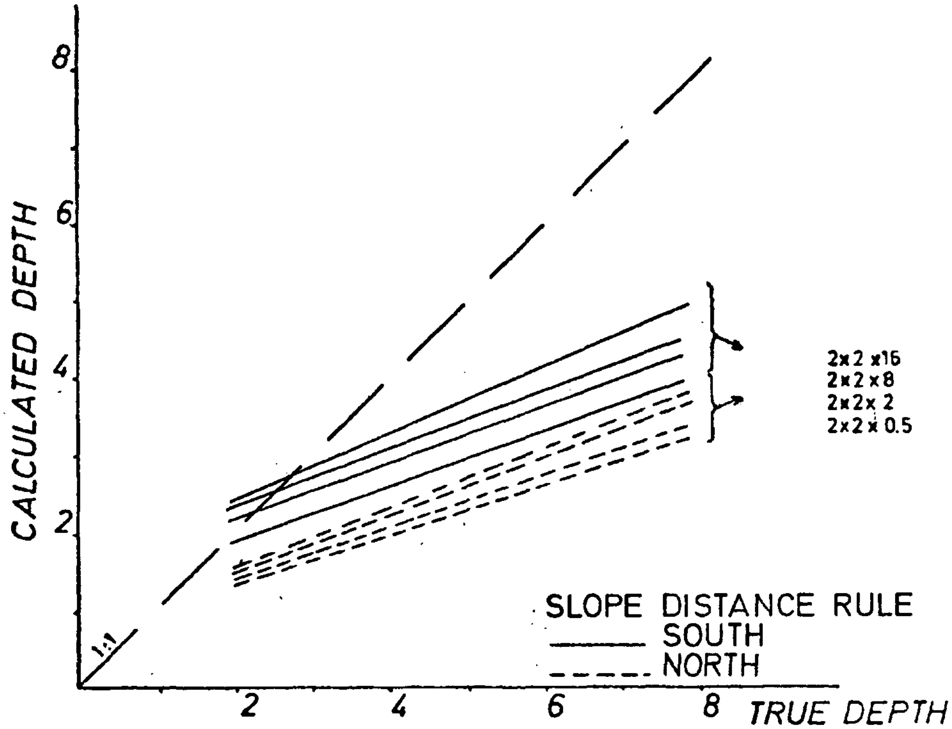

CALCULATED DEPTH
2
4
6
8
TRUE DEPTH
1:1
2x2 x16
2x2 x8
2x2x 2
2x2 x 0.5
SLOPE DISTANCE RULE
SOUTH
NORTH

FIG. 19

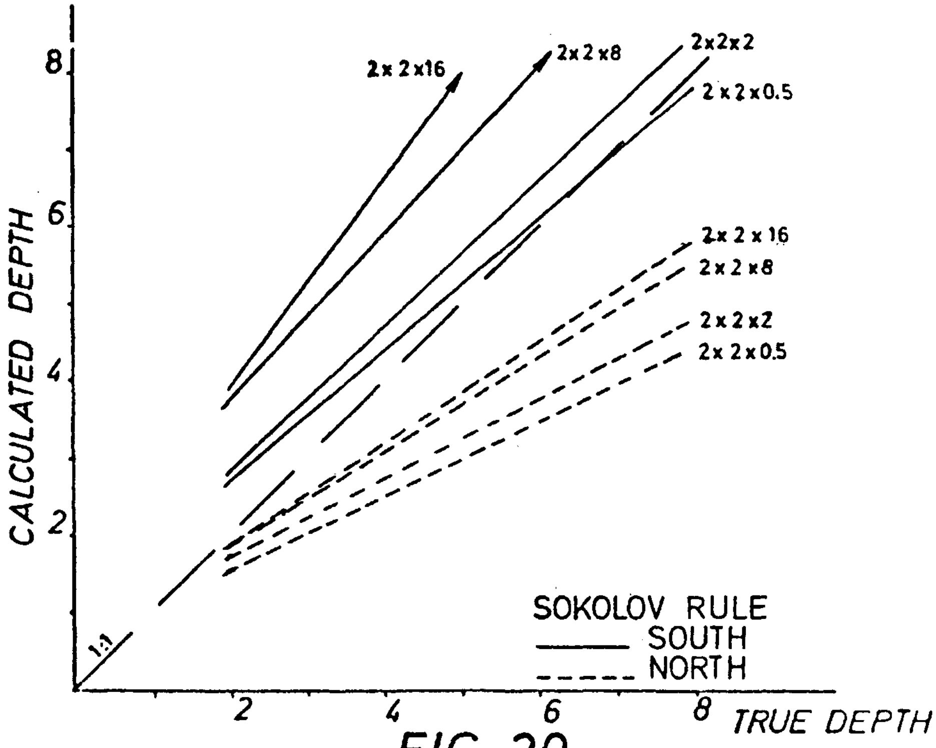

CALCULATED DEPTH
2
4
6
8
TRUE DEPTH
1:1
2x 2x16
2x2x8
2x2x2
2x2x0.5
2x 2 x 16
2x 2 x8
2x 2x2
2x 2x0.5
SOKOLOV RULE
SOUTH
NORTH

FIG. 20

For the series of models ranging from a plate to a vertical pipe, the amplitude techniques have about the same sensitivity to the depth extent of the model and show a similar range of values for calculated depths over the range of the depth extent of the body. Note that although the Slope-distance Rule does not seem to be very sensitive to depth extent, the actual variation in depth (i.e. variation in true depth for a certain calculated depth) is greater than for most other techniques.

The coefficients used for the Hannel and Tiburg Rules result in very good approximation to the 1:1-correspondence curve for a body of great vertical extent. The coefficient for the Mac Rule seems to be too small, while a slightly too large value is used for the Thalén Rule.

The increase in depth extent of a model of large lateral extent (horizontal pipe to dike) has approximately the same effect as the depth increase for a pipe-like body (Fig. 21 to 26). Comparison of the various curves show that, when a dike-like body is approached, the depth to the top of the model is underestimated when compared to a pipe-like body of similar depth extent (Compare for example Fig. 15 and Fig. 21).

It can be said in summary that all techniques are strongly sensitive to the depth extent of the model. A numerical comparison will be attempted in the final conclusions.

Horizontal Extent

The variation in response of the various depth-determination techniques to a variation in horizontal extent of the body was investigated for the following models with body dimensions of 2x2x16 and 2x12x16, 2x2x8 and 2x12x8, and 2x2x2 and 2x12x2 units. The results are shown in Fig. 27 to Fig. 34.

The results in general are small but noticeable. For the amplitude techniques, an increase in horizontal extent

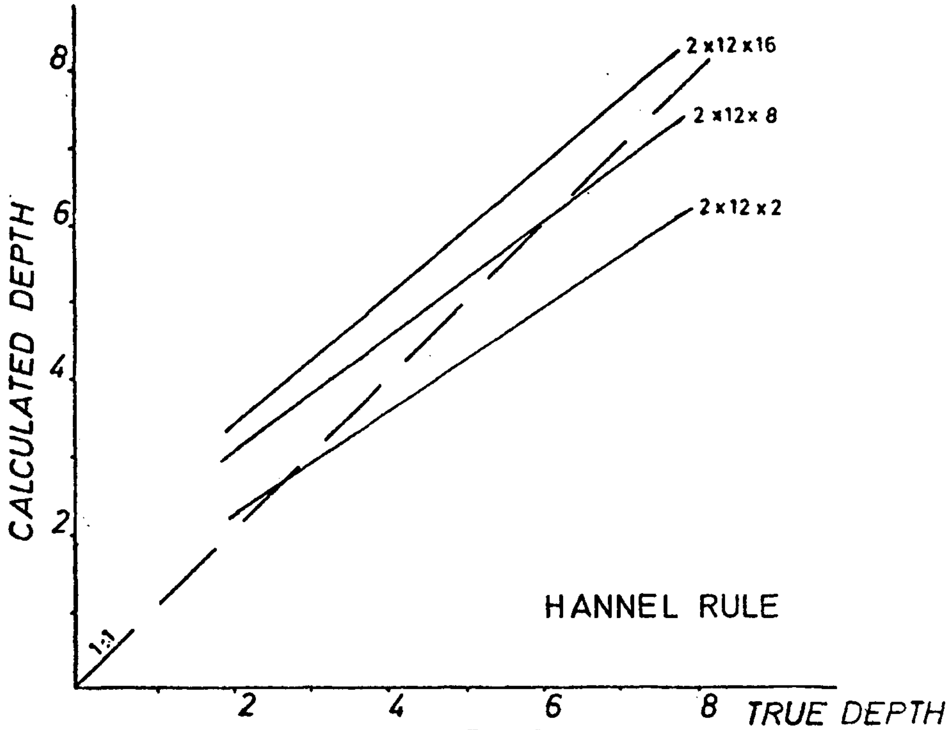

CALCULATED DEPTH
2
4
6
8
2
4
6
8
TRUE DEPTH
2 x 12 x 16
2 x 12 x 8
2 x 12 x 2
1:1
HANNEL RULE

FIG. 21

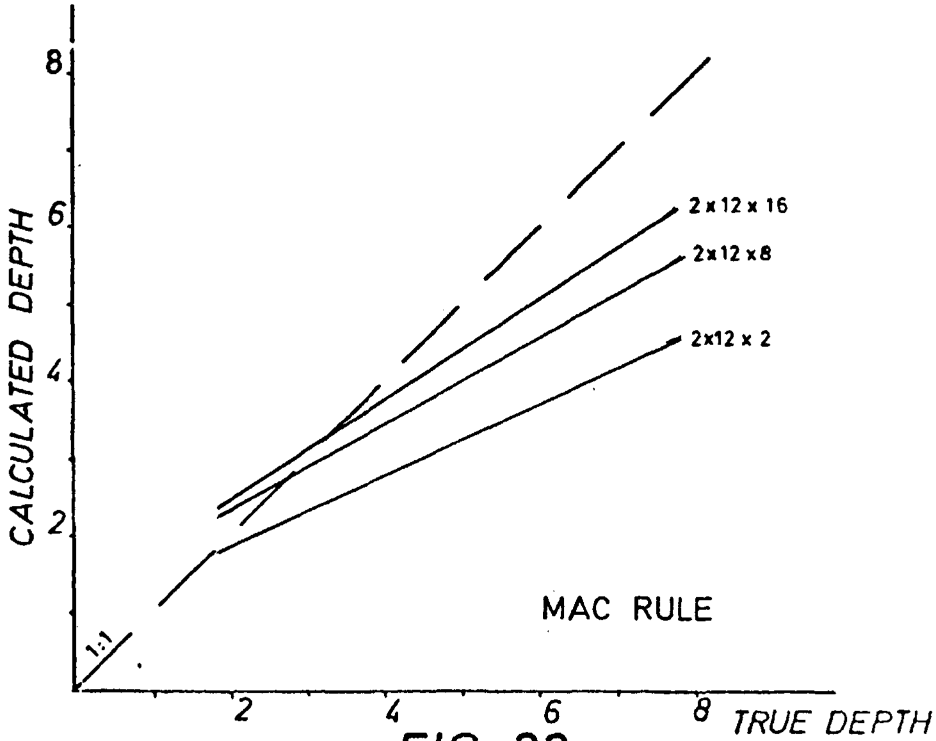
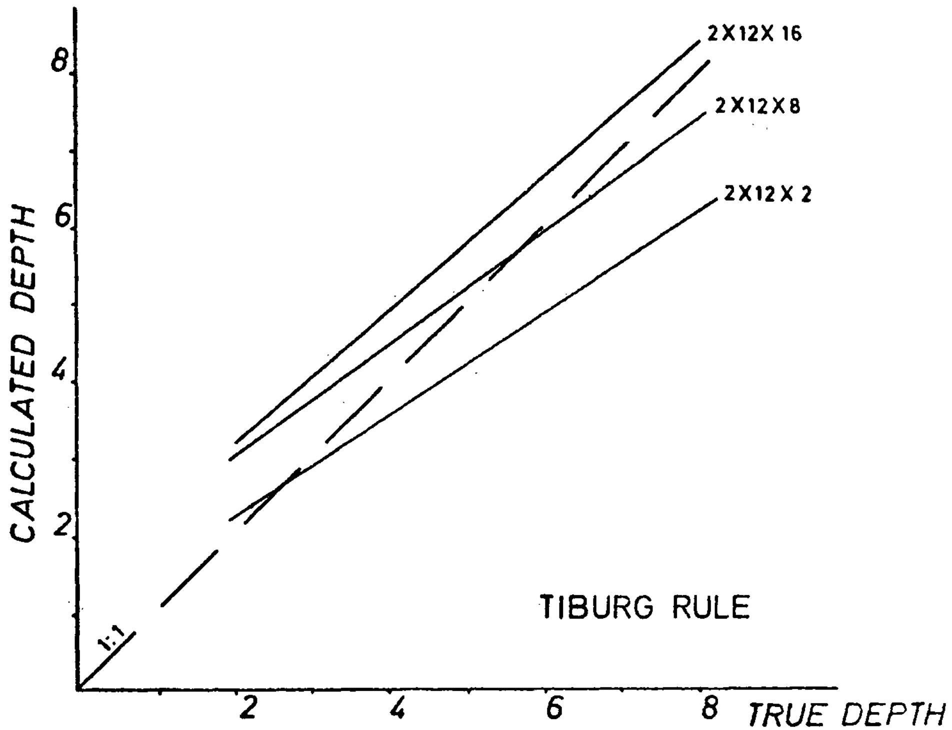
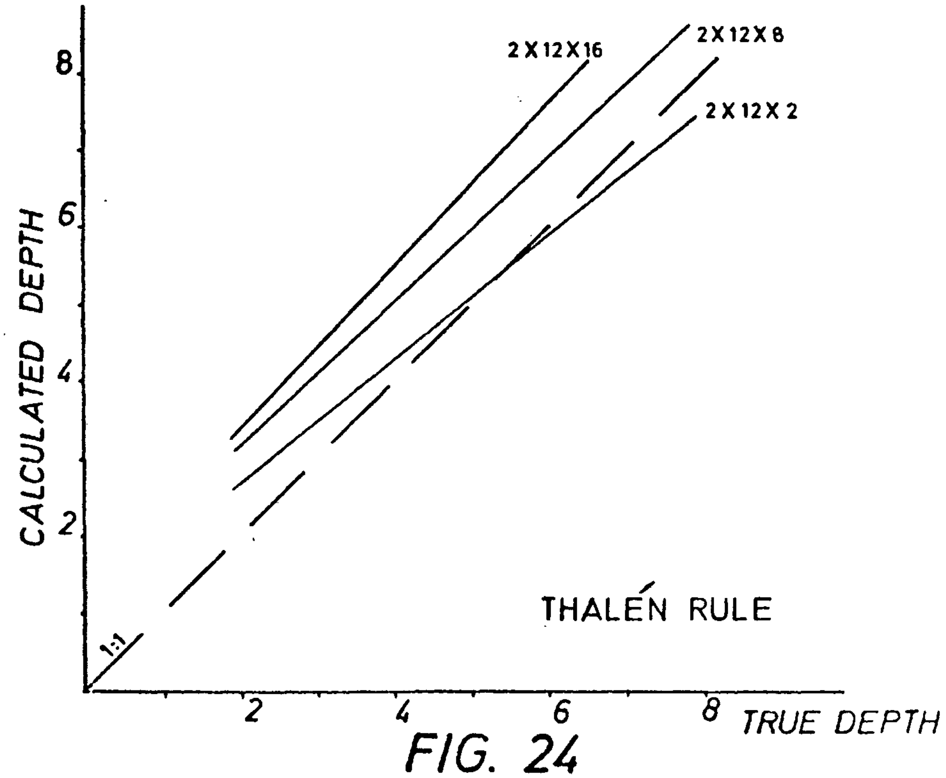

CALCULATED DEPTH
2
4
6
8
2
4
6
8
TRUE DEPTH
2 x 12 x 16
2x12 x8
2x12 x 2
1:1
MAC RULE

FIG. 22



CALCULATED DEPTH
8
6
4
2
2X12X16
2X12X8
2X12X2
1:1
TIBURG RULE
2
4
6
8
TRUE DEPTH

FIG. 23



CALCULATED DEPTH
8
6
4
2
2X12X16
2X12X8
2X12X2
1:1
THALÉN RULE
2
4
6
8
TRUE DEPTH

FIG. 24

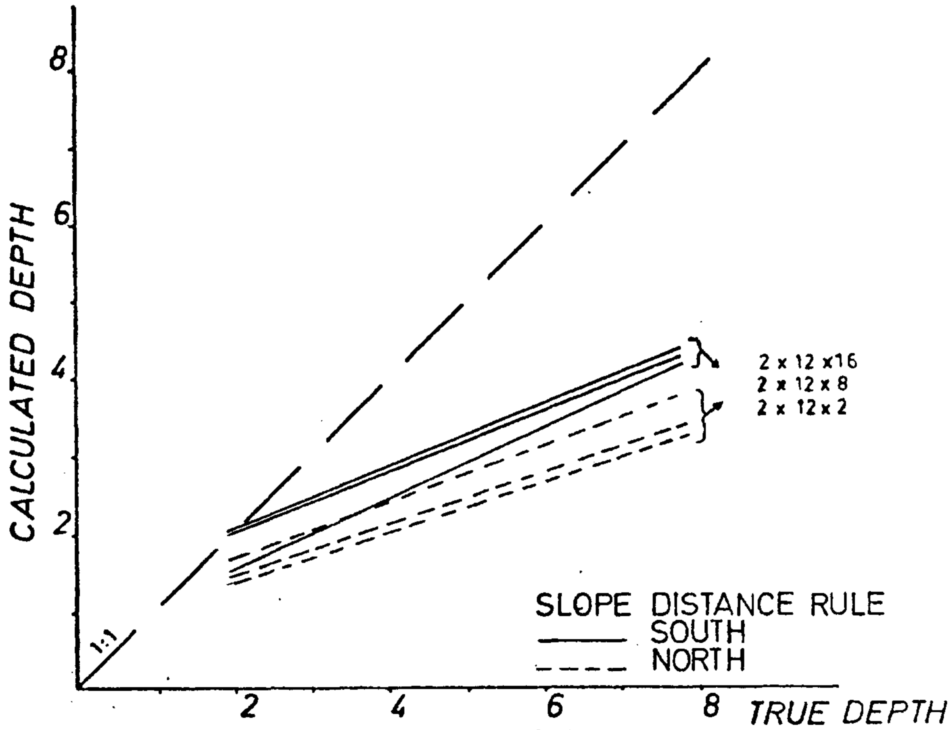

CALCULATED DEPTH
2
4
6
8
1:1
2 x 12 x 16
2 x 12 x 8
2 x 12 x 2
SLOPE DISTANCE RULE
SOUTH
NORTH
2
4
6
8
TRUE DEPTH

FIG. 25

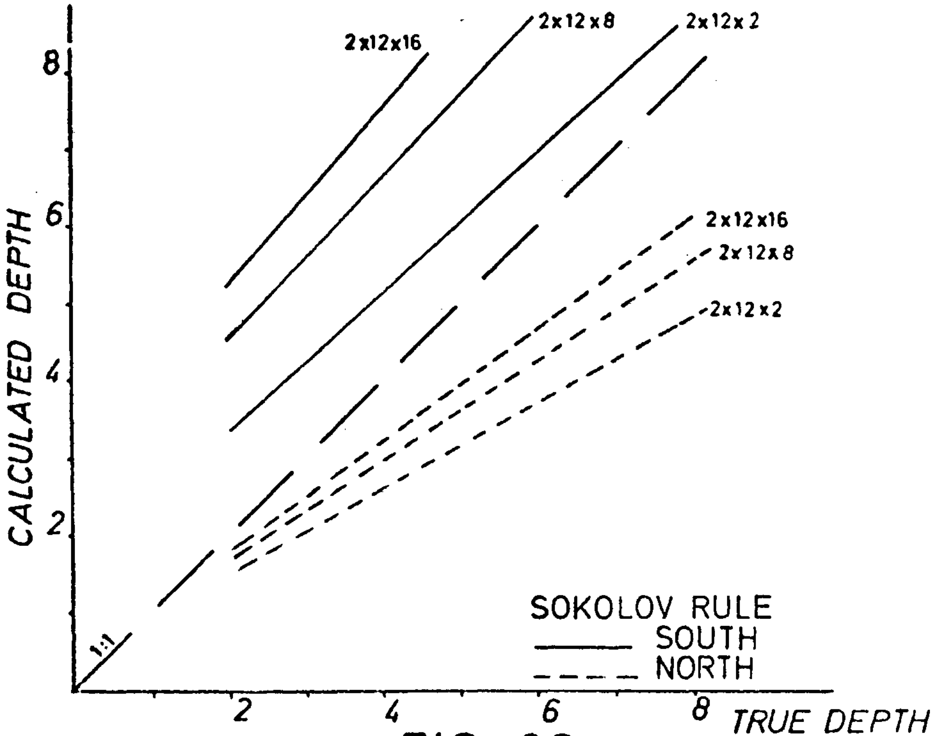

CALCULATED DEPTH
2
4
6
8
1:1
2x12x16
2x12x8
2x12x2
2x12x16
2x12x8
2x12x2
SOKOLOV RULE
SOUTH
NORTH
2
4
6
8
TRUE DEPTH

FIG. 26

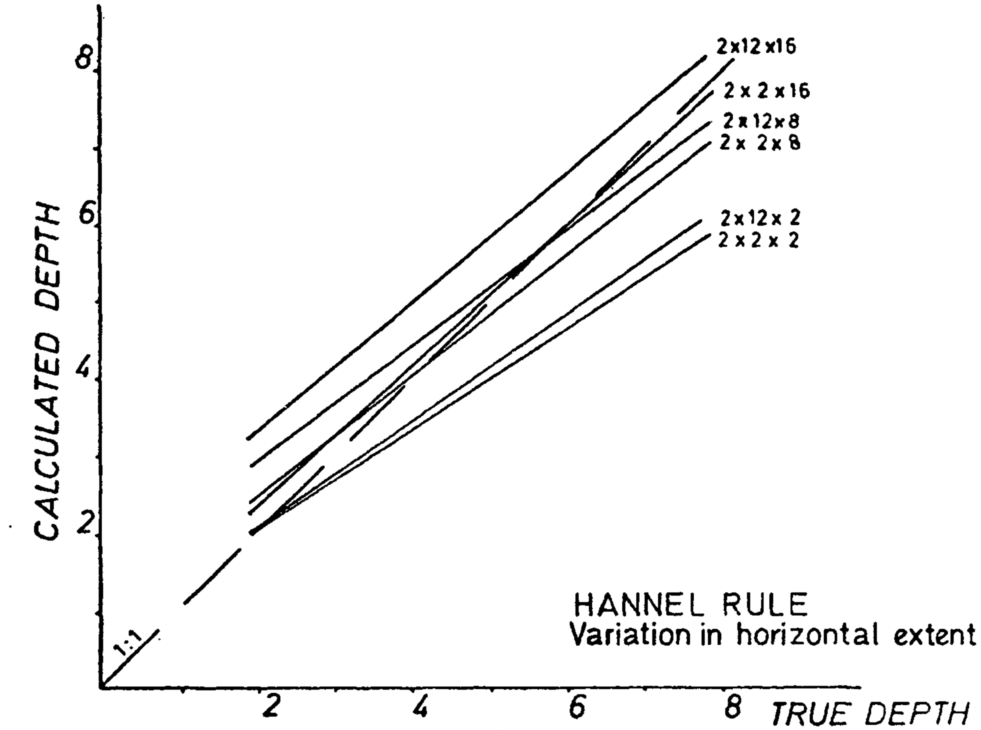

CALCULATED DEPTH
8
6
4
2
1:1
2
4
6
8
TRUE DEPTH
2x12x16
2x2x16
2x12x8
2x2x8
2x12x2
2x2x2
HANNEL RULE
Variation in horizontal extent

FIG. 27

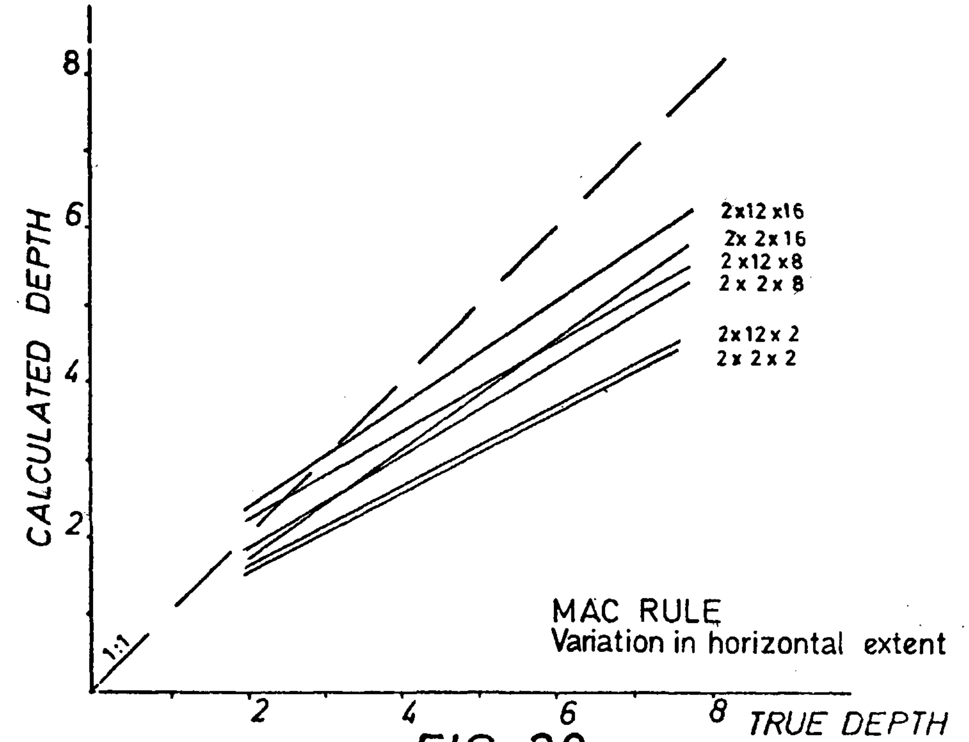

CALCULATED DEPTH
8
6
4
2
1:1
2
4
6
8
TRUE DEPTH
2x12x16
2x2x16
2x12x8
2x2x8
2x12x2
2x2x2
MAC RULE
Variation in horizontal extent

FIG. 28

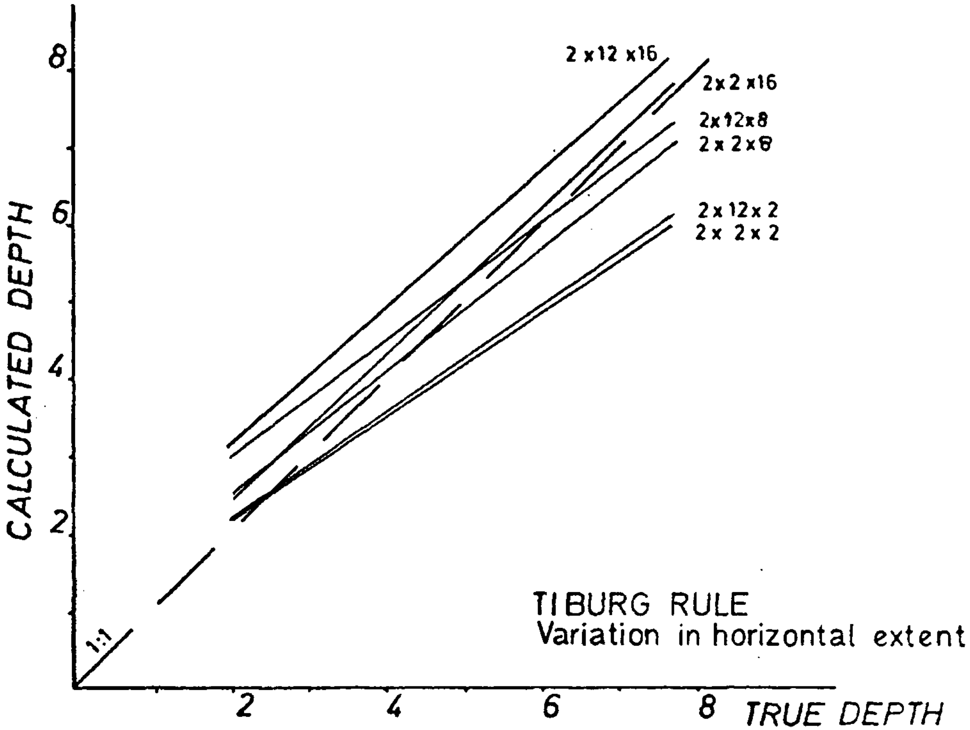

CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
1:1
2 x 12 x 16
2 x 2 x 16
2 x 12 x 8
2 x 2 x 8
2 x 12 x 2
2 x 2 x 2
TIBURG RULE
Variation in horizontal extent

FIG. 29

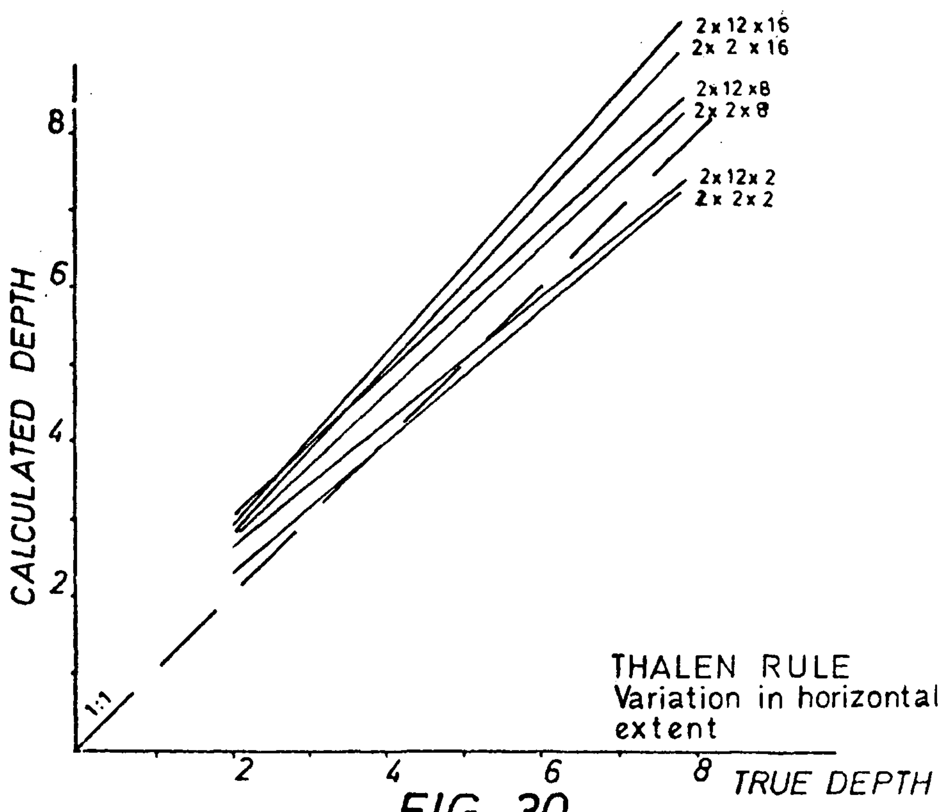

CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
1:1
2 x 12 x 16
2 x 2 x 16
2 x 12 x 8
2 x 2 x 8
2 x 12 x 2
2 x 2 x 2
THALEN RULE
Variation in horizontal extent

FIG. 30

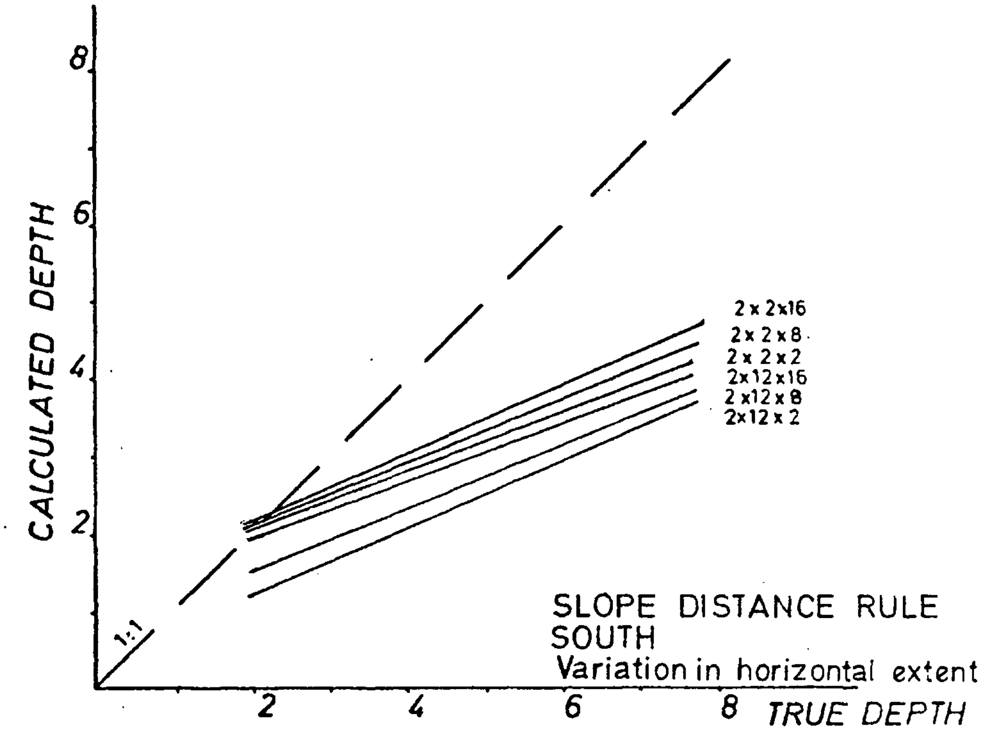

CALCULATED DEPTH
8
6
4
2
1:1
2x2x16
2x2x8
2x2x2
2x12x16
2x12x8
2x12x2
SLOPE DISTANCE RULE
SOUTH
Variation in horizontal extent
2
4
6
8
TRUE DEPTH

FIG. 31

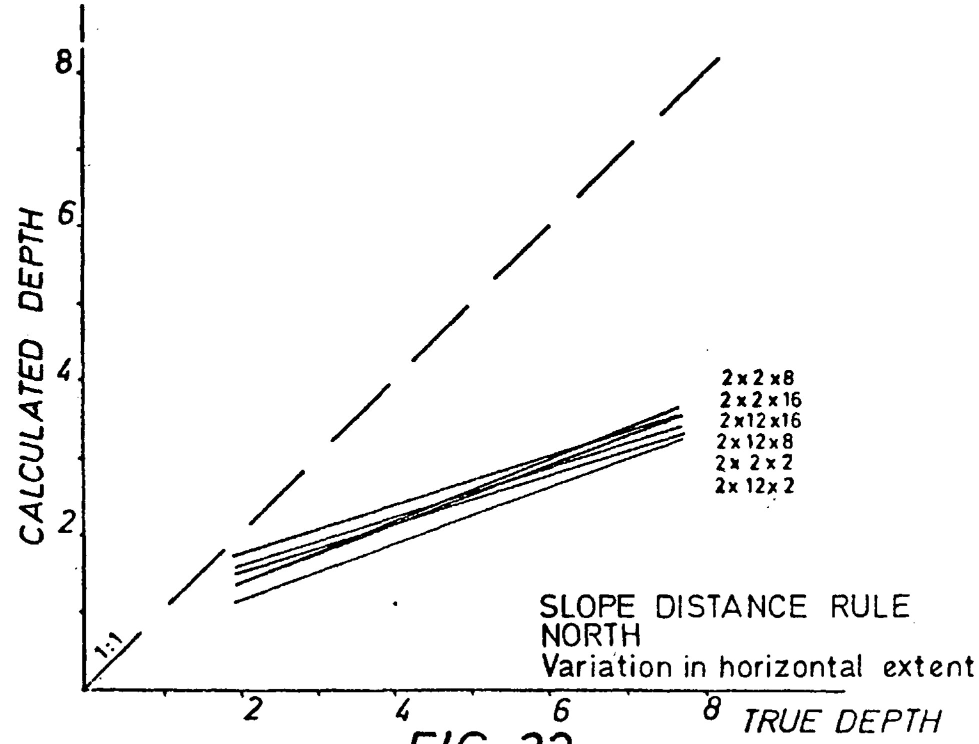

CALCULATED DEPTH
8
6
4
2
1:1
2x2x8
2x2x16
2x12x16
2x12x8
2x2x2
2x12x2
SLOPE DISTANCE RULE
NORTH
Variation in horizontal extent
2
4
6
8
TRUE DEPTH

FIG. 32

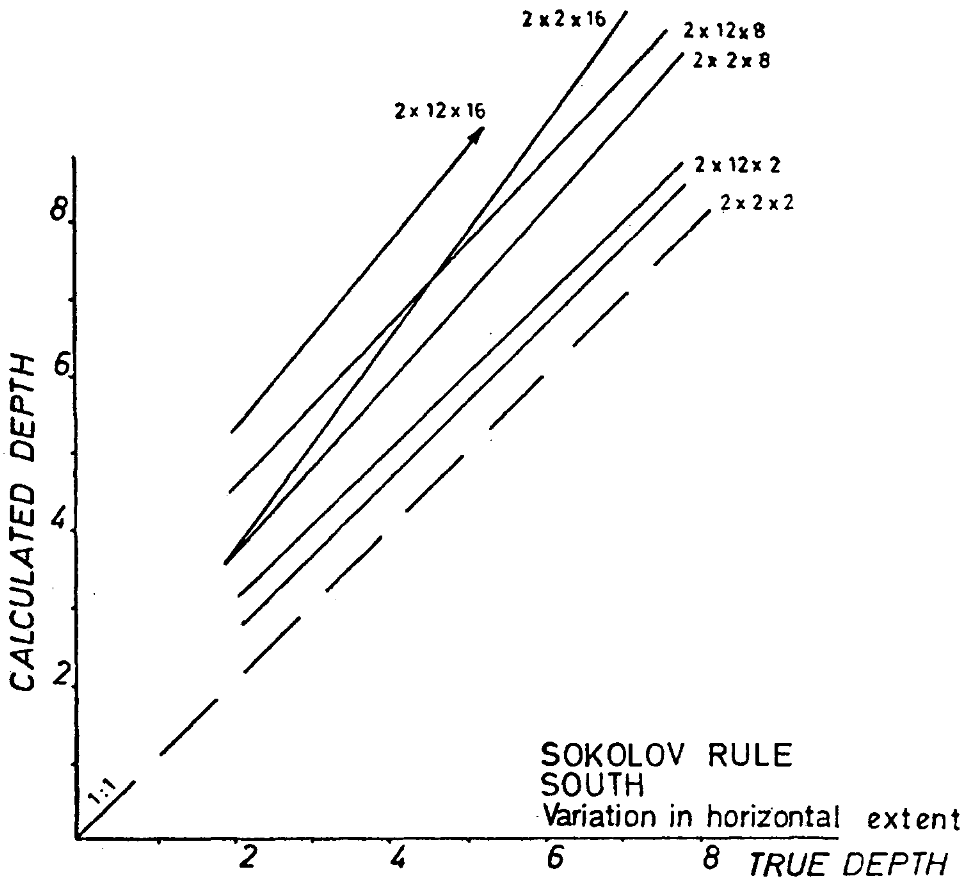

2 x 2 x 16
2 x 12 x 8
2 x 2 x 8
2 x 12 x 16
2 x 12 x 2
2 x 2 x 2
CALCULATED DEPTH
8
6
4
2
1:1
SOKOLOV RULE
SOUTH
Variation in horizontal extent
2
4
6
8
TRUE DEPTH

FIG. 33

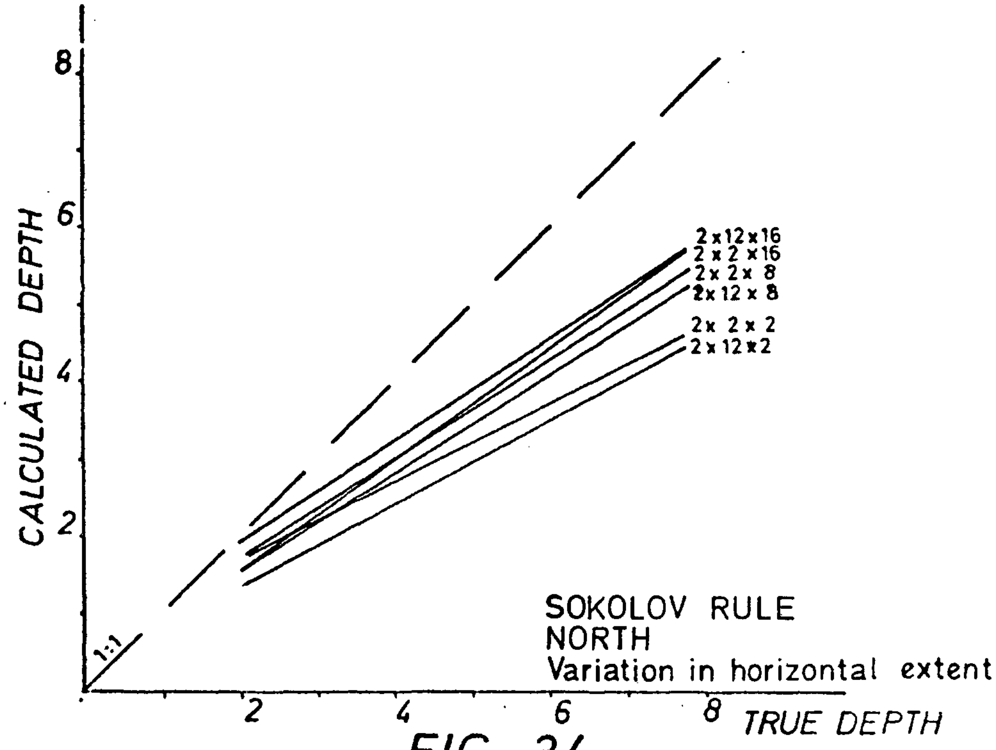

8
6
4
2
CALCULATED DEPTH
2 x 12 x 16
2 x 2 x 16
2 x 2 x 8
2 x 12 x 8
2 x 2 x 2
2 x 12 x 2
1:1
SOKOLOV RULE
NORTH
Variation in horizontal extent
2
4
6
8
TRUE DEPTH

FIG. 34

tends to increase the underestimation of the depth to the top of the model, as was mentioned earlier already. The effect increases with an increasing depth extent of the body, but is much smaller than the effect due to depth extent alone.

For the Slope-distance Rule no significant result could be obtained, and the effect is considered to be smaller than the repeatability of the results. For the Sokolov Rule different responses are obtained for the two sides of the anomaly. This difference can be considered to be due to the fact that the steeper side of the anomaly would be less sensitive to small changes in slope than the southern side.

Changes in Strike

The effect of a change in strike of 10 and 20 degrees from the perpendicular to the profile direction was investigated and the results are shown in Fig. 35 to Fig. 42. The effect is very small in most cases and barely exceeds the sensitivity of the techniques. There is little difference in the results for the two different models, although the effect would seem to be larger for the dike-like structure. Although an effect seems to be noticeable in the Slope-distance Rule (Fig. 39 and 40), the effect is considered to be smaller than the repeatability of the method. The Sokolov Rule is, like the amplitude techniques, little influenced by the changes in strike. It is to be noted that the effect is opposite for opposite sides of the anomaly, an effect that is to be expected.

In general it can be said that any effect due to a variation in body strike from the perpendicular to the profile is negligible, provided that the change in strike is smaller than 20 degrees.

Variation in Regional

The effects due to a variation in the applied regional are shown in Fig. 43 to Fig. 47. The effects are much larger

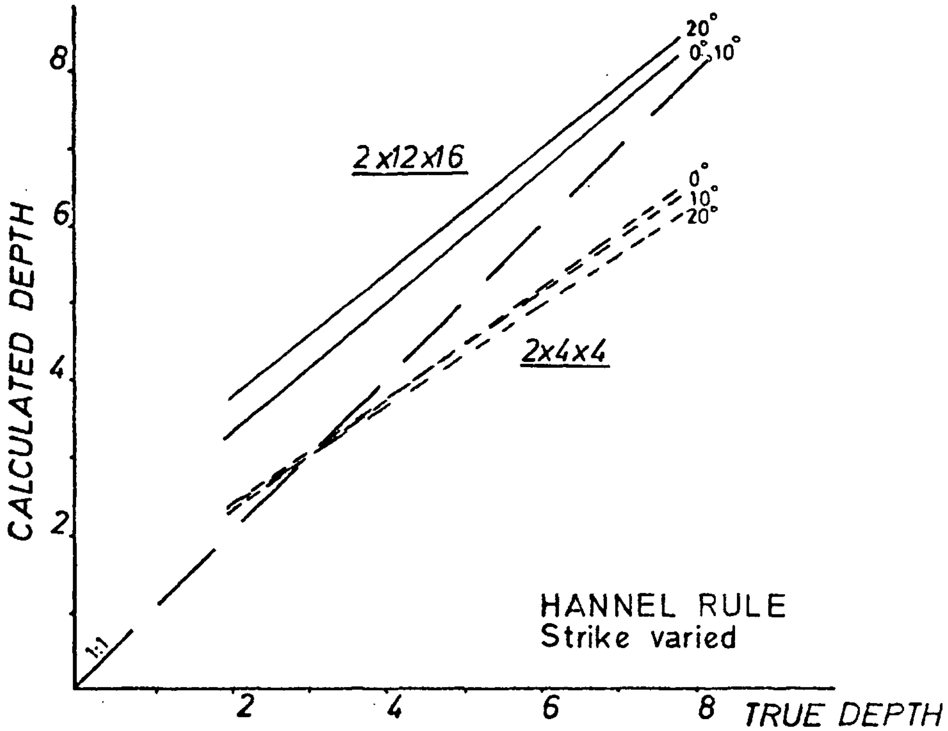

CALCULATED DEPTH
2
4
6
8
TRUE DEPTH
1:1
2x12x16
20°
0°,10°
2x4x4
0°
10°
20°
HANNEL RULE
Strike varied

FIG. 35

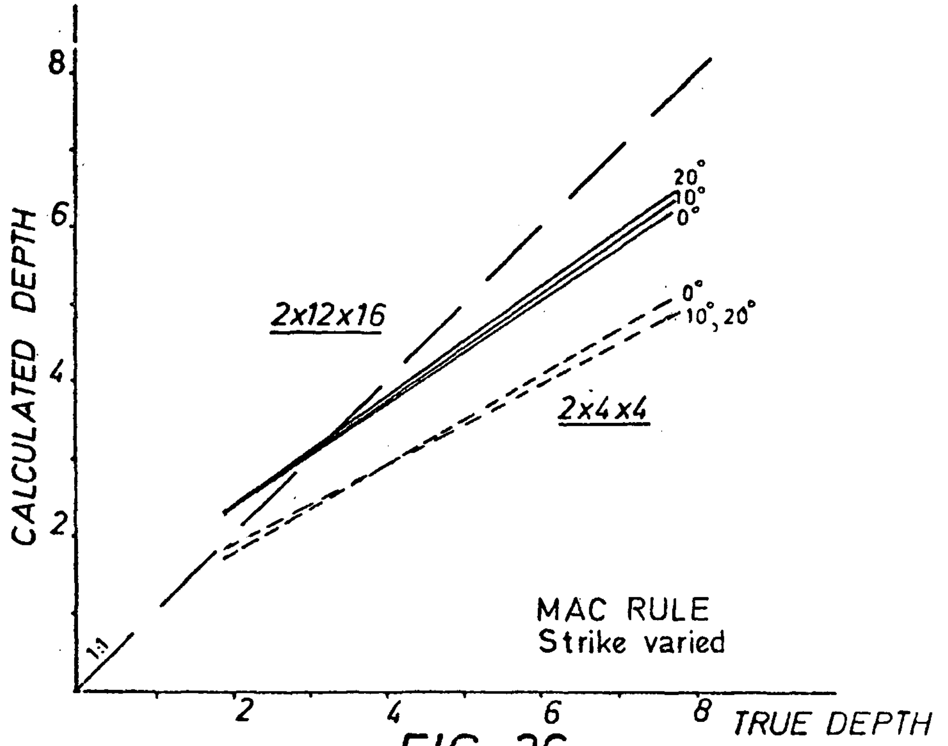

CALCULATED DEPTH
2
4
6
8
TRUE DEPTH
1:1
2x12x16
20°
10°
0°
2x4x4
0°
10°,20°
MAC RULE
Strike varied

FIG. 36

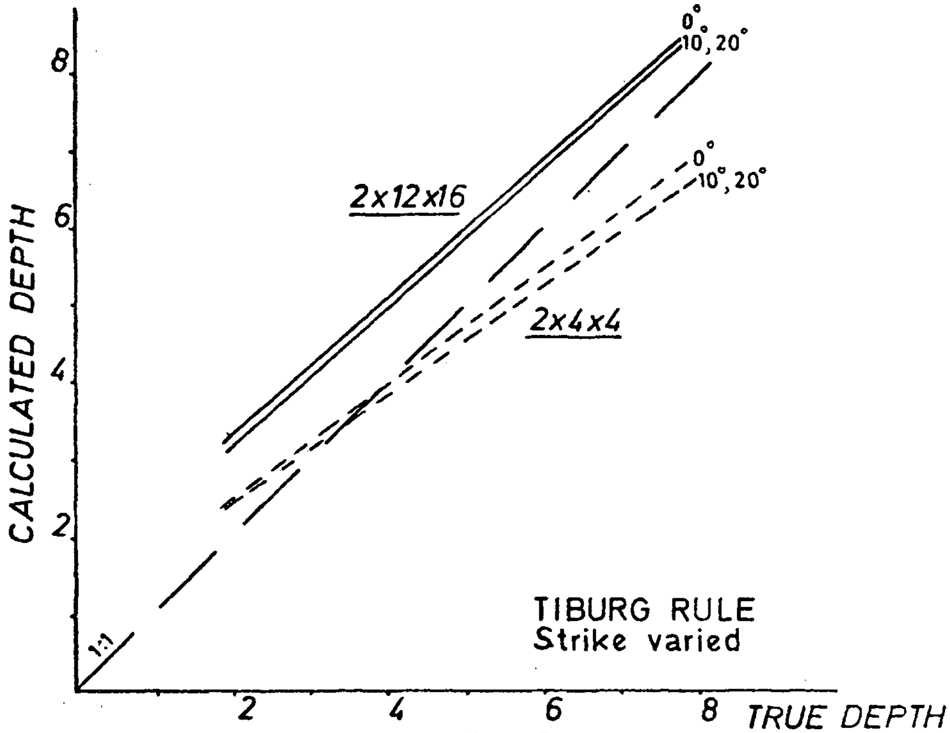

CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
2
4
6
8
1:1
2x12x16
2x4x4
0°
10°, 20°
0°
10°, 20°
TIBURG RULE
Strike varied

FIG. 37

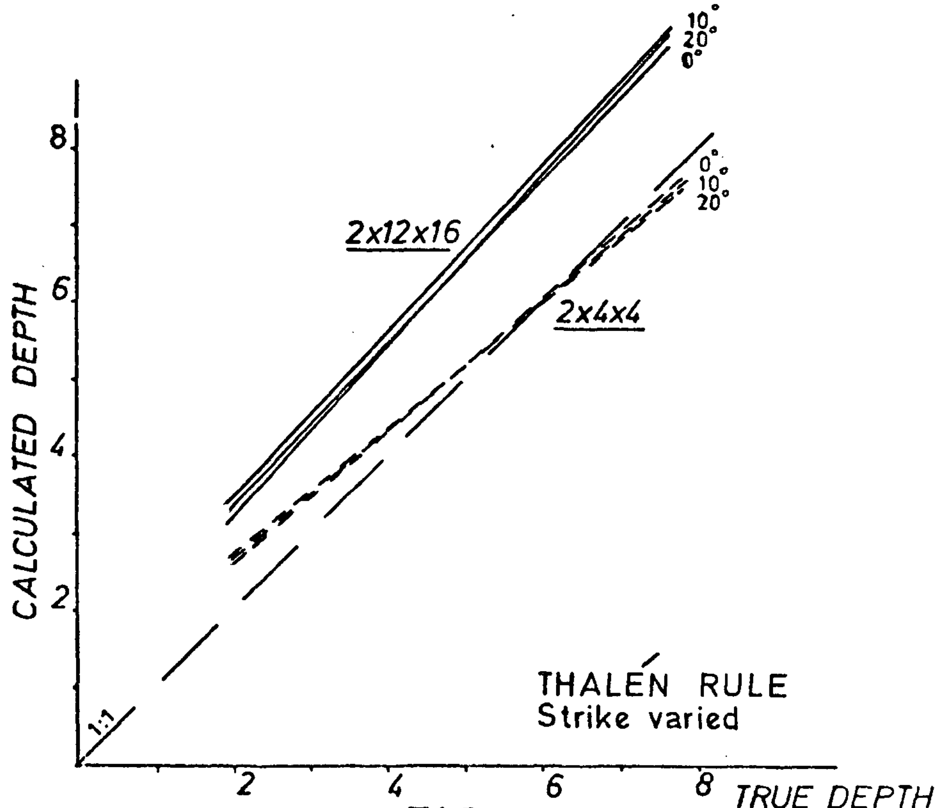

CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
2
4
6
8
1:1
2x12x16
2x4x4
10°
20°
0°
0°
10°
20°
THALEŃ RULE
Strike varied

FIG. 38

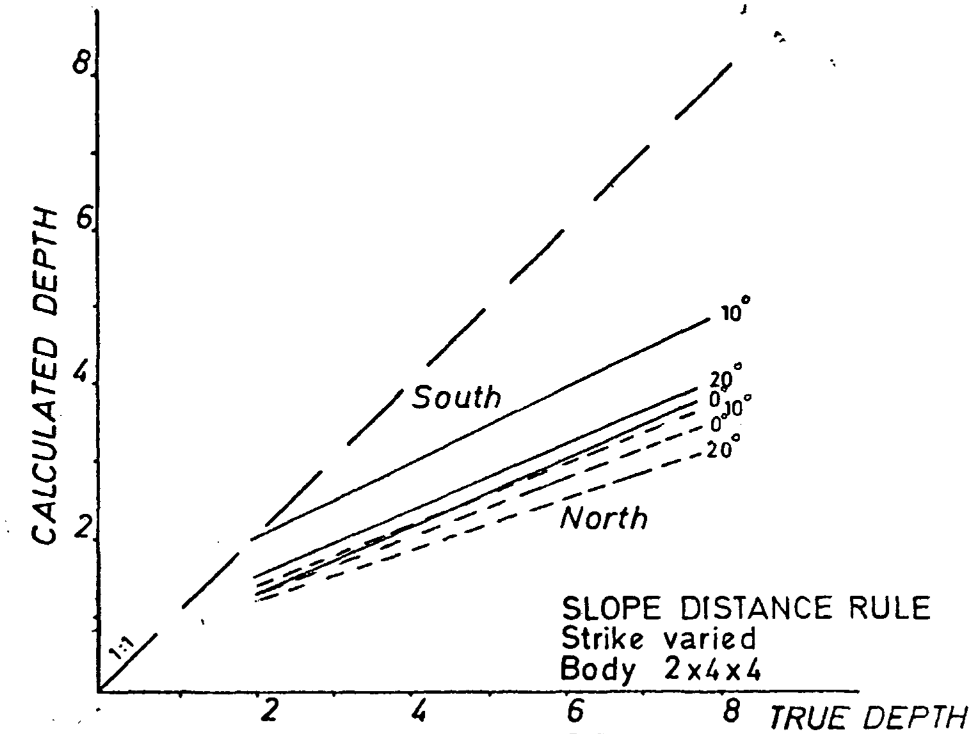

CALCULATED DEPTH
2
4
6
8
1:1
South
North
10°
20°
0°
10°
0°
20°
SLOPE DISTANCE RULE
Strike varied
Body 2x4x4
2
4
6
8
TRUE DEPTH

FIG. 39

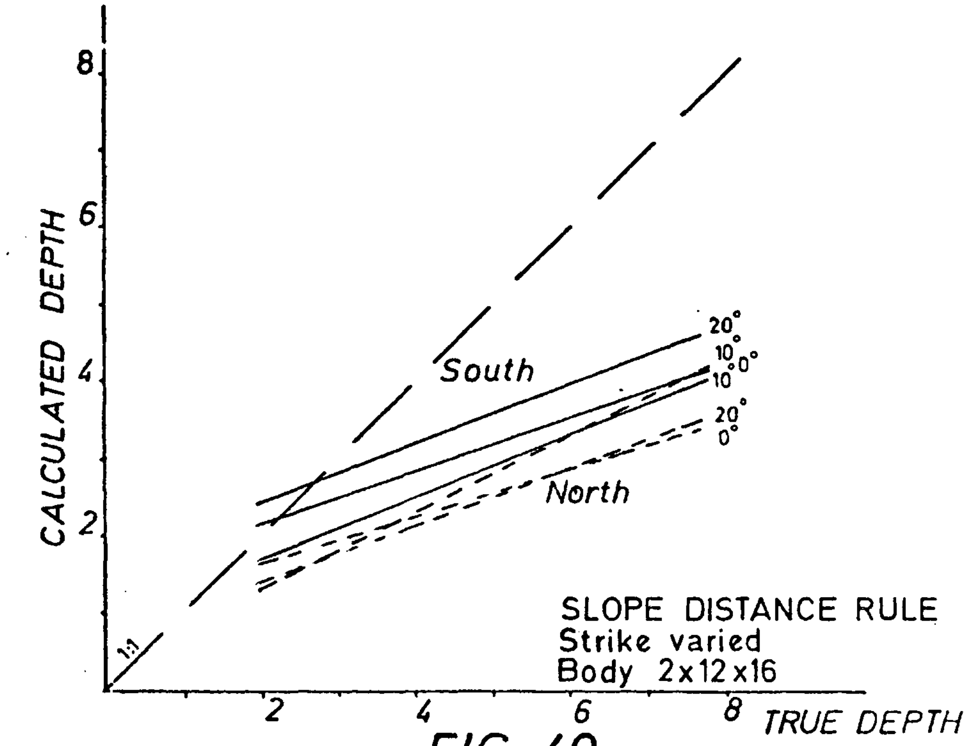
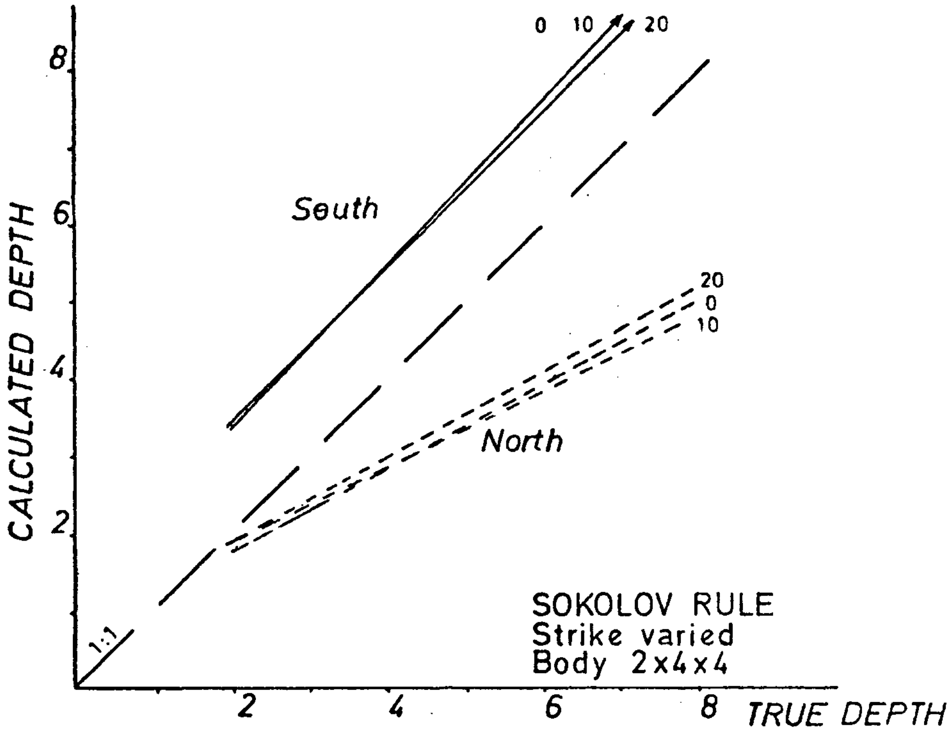
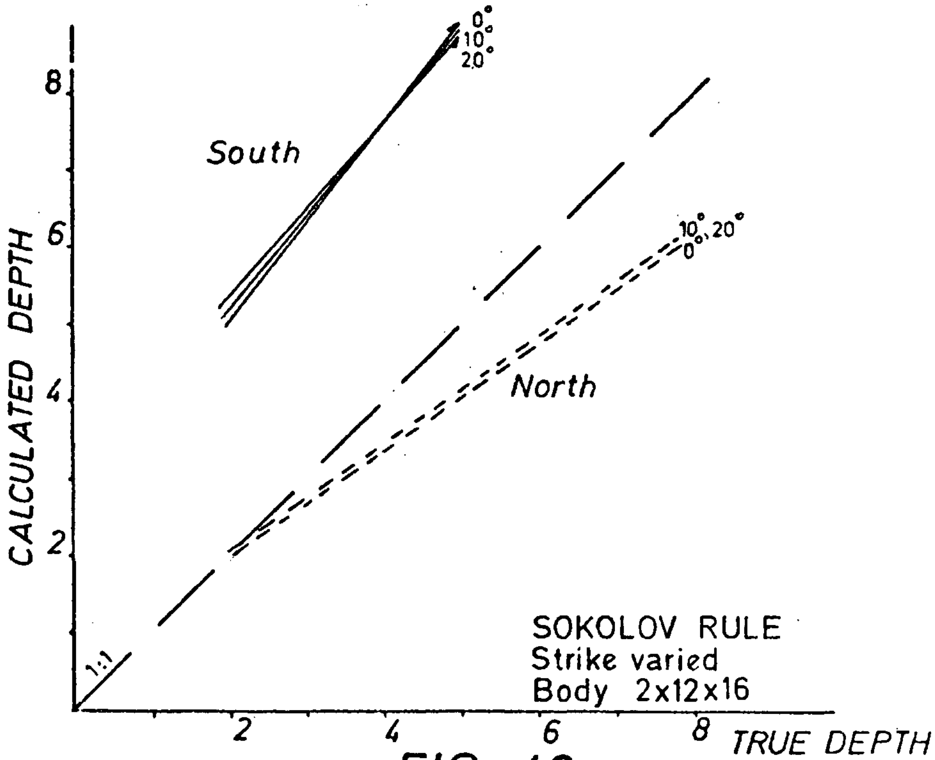

CALCULATED DEPTH
2
4
6
8
1:1
South
North
20°
10°
0°
10°
20°
0°
SLOPE DISTANCE RULE
Strike varied
Body 2x12x16
2
4
6
8
TRUE DEPTH

FIG. 40



CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
0 10 20
South
20
0
10
North
1:1
SOKOLOV RULE
Strike varied
Body 2x4x4

FIG. 41



CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
0°
10°
20°
South
10°,20°
0°
North
1:1
SOKOLOV RULE
Strike varied
Body 2x12x16

FIG. 42

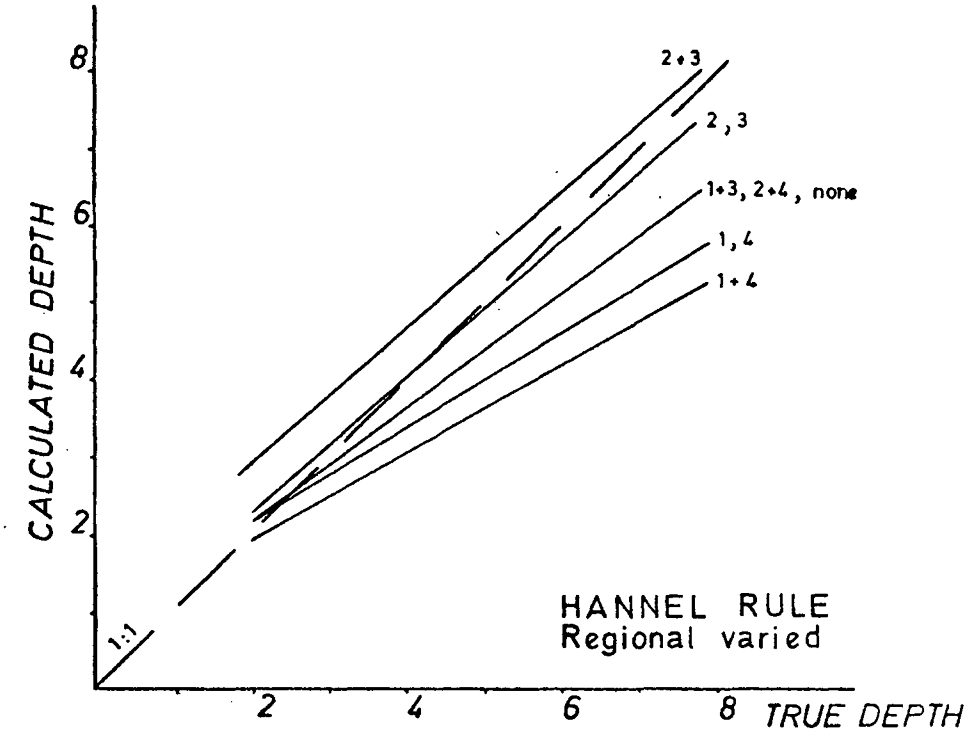

CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
1:1
2+3
2,3
1+3, 2+4, none
1,4
1+4
HANNEL RULE
Regional varied

FIG. 43

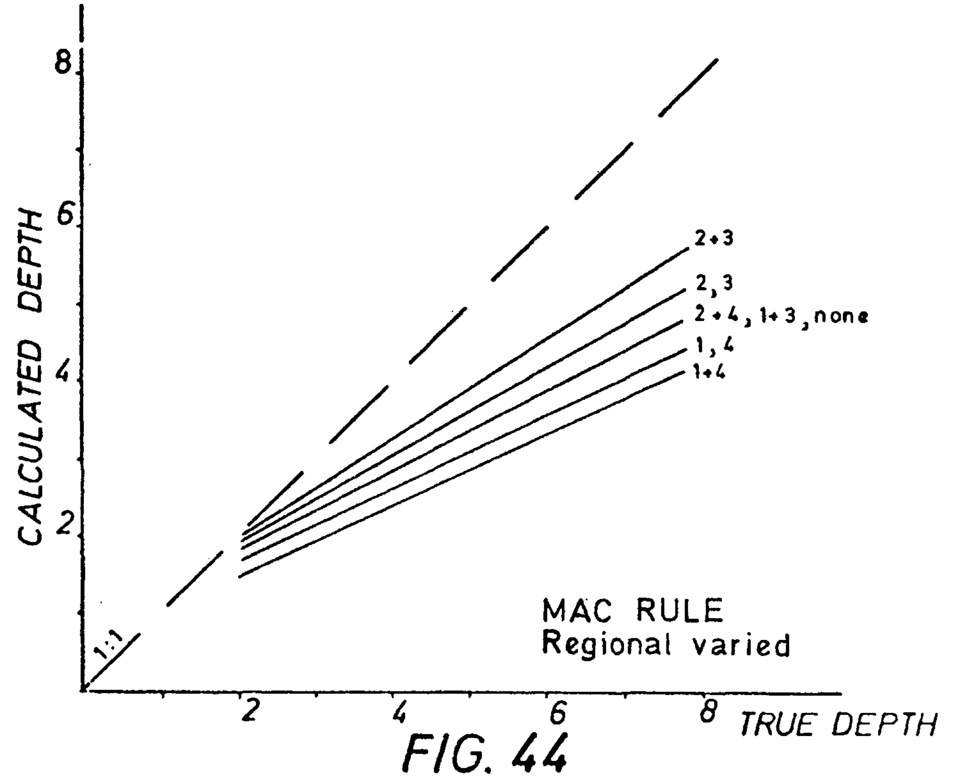
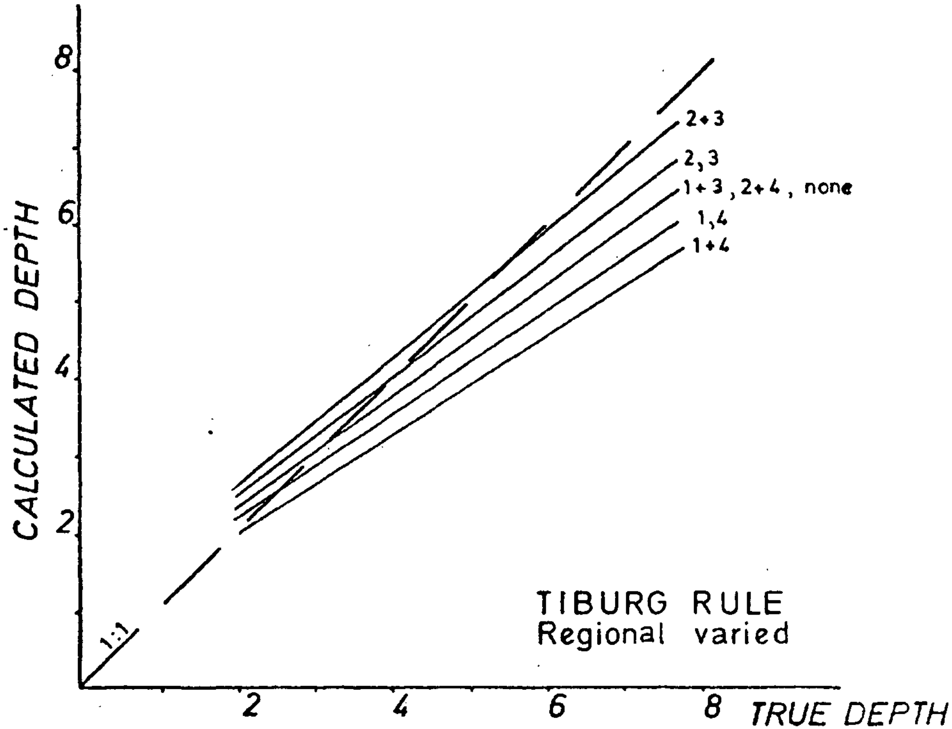
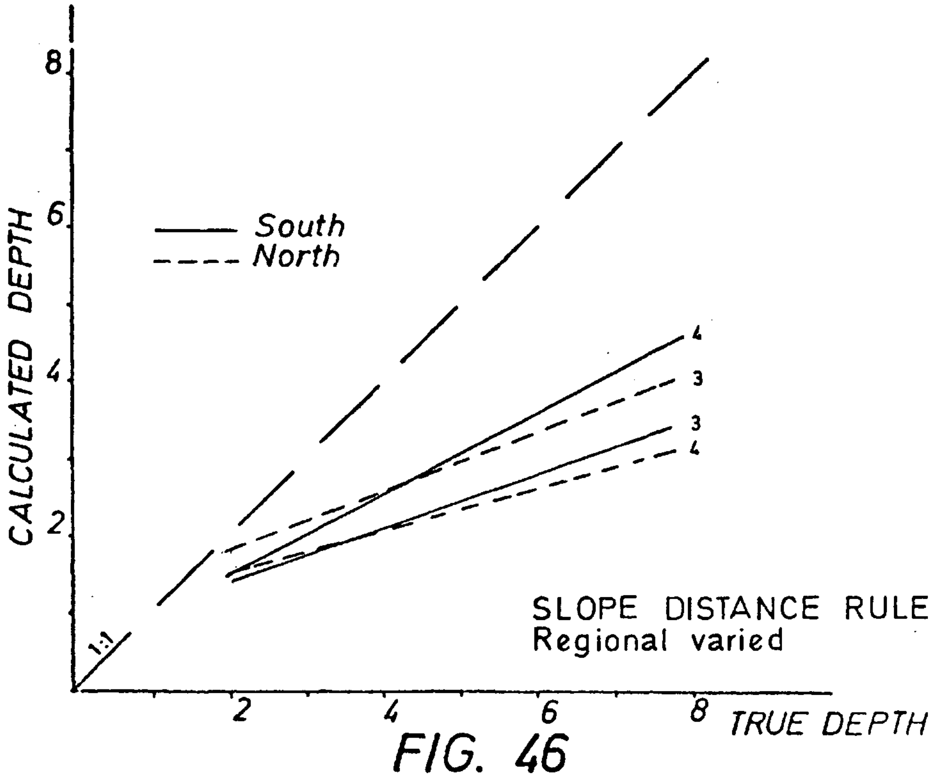

CALCULATED DEPTH
8
6
4
2
2
4
6
8
TRUE DEPTH
1:1
2+3
2,3
2+4, 1+3, none
1,4
1+4
MAC RULE
Regional varied

FIG. 44



CALCULATED DEPTH
2
4
6
8
1:1
2+3
2,3
1+3, 2+4, none
1,4
1+4
TIBURG RULE
Regional varied
2
4
6
8
TRUE DEPTH

FIG. 45



CALCULATED DEPTH
2
4
6
8
1:1
South
North
4
3
3
4
SLOPE DISTANCE RULE
Regional varied
2
4
6
8
TRUE DEPTH

FIG. 46

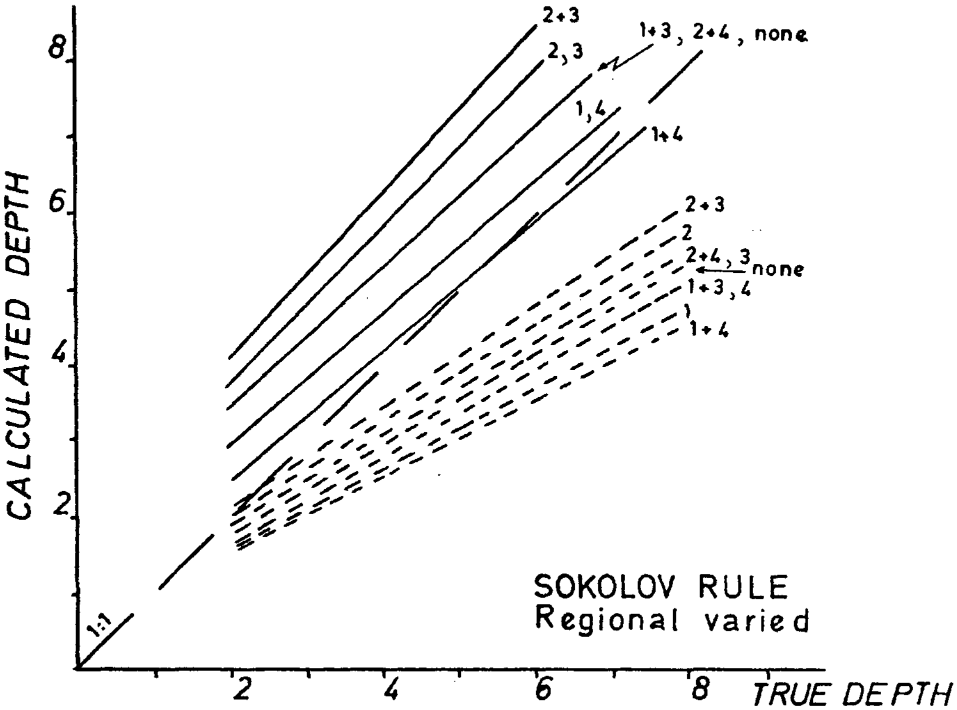

CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
1:1
2+3
2,3
1+3, 2+4, none
1,4
1+4
2+3
2
2+4, 3
none
1+3, 4
1
1+4
SOKOLOV RULE
Regional varied

FIG. 47

than was expected, and for most techniques constitute the primary error that can occur in the determination of the depth of the anomalous body. The removal of the correct regional is therefore a very important task to be attempted before any depth determinations can be satisfactorily completed. A very important fact to be noted is that the Thalén Rule is relatively insensitive to any variation in the regional, as even the effect of tilting of the anomaly could not be determined within the sensitivity of the technique. This rule is not included in the following discussions.

The amplitude-measuring techniques (Fig. 43 to 45) show large variations due to regional fluctuations. The smallest effect is noticeable in the Tiburg Rule, where it is only slightly smaller than the effect due to variations in depth extent of the model. An upward translational movement and anti-clockwise rotation of the regional decrease the determined depths, whereas for both downward translation and clockwise rotation of the regional an increase in the calculated depth is obtained. These effects are about equal in magnitude for the amounts of translation and rotation studied in this thesis, so that in combination the effects are either cancelled or doubled in strength.

In the Slope-distance Rule the length of the "straight slope" segment is independent of the level of the regional, so that rotation of the regional only influences the measured depths. The effects are of considerable magnitude and are opposite for different sides of the anomaly.

A considerable amount of variation in the depth of the model due to changes in the regional is evident in the Sokolov Rule. The observed differences in the effects on the two sides of the anomaly are the result of the fact that the length of the so-called "Sokolov segment" depends on two intersection points. For a translation of the regional, only the position of the intersection with the regional changes. A rotation of the regional manifests itself in both intersections on either side of the anomaly. Different effects are therefore obtained for the various changes in the regional.

Changes in Declination

The effects due to small changes in the declination of the earth's field, which are considered equivalent to small changes in the remnant magnetism of the model, are surprisingly small. In most of the techniques the effects are considered to be smaller than the repeatability of the method. Only in the Thalén and Sokolov Rules could any differences be determined (Fig. 48 and 49).

In summary it would seem that if variations in declination are smaller than 20 degrees, the effect upon the determined depths can be considered to be negligible. This result, however, can only be assumed for the three-dimensional model investigated in this study.

Changes in Dip

A variation in the dip of two bodies, the vertical pipe and the vertical dike, was investigated and the results are shown in Fig. 50 to Fig. 56. Variations in depth determinations are shown for a southerly dip of 20 and 40 degrees from the vertical. The effects are appreciable and in general are larger for the dike-like body than for the pipe-like model. The effects increase with an increase in horizontal extent of the model.

The Thalén Rule shows the least amount of sensitivity to changes in the dip of the model when compared to the other amplitude-measuring methods. The distance measured in the Thalén Rule is situated on the northern side of the anomaly, and the effects are therefore expected to be greater for a northerly dipping model. The other amplitude-measuring methods, using both flanks of the anomaly, would seem to be less sensitive to the direction of dip.

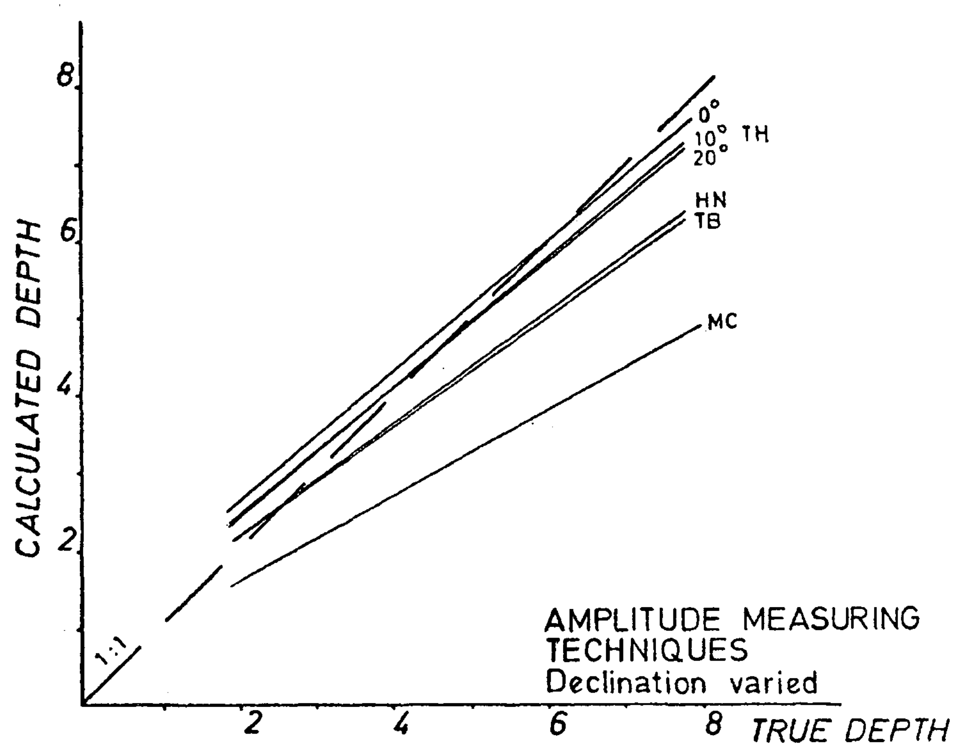

CALCULATED DEPTH
8
6
4
2
0°
10° TH
20°
HN
TB
MC
1:1
AMPLITUDE MEASURING
TECHNIQUES
Declination varied
2
4
6
8
TRUE DEPTH

FIG. 48

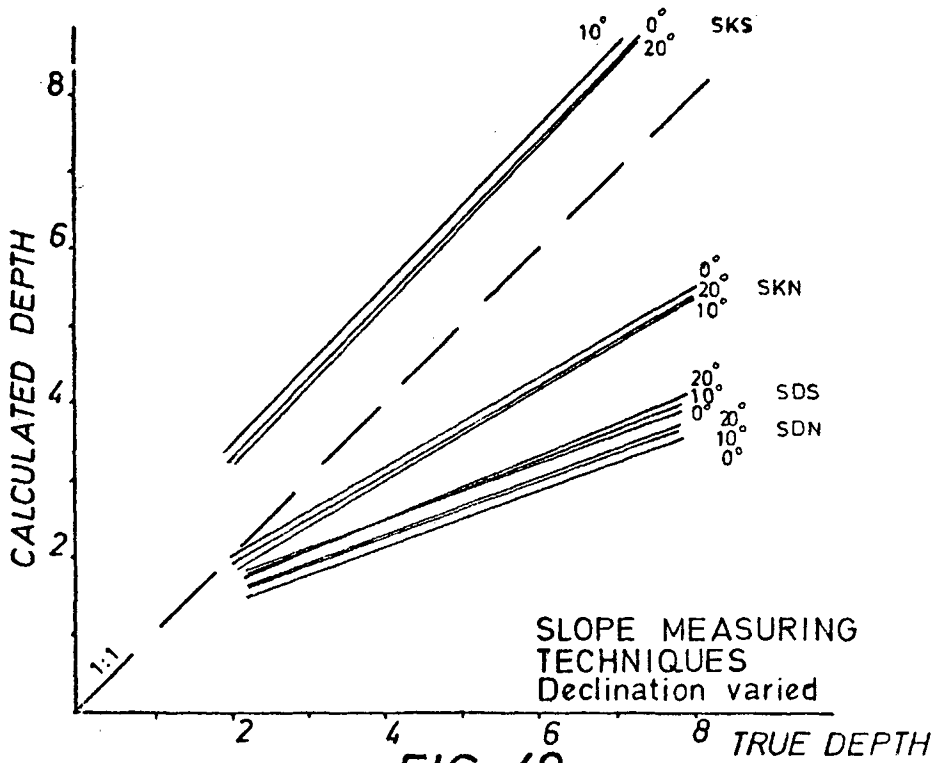

10°
0°
20°
SKS
CALCULATED DEPTH
8
6
4
2
0°
20° SKN
10°
20°
10° SDS
0°
20°
10° SDN
0°
1:1
SLOPE MEASURING
TECHNIQUES
Declination varied
2
4
6
8
TRUE DEPTH

FIG. 49

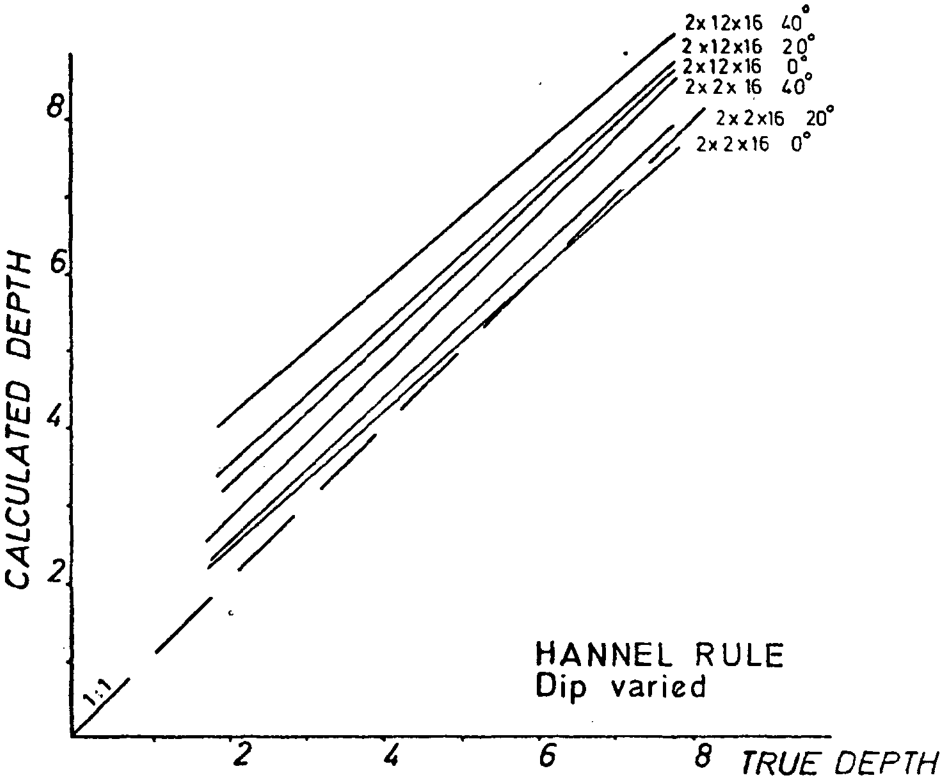

2x12x16 40°
2x12x16 20°
2x12x16 0°
2x2x16 40°
2x2x16 20°
2x2x16 0°
CALCULATED DEPTH
2
4
6
8
1:1
HANNEL RULE
Dip varied
2
4
6
8
TRUE DEPTH

FIG. 50

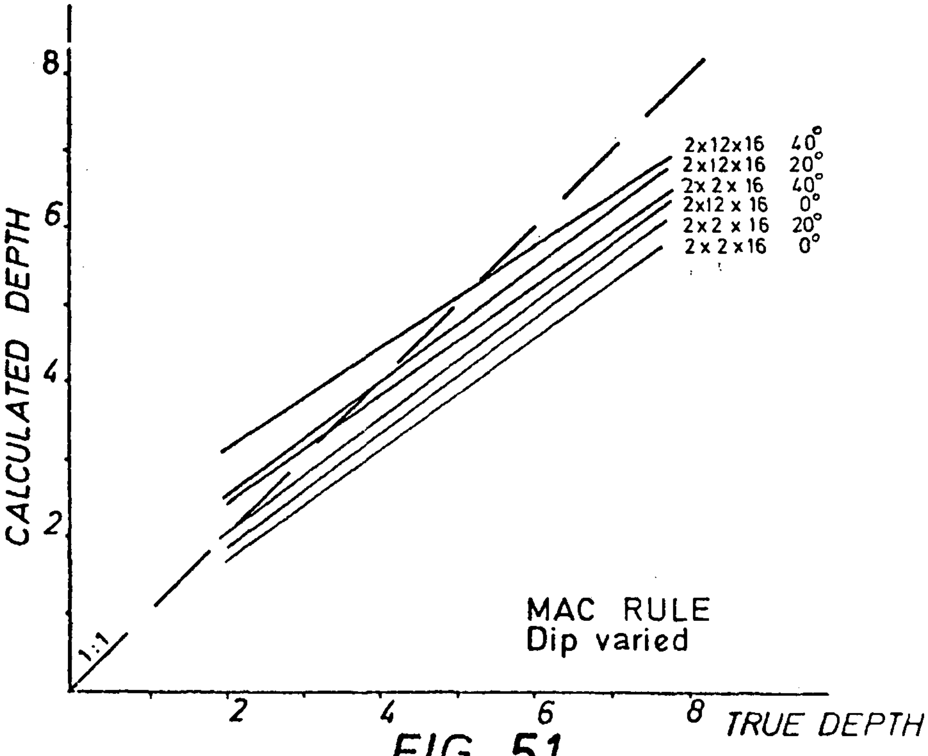

2x12x16 40°
2x12x16 20°
2x2x16 40°
2x12x16 0°
2x2x16 20°
2x2x16 0°
CALCULATED DEPTH
2
4
6
8
1:1
MAC RULE
Dip varied
2
4
6
8
TRUE DEPTH

FIG. 51

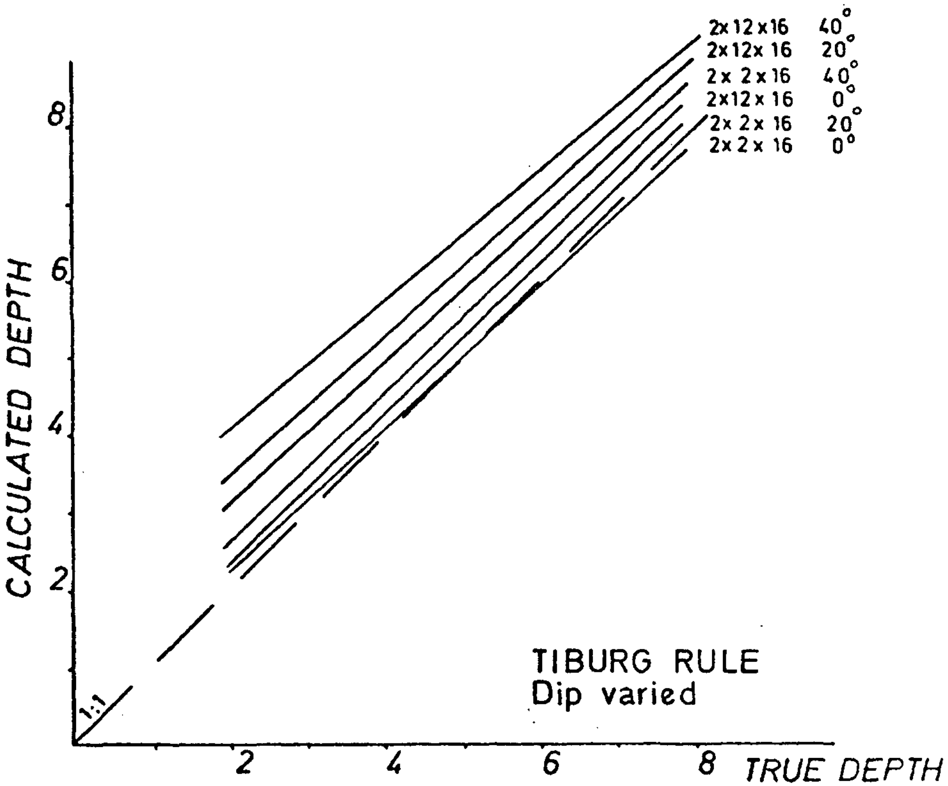

2x12x16 40°
2x12x16 20°
2x 2x16 40°
2x12x16 0°
2x 2x16 20°
2x 2x16 0°
CALCULATED DEPTH
8
6
4
2
1:1
TIBURG RULE
Dip varied
2
4
6
8
TRUE DEPTH

FIG. 52

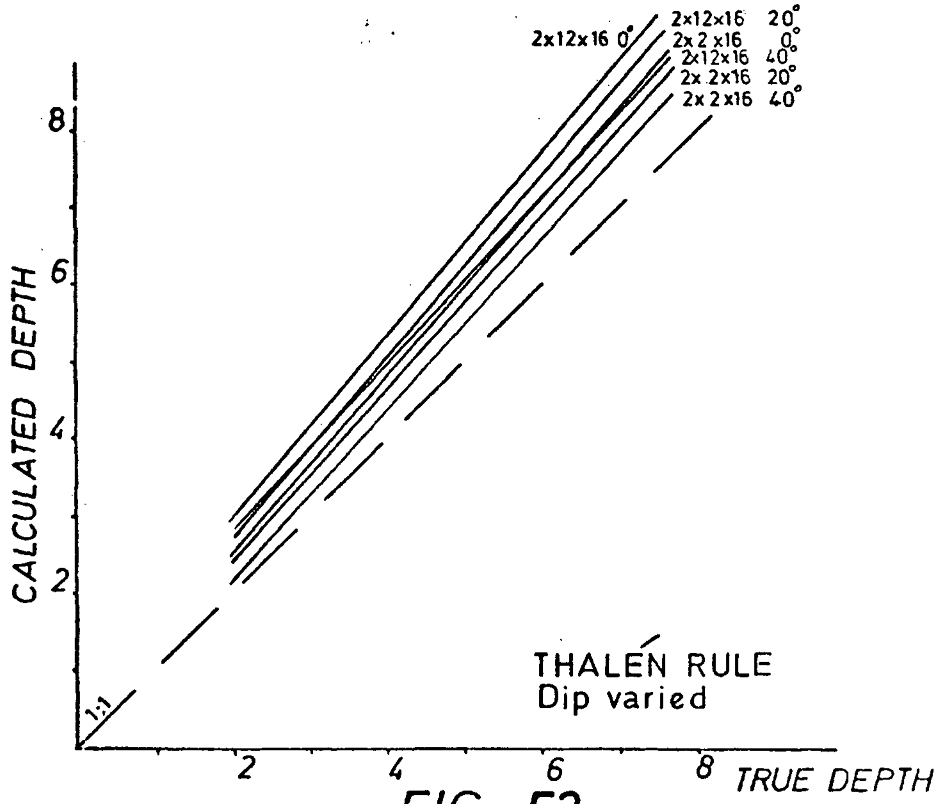

2x12x16 0°
2x12x16 20°
2x2x16 0°
2x12x16 40°
2x 2x16 20°
2x 2x16 40°
CALCULATED DEPTH
8
6
4
2
1:1
THALÉN RULE
Dip varied
2
4
6
8
TRUE DEPTH

FIG. 53

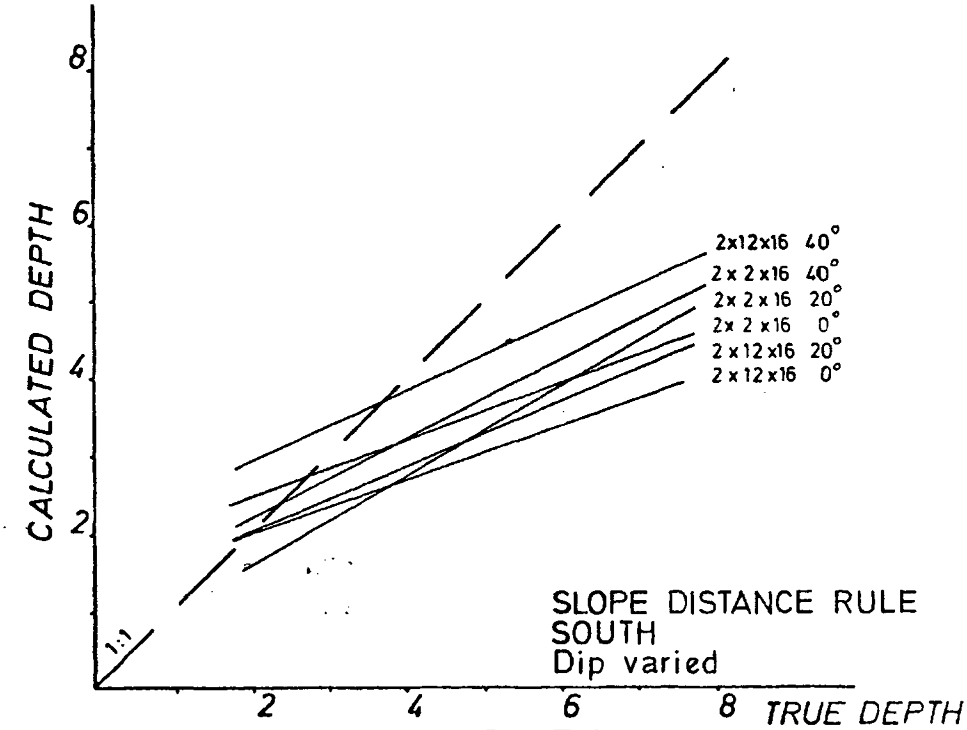

CALCULATED DEPTH
8
6
4
2
1:1
2x12x16 40°
2x2x16 40°
2x2x16 20°
2x2x16 0°
2x12x16 20°
2x12x16 0°
SLOPE DISTANCE RULE
SOUTH
Dip varied
2
4
6
8
TRUE DEPTH

FIG. 54

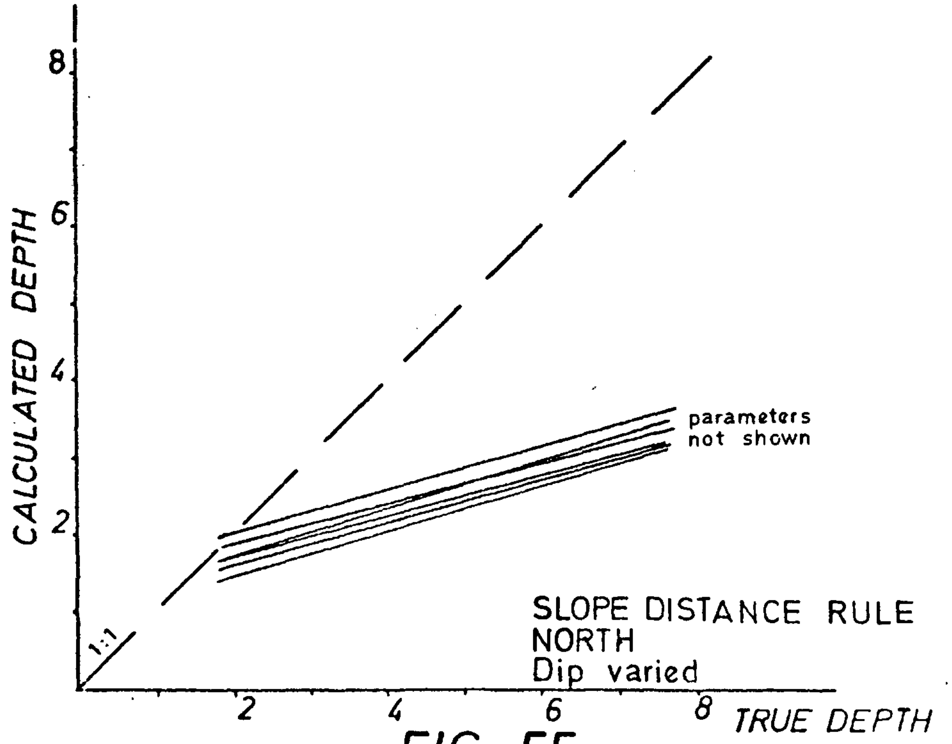

CALCULATED DEPTH
8
6
4
2
1:1
parameters
not shown
SLOPE DISTANCE RULE
NORTH
Dip varied
2
4
6
8
TRUE DEPTH

FIG. 55

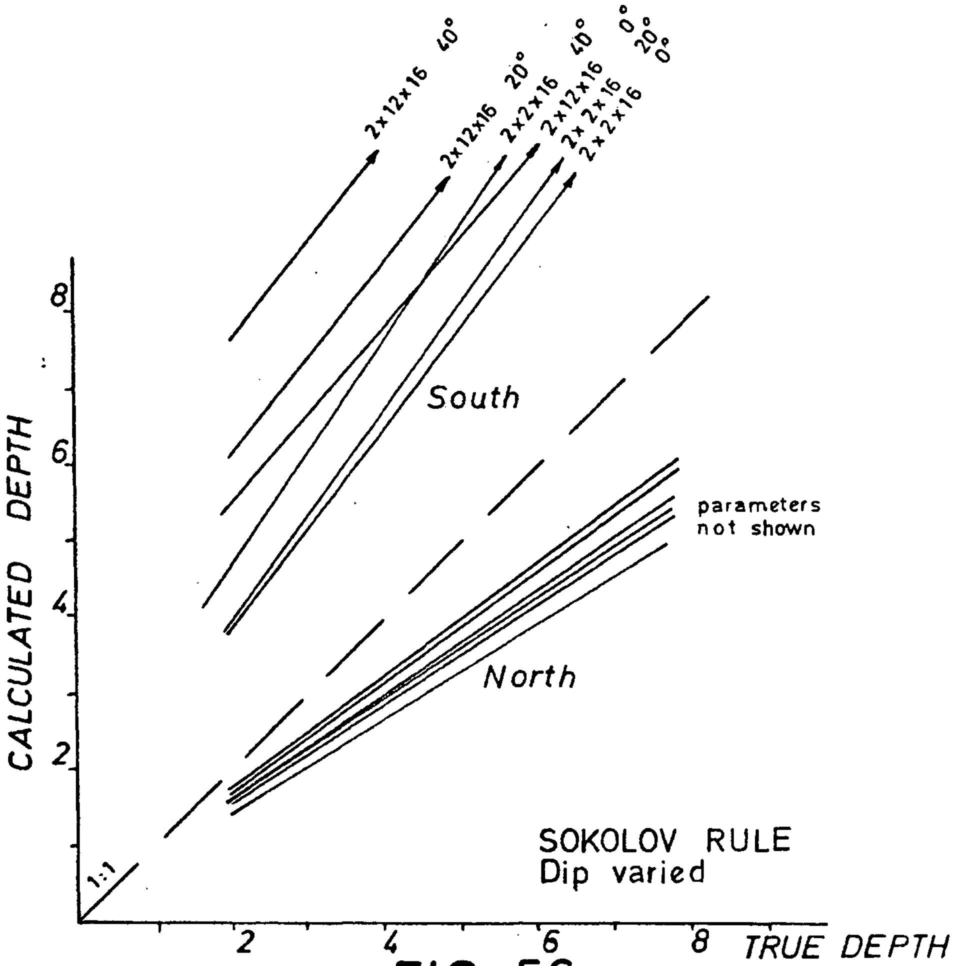

2x12x16
40°
2x12x16
20°
2x2x16
40°
2x12x16
0°
2x2x16
20°
2x2x16
0°
South
parameters not shown
North
SOKOLOV RULE
Dip varied
1:1
CALCULATED DEPTH
TRUE DEPTH
2
4
6
8
2
4
6
8

FIG. 56

The results of the Slope-distance Rule could not be determined with any accuracy and the results are considered to be smaller than the repeatability of the method. The effects in the Sokolov Rule are of considerable magnitude and show that the two sides of the anomaly have a different susceptibility to the direction of dip of the model.

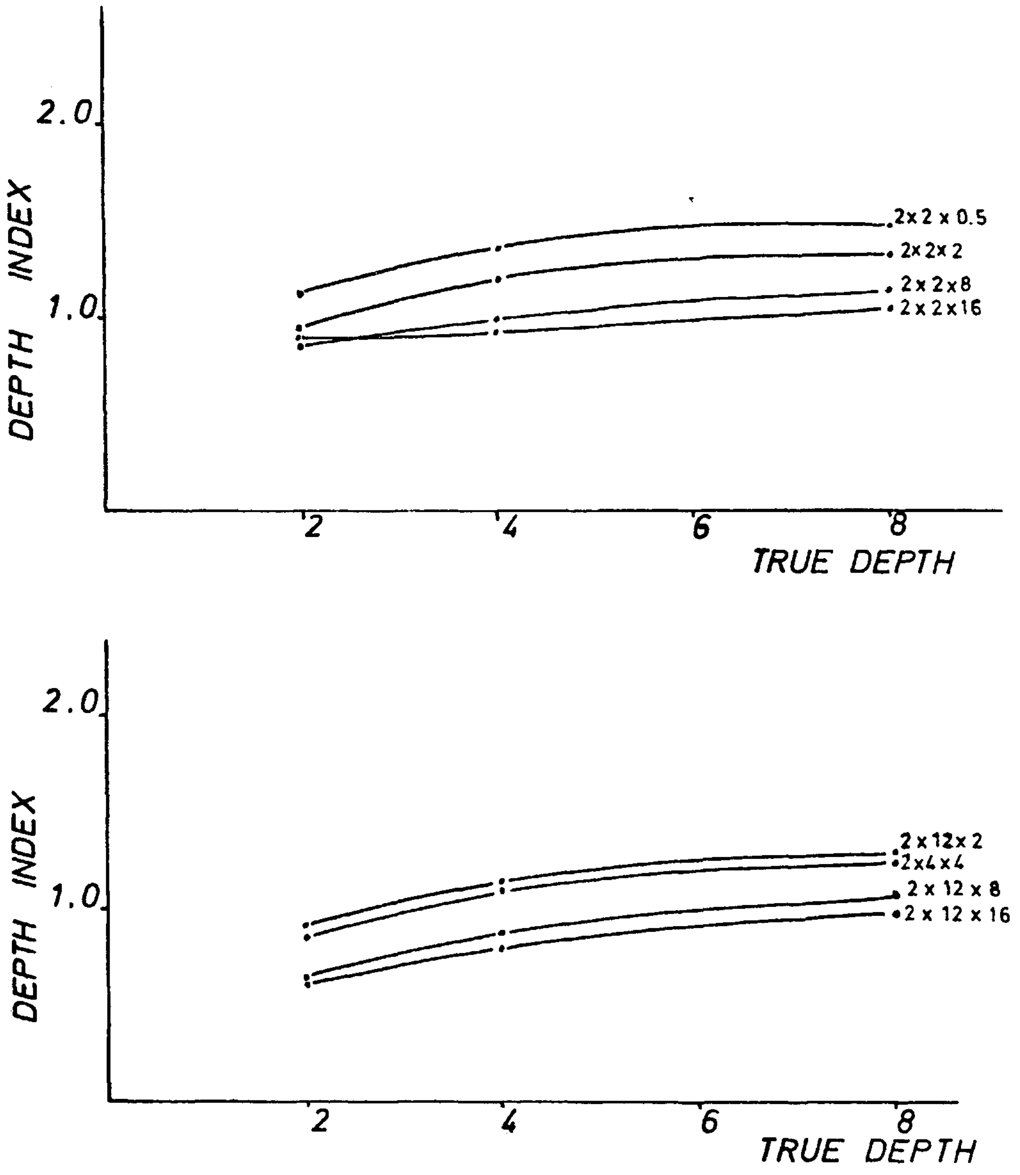
It can be stated in summary that the effect of a deviation from the vertical of the model has an appreciable effect on the determined depths.

Variation in Profile Position

The effect of moving the profile away from the center of the body is very small and begins to be noticeable only when the profile is situated on the edge of the model. For all positions of the profile on the model, the variations in calculated depths were of the same order, or smaller than, the repeatability of the methods. It would seem therefore that as long as the profile is situated on or near the center part of the body, depth determinations can be satisfactorily executed. Due to the small effects, the results are not shown in graphical form.

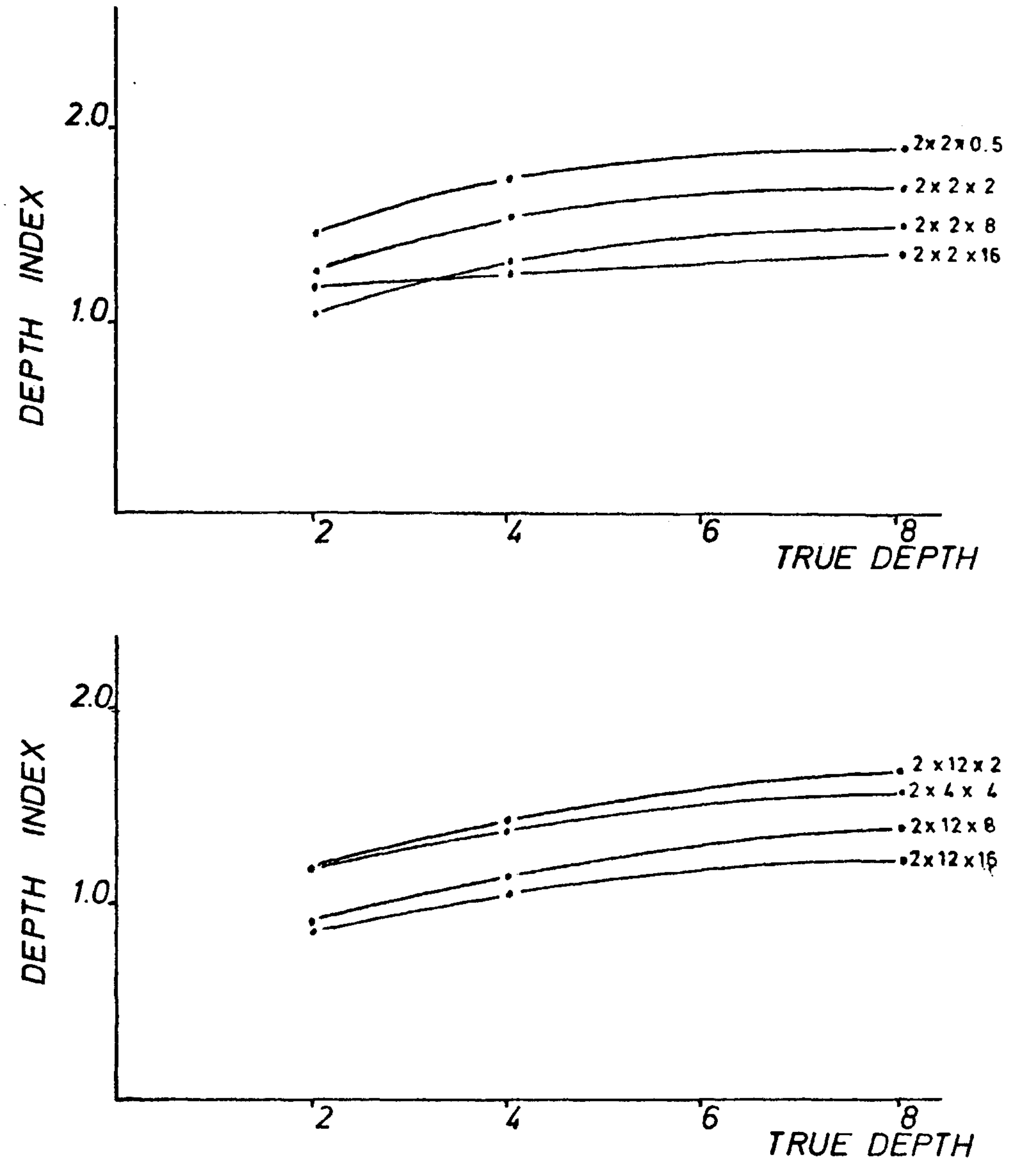
The Depth Indices

In each of the depth-determination techniques discussed in this thesis, it was assumed that a constant depth coefficient could be used, for example a factor of 0.7 in the Thalen Rule and a factor of 0.5 in the Mac Rule, etc. It has now been shown that this is not the case, and that the determined depths are sensitive to a large number of factors, such as vertical extent of the body and others. In Table 2 the coefficients, by which the determined depth has to be multiplied to obtain the true depth to the body, are shown. These coefficients are therefore an indication of the amount by which the originally accepted depth coefficients are in error. These depth indices are shown in graphical form in Fig. 57 to Fig. 64, for the variations in depth extent of the model.



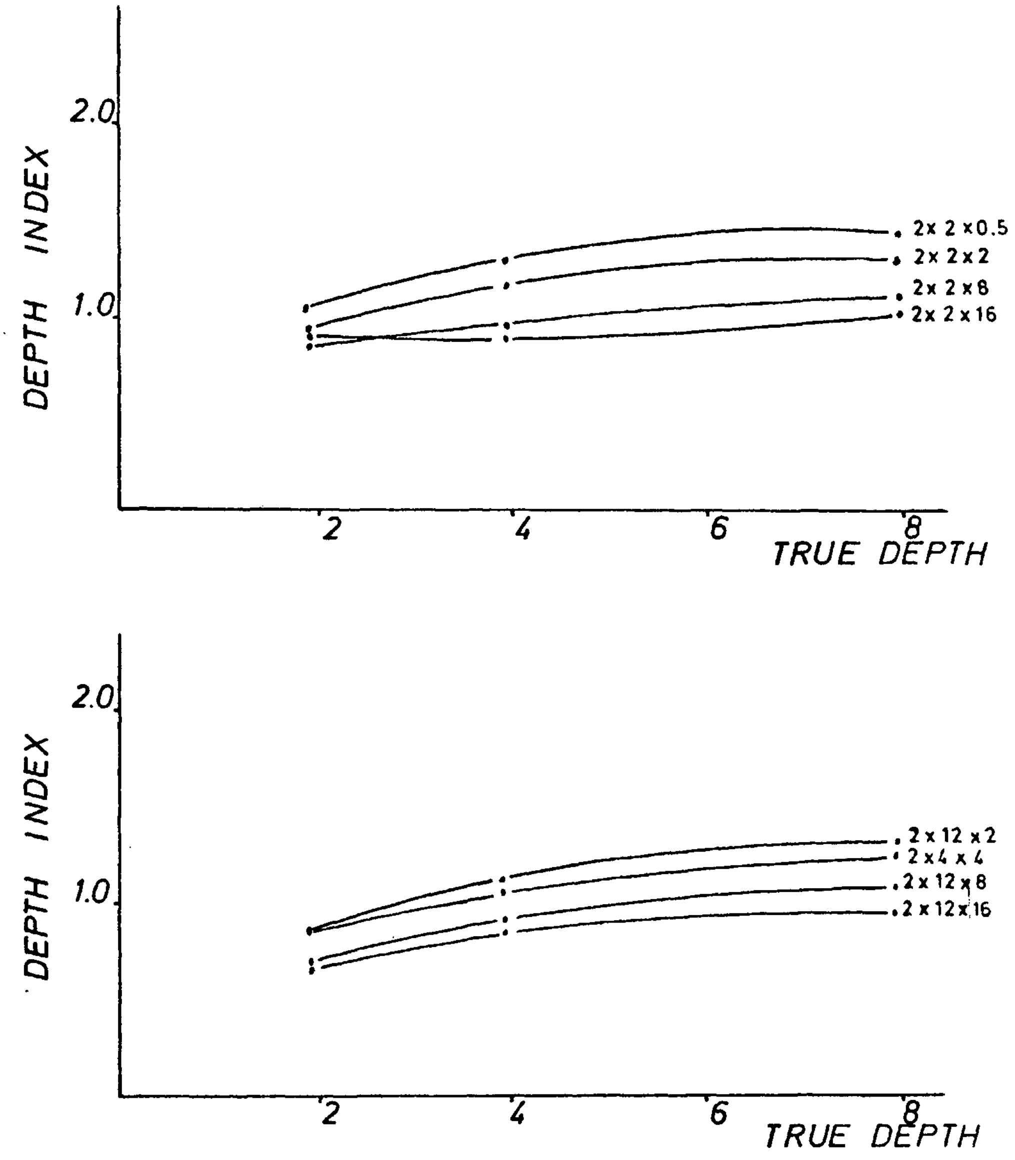
HANNEL RULE – DEPTH INDICES

FIG. 57



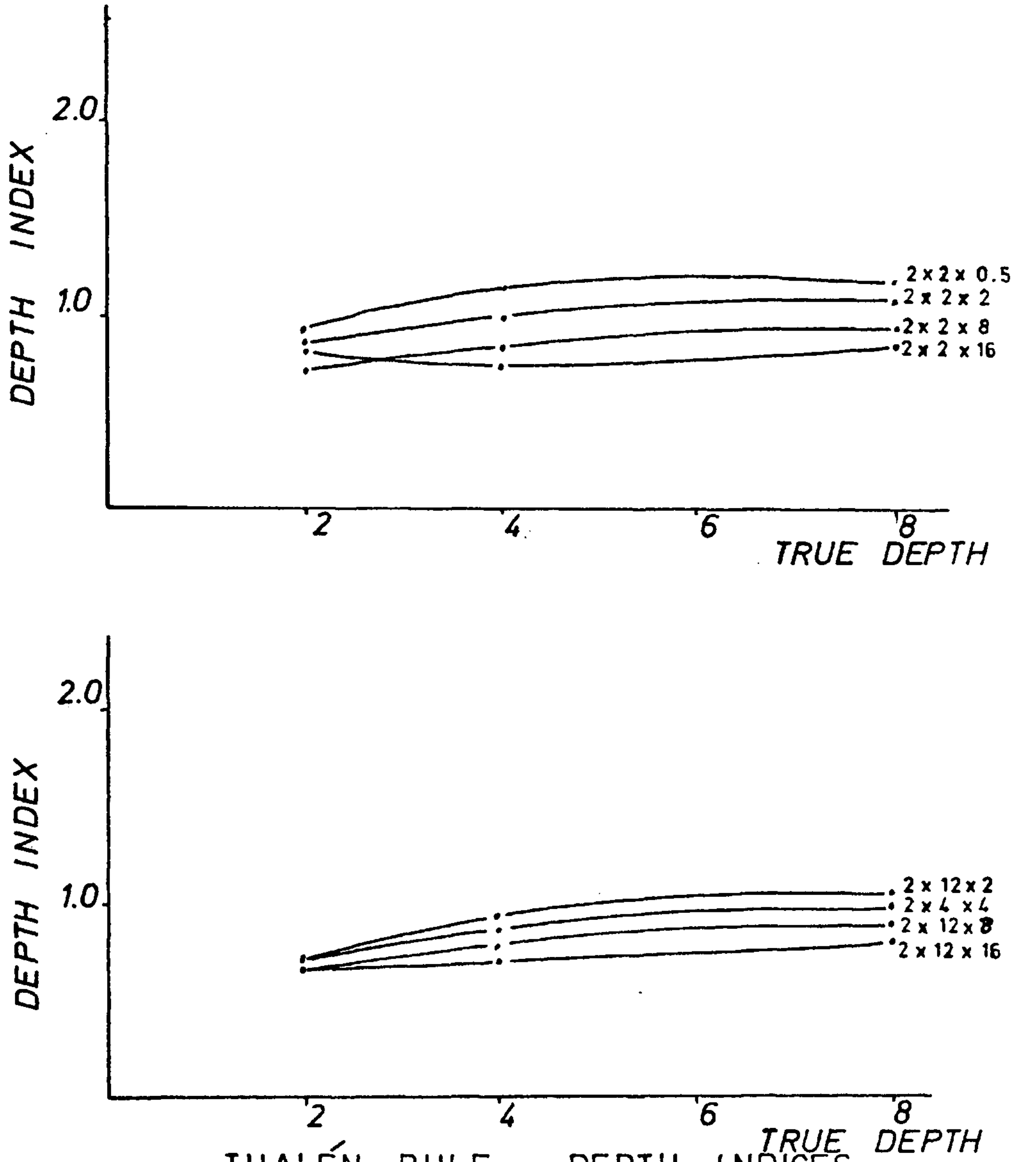
MAC RULE - DEPTH INDICES

FIG. 58



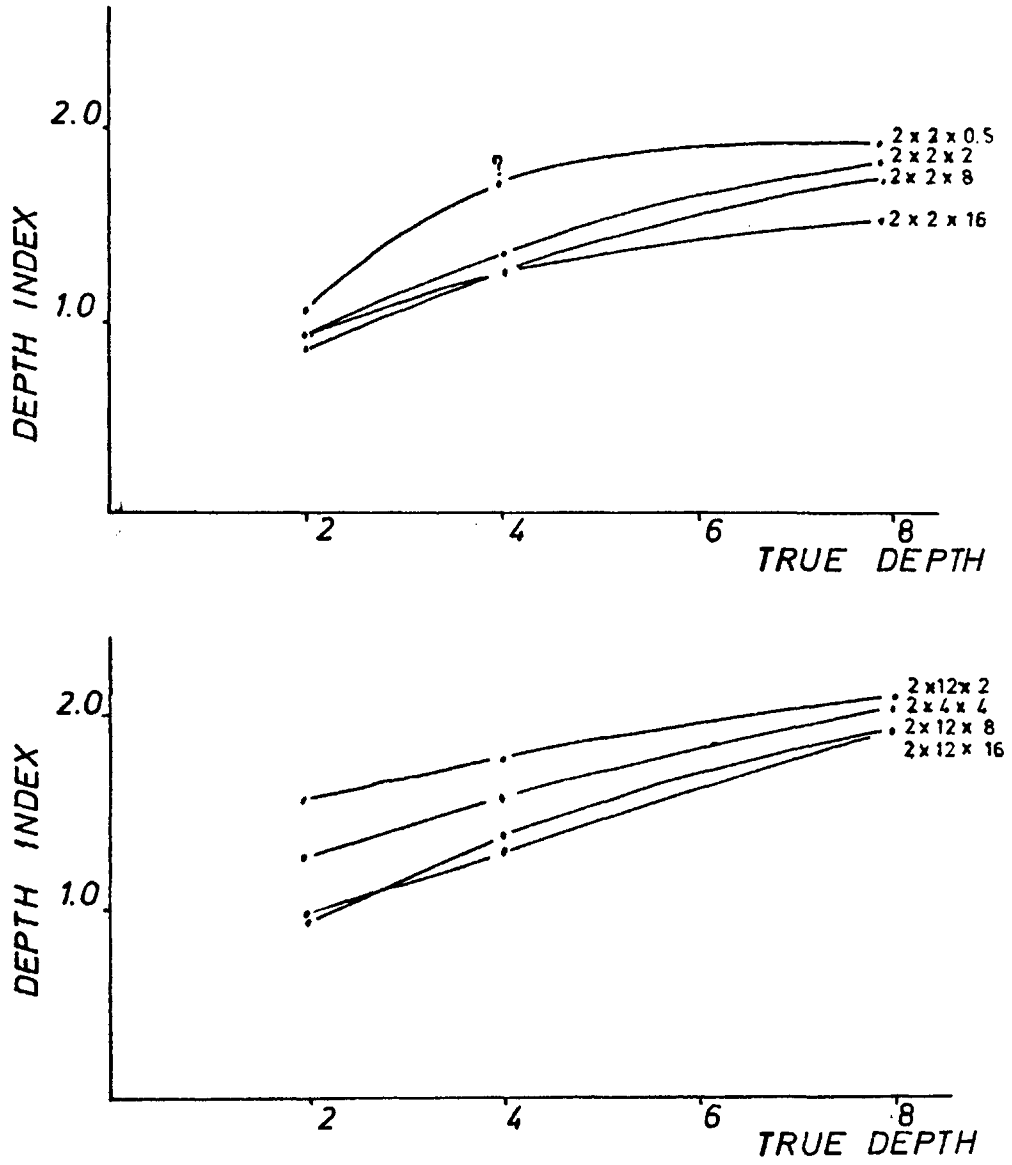
TIBURG RULE - DEPTH INDICES

FIG. 59



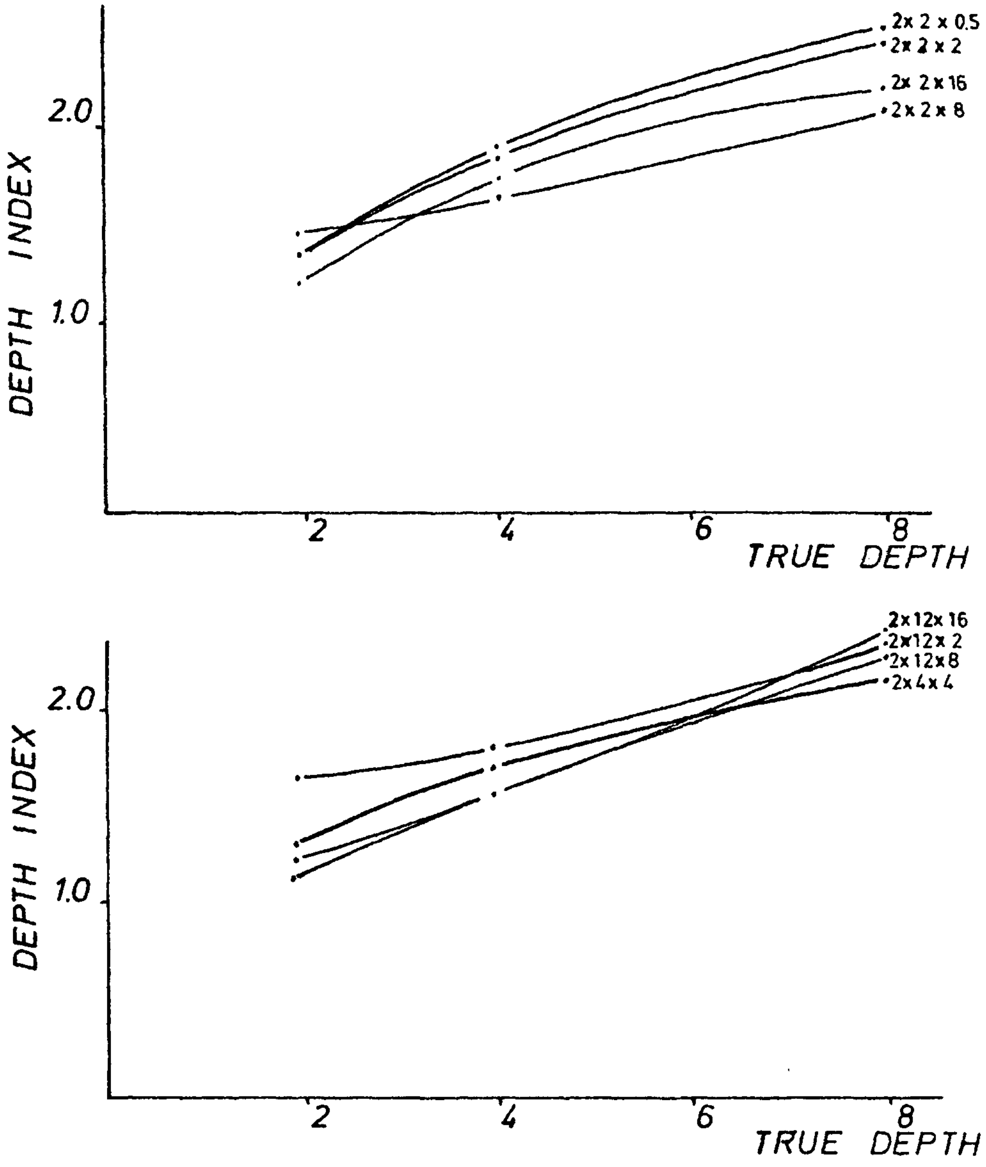
THALÉN RULE - DEPTH INDICES

FIG. 60



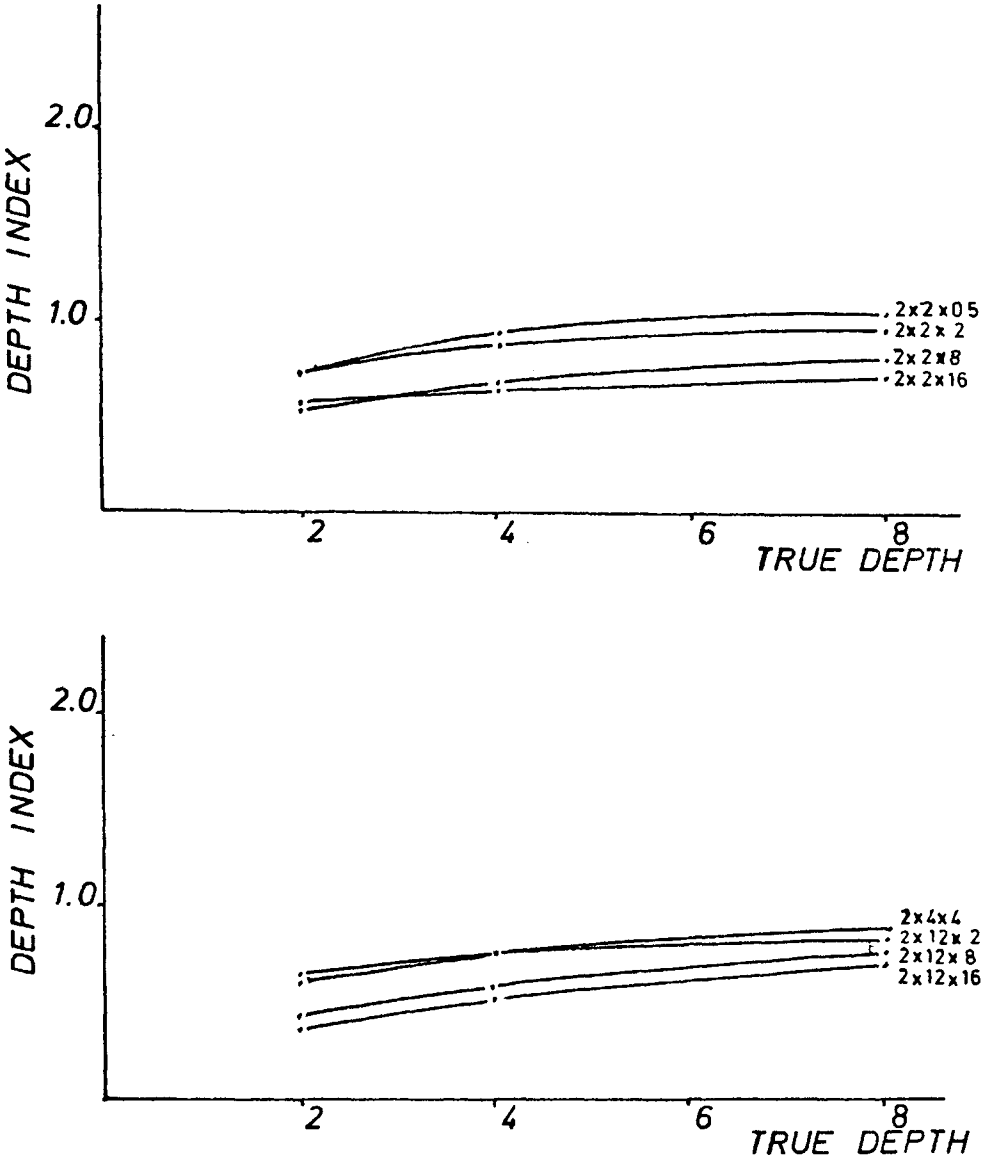
SLOPE DISTANCE RULE SOUTH- DEPTH INDICES

FIG. 61



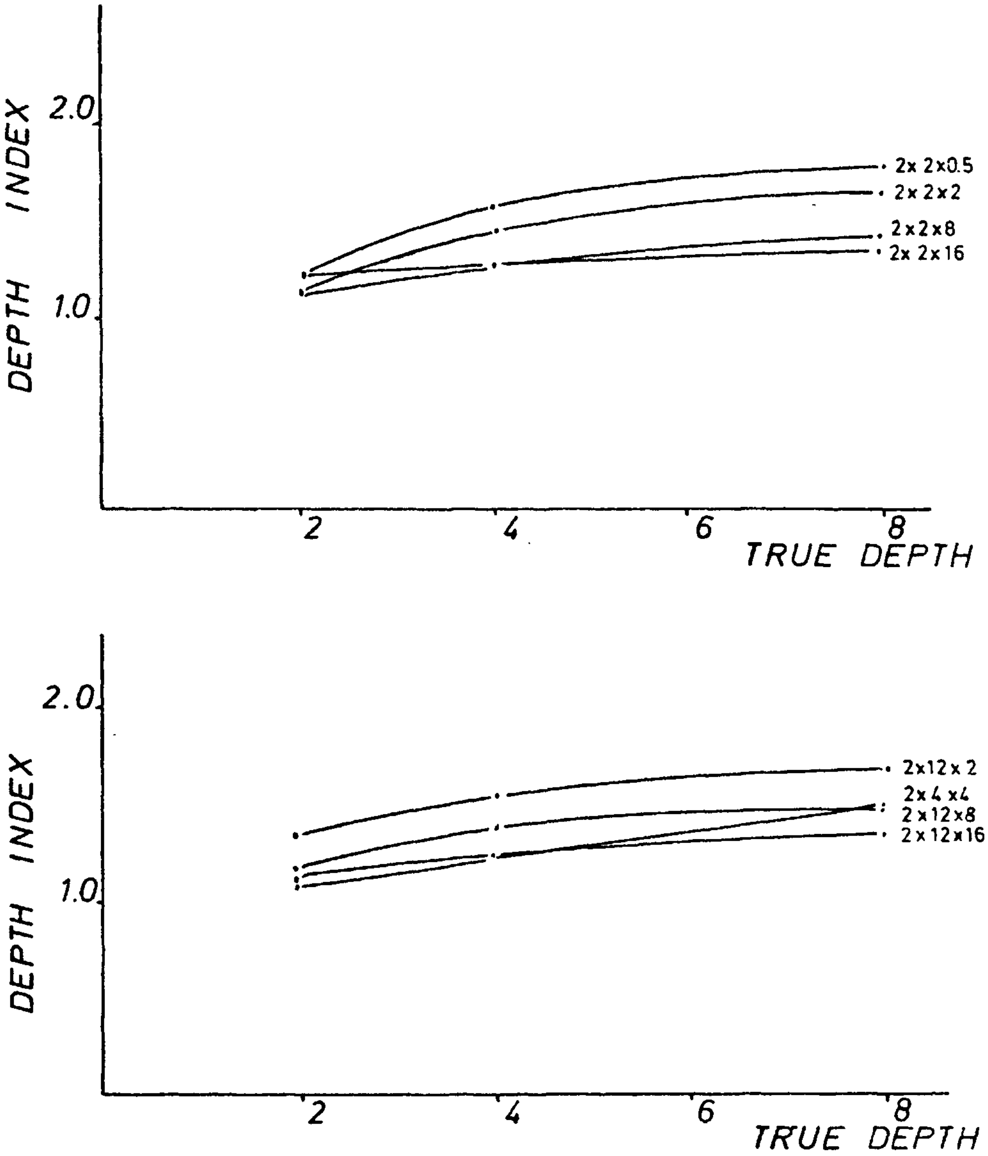
SLOPE DISTANCE RULE NORTH – DEPTH INDICES

FIG. 62



SOKOLOV RULE SOUTH – DEPTH INDICES

FIG. 63



SOKOLOV RULE NORTH – DEPTH INDICES

FIG. 64

For the amplitude-measuring techniques (Fig. 57 to Fig. 60, upper part of the figure) the depth-index curve approaches a straight horizontal line for increasing depth extent of the model, which corresponds to the determined depth-true depth curve approaching the 1:1-correspondence line in the previously discussed figures.

The irregularities present in the depth-index curves for the Slope-distance Rule (Fig. 61 and 62) are considered to be due to the bad repeatability of the method. The depth indices for the Sokolov Rule (Fig. 63 and 64) show a similar relationship to the depth extent of the model than the amplitude-measuring techniques.

The results presented in Fig. 57 to Fig. 64 are the same as those presented in a different form in previous parts of this thesis and will therefore not be discussed in any detail.

SUMMARY OF THE RESULTS

The variation in true depth for a calculated depth of 4 units was scaled from the preceding results, for each of the varying parameters. This maximum variation in true depth was recalculated as a percentage of the determined depth, and these percentages are shown in Table 4. This table then states the variation in the true depth to the top of the body due to variations or uncertainties in the model parameters or the profile. Note that this table states only the range of the variations in the depth of the model. As the range in variation is not necessarily symmetric about the depth to the body, the variation in the true depth is approximated by one-half the numerical value shown in Table 4.

It should be understood that these values are approximate only and can not be considered accurate to within the repeatability of the various techniques, which is included in the table for comparison. The values in Table 4 are to be taken as an indication of the order to which the various techniques are influenced by the variations in parameters as discussed in this thesis.

From the preceding discussion of the results, as well as from Table 4, the following conclusions can be made about the relative accuracy of the depth-determination techniques discussed in this thesis.

1. The repeatability of the method is an important factor in the accuracy of the determined depth. The amplitude-measuring methods are decidedly superior in this aspect to the slope-measuring techniques. The Slope-distance Rule has a very poor repeatability, and on this basis alone should not be considered a satisfactory method.

PARAMETER VARIATION		PERCENTAGE VARIATION IN DEPTH							
		Hannel Rule	Mac Rule	Tiburg Rule	Thalén Rule	Slope Rule South	Slope Rule North	Sokolov Rule South	Sokolov Rule North
plate_pipe		43	63	43	48	55	52	35	43
pipe_dike		43	55	43	28	25	33	45	35
horizontal extent	2x12x16 2x2x16	8	3	18	18	<28	<25	33	5
	2x12x8 2x2x8	5	3	18	10	<28	<25	20	8
	2x12x2 2x2x2	5	8	5	3	<28	<25	10	8
strike	2x12x16	13	5	3	5	<28	<25	10	5
	2x4x4	5	3	3	3	<28	<25	<5	8
regional		58	55	35	<3	63	72	50	55
declination		<3	<3	<3	10	<28	<25	8	8
dip	2x12x16	25	25	28	8	<28	<25	40	18
	2x2x16	15	15	13	10	<28	<25	15	23
repeatability		<3	<3	<3	<3	28	25	5	3

TABLE 4. SHOWING RANGE OF MAXIMUM TOTAL VARIATION IN DEPTH FOR A DETERMINED DEPTH OF 4 UNITS.

2. All methods are sensitive to the depth extent of the body. Errors up to 50 percent and more must be accepted in the calculated depth of the body due to variation of the body from the basic assumptions made in the derivation of the depth rule. There is little difference between the methods in their sensitivity to the depth extent of the model.

3. All methods are sensitive to a lesser degree to the lateral extent of the body. The sensitivity increases with an increasing depth extent of the model. The best results were obtained with the Hannel and Mac Rules, but even in these methods errors up to 10 percent can be expected if the horizontal extent of the anomaly is not accurately known.

4. The strike of the body, the position of the profile with respect to the center of the body, and the presence of small amounts of remnant magnetism do not seem to have an appreciable effect on the depth-determination methods. As long as the profile is near the center half of the body and approximately rectangular to the strike of the model, the variations in the calculated depths are of the same order, or smaller than, the repeatability of the methods.

5. The presence of a residual regional in the anomaly has a pronounced effect on the determined depths. A residual regional with an amplitude of one-half of the amplitude of the negative part of the anomaly, and/or a slope of 10 degrees, can produce errors up to 30 percent or more in the determined depths. The Slope-distance Rule in this respect is inferior to the Sokolov Rule or to any of the amplitude-measuring techniques. The Thalén Rule is the important exception in this case, as it exhibited a very small sensitivity to variations in the residual regional.

6. Most of the depth-determination methods are based on the anomaly over a vertical dipole of infinite depth extent. A deviation of the vertical of the body has a serious effect on the accuracy of the determined depths. This effect is larger for dike-like structures than for pipe-like bodies. Errors in the calculated depth of up to 20 percent can be caused by a deviation from the vertical of 40 degrees. This effect can be reduced, but not eliminated, in the slope-

measuring methods by using the up-slope side of the anomaly.

What Method to Use?

This question can not be answered easily, and the answer would to a large extent depend on what one would expect to get out of the anomaly.

The Slope-distance Rule, or straight-slope segment measurement, does not seem to be suitable for depth determinations due to the poor repeatability of the method and its high sensitivity to regional fluctuations and body shape. If the ambiguity regarding the definition of the term "straight" slope can be removed (such as is done in the Sokolov Rule), this method might justify its applicability. At present there does not seem to be any evidence, either theoretical or practical, which warrants its popularity.

There is little to choose between any of the other methods. All have about the same sensitivity to the various parameters. The Thalén Rule is the only exception as far as regional variations are concerned. For a "quick-and-dirty" depth measurement, when no information is available about the area, and when a regional cannot be drawn with any geological justification, the Thalén Rule would seem to give the best result, with an accuracy of maybe 20 percent at best.

If a more detailed interpretation is to be attempted, with attention to and a knowledge of geological detail, the amplitude-measuring techniques are prefereable over the slope-measuring methods. Application of the methods with a single coefficient, however, cannot be justified, as indicated by the results of this investigation. Series of depth indices would have to be made available for different parameters of the body to do justice to the method and to obtain the necessary accuracy. Whether this approach would be more advantageous than, say, a computer-assisted model-building technique (Which would not only give depth) is highly debatable.

The only justifiable application of some of the better depth-determination methods discussed in this paper would be in the determination of relative depth differences between adjoining and similar bodies under similar geological conditions. Then the variations in absolute depth, caused by the variations in the different parameters, would play no role, or only a very small one.

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