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INTERPRETATION
OF
AEROMAGNETIC MAPS

BY
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CHAPTER I. FOREWORD

BY V. VACQUIER

//The airborne magnetometer developed during World War II for tracking submerged submarines, combined with radio-location or other means for accurately locating the airplane, constitutes a new tool of modern geophysics by means of which magnetic surveys can be made with amazing speed over land or water. This memoir presents a method of interpreting magnetic surveys which, if extensively applied, might yield new knowledge regarding the structure of the earth's crust and shed light on specific problems of regional geology, such as the maximum depth of sedimentation in geologic basins. It can be applied also to the delineation of buried contacts and the location of probable areas of rock differentiation and of mineralization in regions where the igneous rocks crop out.¹

Airborne magnetic surveys are not essentially different from land magnetic surveys of the vertical magnetic intensity carried out in the past with the Schmidt-type magnetic balance. There is no reason to expect that airborne magnetic surveys can yield more geological information, or that what information they might give is different in kind. There is some benefit derived from removing the magnetometer a few hundred feet above glacial till and other near-surface magnetic disturbances which occasionally affect the readings of the land magnetometer. Except when prospecting in regions where the igneous rocks crop out, this factor is of minor importance. Surveying from more than one altitude is of little value because, if the magnetic intensity has been surveyed at a given height above the surface of the magnetic rocks, it is possible to calculate what it is at any greater height (Henderson and Zietz, 1949).² Thus no new information can be obtained by resurveying the same area at a greater altitude, but some information would be lost because the smaller anomalies would be obscured by the experimental errors.

This memoir does not cover all aspects of magnetic prospecting.³ It starts with the magnetic map. Nothing is said of instrumentation, of the techniques of surveying, and of the reduction of the observations that involve the elimination of diurnal magnetic variations.

The method of interpretation described here consists of comparing the magnetic features of actual surveys with model anomalies. The method of comparison is treated in Chapter III. The construction of the models is described in Chapter IV. Although the calculation is elementary, it is given in full, so as to be useful to anyone who would like to compute approximately the magnetic effect of an assumed geologic structure.

In the process of comparison, a second vertical derivative or curvature map is constructed from the field data: The use of the higher derivatives of magnetic and gravity maps is widespread among geophysicists (Skeels, 1947; Evjen, 1936; Pirson,

¹ See, for example, the Bagdad aeromagnetic and geologic maps (Pls. 8, 9). Mineralized regions exist around the periphery of a granite body. This is reflected on the magnetic map by a low, featureless area over the granite proper with steep magnetic gradients over the flanks.

² This statement is true only if the survey at the lower altitude is surveyed with sufficiently close control to insure an adequate representation of the field.

³ For general discussion of magnetic prospecting, we recommend *Geophysical prospecting for oil*, by L. L. Nettleton, p. 127-228, McGraw-Hill, N. Y.

1945; Peters, 1949; Henderson and Zietz, 1949; Elkins, 1951). The function of the derived quantities is to measure the curvature of selected features of the magnetic contour maps. The second-derivative maps in this volume were computed by a method devised by Henderson and Zietz (1949).

Since this memoir is written primarily for geologists, the fundamental facts and concepts are outlined in Chapter II. An attempt is made to describe the origin of magnetic anomalies in geometric terms, so as to give the reader a true perspective of the potential usefulness and of the inherent limitations of magnetic surveys applied to geological investigations.

This memoir is a co-operative undertaking between the Department of Geology of Columbia University and the Geophysics Branch of the U. S. Geological Survey. Some of the model charts were computed by Mlle. J. Roquet of the Institut de Physique du Globe, University of Paris, France, who was working at Columbia University on a scholarship granted by the American Association of University Women.

All magnetic survey maps have been contributed by the Geophysics Branch of the U. S. Geological Survey. The help and co-operation of Dr. H. R. Joesting, Chief of the Geophysics Branch of the U. S. Geological Survey, and Prof. Maurice Ewing of Columbia University, are gratefully acknowledged.

CHAPTER II. GENERAL PRINCIPLES

BY V. VACQUIER

Among the methods of geophysical investigation, the detailed mapping of the earth's magnetic field should be helpful in guiding our speculations with regard to the structure of that portion of the earth's rock mantle which contains appreciable amounts of ferromagnetic minerals. The crystalline rocks of igneous origin, such as granite, basalt and gabbro, are sufficiently magnetic to influence the earth's magnetic field above the surface of the earth, even in regions where they lie buried under a great thickness of sedimentary rocks. In general, most sedimentary rocks are practically nonmagnetic, whereas the magnetic rocks probably lose their ferromagnetic properties at a depth of some 13 miles (Vacquier and Affleck, 1941) where their temperature rises above the Curie point. The anomalies in the earth's magnetic field with which we are concerned here originate in that portion of the earth's crust which extends from this depth of 13 miles to the top of the crystalline basement complex.

The study of magnetic anomalies that originate from large-scale differences in ferromagnetism within the basement complex can reveal three things: (1) the large-scale structural pattern of the magnetic rock mantle, (2) the maximum depth to its upper surface, and (3) a rough figure for the depth at which the rocks cease to be magnetic (Vacquier and Affleck, 1941).

Plate 3 is an example of a typical aeromagnetic survey. The contours are lines of equal total magnetic intensity. The areal extent of the features roughly represents the extent of contrasts in average content of ferromagnetic minerals of the underlying basement rock.

The manner in which magnetic surveys reveal the general structure of the basement complex is illustrated in the simplified diagram of Figure 1. The horizontal component of magnetic intensity is neglected; the polarization of the rocks is assumed to have no horizontal component. In high latitudes these approximations would introduce negligible errors. The lower portion of Figure 1 represents a hypothetical section through the magnetic portion of the basement rock. The body $ABCD$ represents a complex of rock whose magnetic polarization exceeds that of its surroundings by a constant amount. The magnetic polarization of the body $ABCD$ is due to small magnetic particles scattered throughout its volume which, under the influence of the earth's magnetic field, are lined up so that their south-seeking ends are uppermost. The magnetic fields from the north- and south-seeking poles of the particles cancel each other at the magnetometer M except for the magnetic poles on the surfaces AB and CD . The vertical magnetic intensity at the magnetometer M is proportional to the difference of the solid angles subtended by the surfaces AB and CD respectively. A study of this geometry will show that anomalies caused by deep bodies such as $ABCD$ will be much greater in magnitude and different in character from anomalies caused by shallow bodies such as $ABC'D'$. This is indicated by the magnetic profiles in the upper half of Figure 1.

From inspection of magnetic survey maps and from measurements of the magnetic properties of samples of igneous rock (Table 28), it can be inferred that the magnetic

anomalies of large areal extent are deep-seated. On the scale of Figure 1 a basalt flow 1000 feet thick would appear as a thin slab, the top and bottom of which would subtend almost equal solid angles except when the magnetometer is near one of its edges. The fact that magnetic anomalies of more than 200 gammas⁴ exist in regions where

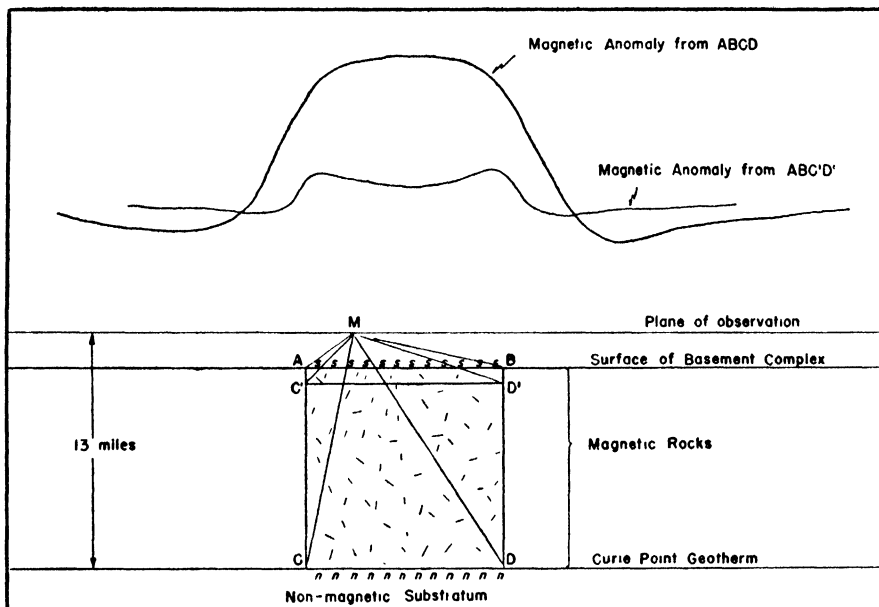


FIGURE 1.—Vertical magnetic intensity from contrasts in vertical polarization

the surface of the basement is estimated to be more than 25,000 feet deep testifies to the fact that contrasts of average magnetic polarization extend down to the depths where the rocks cease to be magnetic. It is most unlikely that the average magnetic polarization contrasts between these large masses of basement rocks are due to the sum of magnetic effects of many thinner layers of individual rock, which happen to be distributed slightly differently, because the magnitude of the larger magnetic anomalies is such that they would require, for bodies that would extend down to the bottom of the magnetic rocks, polarization contrasts of the same order of magnitude as the contrasts between the magnetic properties of known types of rock. It is not necessary to assume that these cells of which the basement complex seems to be composed are petrologically homogeneous. The magnetic data suggest that the rocks in these cells originated from a magma, the iron content of which was different from that of the rocks in the surrounding cells. Perhaps the word "cell" is misleading in view of the complexity and lack of symmetry of most features on magnetic survey maps. A more conservative statement would be that the magnetic maps themselves suggest the presence in the basement complex of boundaries between rocks of contrasting magnetic properties. These boundaries extend downward several miles, and the lateral extent of the rock masses is often 10 miles or more.

⁴ One gamma is 10^{-5} oersteds.

The features of the magnetic maps surveyed from a height of several thousand feet above the basement surface present a certain grain which might or might not reflect the known tectonic history of the region. So called "trends" read into magnetic contour maps are often misleading, although some orogenic trends and major structural zones seem to be associated with large-scale features on magnetic maps (Pl. 6).

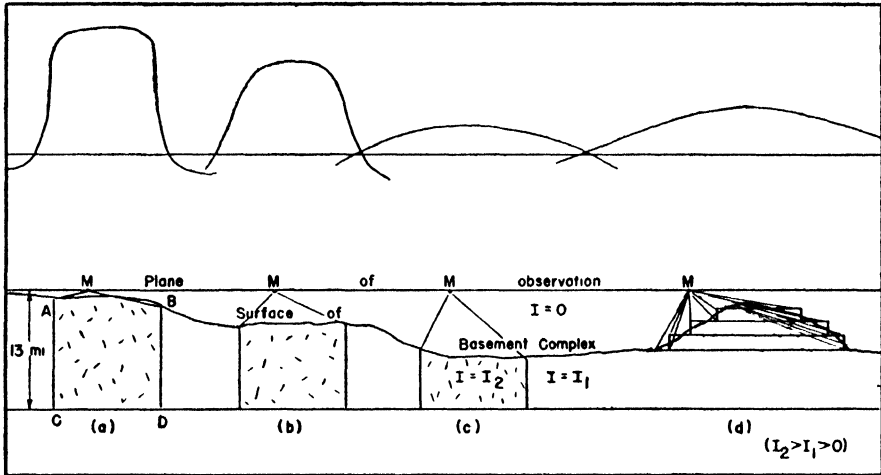


FIGURE 2.—Variation of character of vertical magnetic intensity anomalies with depth of burial

In many cases, however, no such correspondence exists, and the grain of the magnetic map probably reflects the structure of deep-seated Archean intrusives.

Returning now to the geometrical considerations of Figure 1, imagine that the magnetometer is observing on a horizontal plane only a short distance above the upper boundary of the magnetic rocks, as shown on Figure 2a. As the magnetometer approaches the edge of the polarization contrast at *A*, the solid angle subtended by the upper surface of *AB* increases from a few degrees to almost a half-space in a short distance. A change in the reverse direction takes place over the edge *B*. The negative contribution of the surface *CD*, although not small in absolute value, does not suffer abrupt changes, and therefore it is difficult to isolate in an actual survey. The magnetic anomaly will appear almost as a step with extremely steep sides. When the upper surface of the polarization contrast is buried at greater depth, the anomaly becomes progressively smoother, as illustrated in Figures 2b and 2c. Curvatures of the anomalies constitute a more sensitive index of the depth than the relief of the magnetic map, and the contribution to the curvature of the anomaly by the bottom *CD* can be neglected, which is equivalent to assuming it to be infinitely remote.

If the polarization contrast has sloping instead of vertical boundaries (Fig. 2d), as a buried mountain, its magnetic effect can be computed approximately by subdividing it into thin slabs and then adding the solid angles subtended by the tops and subtracting the solid angles subtended by the bottoms. It is evident that the contribution of areas common to the top and bottom of two slabs will be zero, so that

the anomaly will consist of the sum of the solid angles subtended by the horizontal areas of the steps approximating the sloping boundary of the polarization contrast. Although the tops of the polarization contrasts of Figures 2a and 2d are at the same depth, 2d, because its sides are sloping, produces a magnetic picture that is of the same character as the deep body of Figure 2c. Thus, a polarization contrast with sloping sides, the top of which is shallow, gives a magnetic anomaly similar to that associated with a deeply buried contrast with vertical sides. The deeply buried contrast such as the one of Figure 2c cannot, however, give rise to a sharp anomaly characteristic of shallow burial such as anomaly 2a without assigning impossible values to the polarization of the rocks. Thus, the sharpness of magnetic anomalies is a measure of the maximum possible depth to the upper surface of the polarization contrasts within the crystalline basement surface (Skeels, 1947; Peters, 1949).

If the regions of major polarization contrast are bounded by approximately vertical surfaces that extend all the way from the nonmagnetic layer to the lower surface of the basement complex, it becomes possible to estimate the depth of burial of the upper surface of the basement. Conversely, if the depth of burial is known, the sharpness of the anomalies indicates whether or not the boundaries between rock bodies are vertical. The object of this memoir is to provide a method for quantitative interpretation of magnetic surveys with reference to these two problems.

With the advent of the airborne magnetometer it becomes possible to test whether the thickness of the sedimentary section in geologic basins can be quantitatively estimated from the sharpness of magnetic anomalies. The instrument can be flown over igneous exposures such as the Canadian Shield and the maximum altitude of the airplane computed from the magnetic data. It may be objected that although the test is successful in Canada, it does not mean that elsewhere, where the surface of the basement complex is inaccessible, the boundaries between the rock masses will be sufficiently vertical for the method to be valid. However, the greater the diversity of igneous exposures surveyed by airborne magnetometers, the sounder will be the basis of interpretation of magnetic data in basin areas. If in most cases the computed maximum heights of flight over igneous outcrops approximate the actual altitudes, then the structure of the basement complex consists in part of deep, nearly vertical boundaries between rock masses of different magnetic properties. This fact alone would shed some light on the general structure of the ferromagnetic part of the earth's crust.

The method of interpretation of magnetic surveys, the subject of this study, consists of comparing observed anomalies with the computed magnetic effects of idealized bodies. Since the airborne magnetometer measures field-intensity variations along the total magnetic vector, the same body will produce different magnetic effects at different latitudes and for different geographic orientations. The selection of the appropriate model with which the actual magnetic anomaly is compared is determined from the areal shape of the anomaly. The maximum depth is determined by comparison of the curvatures (which are proportional to sharpness) of the model and the actual anomalies.

The models (Figs. A1-A60; A64-A83) are bottomless rectangular prisms with vertical sides and having a uniform polarization higher than that of the surrounding

material. The polarization vector is in the same direction as the present earth's field, and the magnetic intensity along the same direction is computed by the method of Chapter IV and contoured on the right side of the maps. On the left side is the curvature or the second vertical derivative of the magnetic intensity (the curvature is plotted in quarter-units) which is computed by the method of Chapter III. A fuller description of the models and the methods of computation constitutes Chapter IV.

The foregoing discussion of Figures 1 and 2 presents an over-simplified picture of the origin of magnetic anomalies. Although in areas of deep sedimentation the magnetic data themselves tell us of the great depth of the boundaries between rocks of different magnetic properties, the comparison of the field map anomaly with that of a rectangular vertical prism of infinite length and constant polarization contrast requires confirmation by a statistical analysis of experimental results. There exist geological situations where these assumptions are invalid, but this lack of validity itself can be useful information when combined with other facts. It is fully realized that rock bodies in nature are not rectangular parallelepipeds. The labor of computing other shapes was too great for the means at our disposal, and the benefits derived from multiplying the number of the types of distribution is not at all obvious. The method is useful only if the postulated type of distribution—i.e., constant polarization with depth—is in general approximately true and if the results are not too dependent on the shape of the cross section of the bodies. Reasonable departures from these geometric postulates should be allowed, or the method loses its utility. Thus, on the average, the contacts may be slanting 50° which may account for a certain spread in the maximum depths computed from different anomalies on the same map. The assumption of infinite depth extent should be extended to mean that the body is thicker than the depth of burial of its upper surface. Thus, if an airplane flies at 1000 feet over igneous outcrops and its height of flight can be computed from the magnetic expression of a rock body, it may be deduced that the contact between this body and the country rock extends to more than 1000 feet below the surface. Its bottom need not lie on the Curie point geotherm 13 miles down.

The neglect of the horizontal components of field and polarization does not fundamentally alter the consideration of Figures 1 and 2. Unfortunately, an exposition of what happens when nothing is neglected is more likely to confuse the issue than to clarify it. The progressive change of the magnetic expression of the same idealized bodies with decreasing magnetic latitude is indicated in the model anomalies (Figs. A1–A83).

The last physical assumption on which this work is based is that the magnetic polarization of the basement rocks is in the same direction as the present direction of the earth's magnetic field. Samples of igneous rocks possessing permanent polarization of the same magnitude as the induced polarization are mentioned in the literature (Haalck, 1942), and there is no reason to expect that this permanent magnetization was acquired when the earth's magnetic field had the same direction as it has today. The vector sum of the permanent and the induced polarizations can therefore differ from the present orientation of the earth's field. There is no real evidence that the polarization of large igneous rock bodies is not aligned with the earth's field. However, if evidence to the contrary is found, it must be recognized as an additional

limitation. Vacquier (1938) suggested that, by carefully repeating a survey across the span of a decade in regions where the secular variation is pronounced, it might be possible to determine *in situ* the ratio of permanent to the induced polarization of contrasts giving rise to the large magnetic anomalies.

The interpretation of magnetic anomalies in terms of topographic relief of a homogeneous basement is not considered in this work and is mentioned here only for the sake of completeness. When the topographic relief is small with respect to the depth of burial, the anomalies due to relief are also small (as illustrated in Fig. 1). They are usually lost among the much larger anomalies arising from contacts between different rock types. Since buried erosional topographic features are often associated with contacts of different types of rocks, there is a definite possibility that buried topographic relief is associated with some magnetic anomalies. Most magnetic anomalies arise from the lithology and not from the topography of the basement rock. The computation of the magnetic effect of a prismatic block such as $ABC'D'$ of Figure 1 can be made by subtraction of the anomalies of two infinitely long prisms and is an obvious extension of the method of computation treated in the first section of Chapter IV.⁵

A last word of caution should be voiced against taking too literally the statement that the features of the magnetic map reflect the areal extent of rock bodies within the basement complex. Except for order of magnitude, there is no one-to-one correspondence between the two except when the bodies have great areal extent with respect to their depth of burial. Most of the model anomalies for the idealized prismatic bodies shown at the end of this volume possess a closed, magnetic low in addition to the magnetic high. Furthermore, the strike of the magnetic intensity contours is often far from coinciding with the strike of the body.

Thus, in practice, the physical assumptions on which the method is based have to be interpreted rather liberally. The accuracy of the depth computations from magnetic data depends on the degree to which the simplifying assumptions are satisfied. As experience is gained, the interpreter will be able to evaluate better the reliability of the answers obtained. One of the objects of this memoir is to provide a uniform method of interpretation for the organizations now engaged in magnetic prospecting so as to pool the practical experience that is essential to the successful application of geophysics.

⁵ For a discussion of the magnetic effect of basement relief see Nettleton (1940).

CHAPTER III. RESULTS OF INTERPRETATION OF SIX AEROMAGNETIC SURVEYS*

BY NELSON CLARENCE STEENLAND

SECTION I. OUTLINE OF METHOD

Six aeromagnetic surveys are interpreted in accordance with the view set forth in the preceding discussion.

For clearer presentation, the method of interpretation is outlined briefly. A square grid is laid over the magnetic map, and the value of the magnetic intensity is interpolated and recorded at each corner of the grid. The choice of grid spacing is determined by the character of the region and of the magnetic map. The second vertical derivative, an approximation to the curvature, is then computed by a simple arithmetic calculation for each grid intersection. The curvature values are contoured, and the features of both the original total intensity survey map and of the computed curvature map are compared with the computed model anomalies of Figures A1 to A83. These models represent the magnetic effect due to rectangular prisms extending infinitely downward with vertical sides and horizontal tops. The models show that the curvature map is most useful in locating the edges of the rock bodies. The depth of burial can be estimated from the distance between the curvature maxima and minima and the zero curvature contour. This is a procedure empirically arrived at from the study of the models. One of these criteria—the distance from the curvature maximum on the south side of the anomaly to the zero curvature contour—is particularly useful. Thus, for the selected magnetic anomalies, the contacts of the rock body giving rise to the anomaly and the country rock are traced from the curvature map. The maximum depth to the top of the magnetic rock body is estimated with an average error of perhaps 10 per cent, and the magnetic susceptibility contrast can be estimated from the relief of the magnetic map.

In the geological discussions of the particular surveys some effort was made to indicate the lithology that might produce a given magnetic anomaly. Unless the lithology is established by actual examination of the rocks, these speculations have no foundation in fact and are merely illustrative of typical situations. It is the delineation of the larger lithologic units of the basement complex and the estimation of the maximum depth to the crystalline rocks that are the principal objects of this study.

SECTION 2. SUMMARY OF RESULTS

The results of the depth estimates are summarized in Table 1.

The actual depth to crystalline rock is known only in three of the areas (Bagdad, Adak, and Umnak). In these three instances the rock is at the surface, and the "depth" is really the altitude of the airborne magnetometer. None of these three surveys is a good test of the interpretational procedure.

In Bagdad, the anomalies are caused by small rock bodies—quartz-monzonite stocks, gabbroic sills, and ferromagnetic intraschist units. Nevertheless the computed flight levels are uniform and accurate, indicating that the bodies extend downward for at least 1000 feet.

* Lamont Geological Observatory (Columbia University), Contribution No. 30

TABLE 1.—*Summary of estimated height of airplane above crystalline rock*
(* Denotes average estimate for anomaly)

Location	Type of rock	Area, sq. miles	Computed Max. Heights			Avg., Int. & Cur.	% Error		Remarks
			Anom- aly	Int. map	Cur. map		Int. Map	Cur. map	
Worcester Co., Md.	Basement complex	220	Snow-Hill	6100 6100 6100*	6500 6500 6500*	6300			Flight level is 500 feet. No actual depth data available in this area. The 6500-foot generalized contour of the basement complex runs through the area.
			Girdle-tree	5300 5100*	5300 4900 5100*	5200			
Central Pennsylvania	Basement complex	1800	(1)	14,200 14,800 20,100 16,400*	15,300 16,500 16,600 16,100*	16,250			Flight level is 1000 feet. No actual depth data available in this area. The stratigraphic section is estimated to be 20,000 feet in thickness.
			(2)	17,800	12,700 16,400 14,600*	16,200			
			(3)	16,600 19,000 19,800 18,500*	15,000	16,750			
			(4)	20,600 18,000 15,500 14,400 16,900 21,100 17,750*	16,100 21,100 15,600 23,400 17,600 15,600 18,250*	18,000			
Mangum, Oklahoma	Granite and gabbro?	100	West Slope	2100 2100 4100 9200	2700 3700 8400	2300 3900 8800			No actual depth data available in the area, but area flown at three levels. Interpreted differences, 1600 and 4900; actual differences, 1000 and 5000.
Bagdad, Arizona	Basement	50	(1) (3) (4) (5)	1060	920 1000 1060 1060	1000	6	-8 0 6 6	Crystalline rock at surface. Mean error: 6% (int.), 1% (cur.).
Umnak Island	Volcanic	6400	(1)	4600 4000 4000 2900	4000 5100 4700 4100 2500 3500 2600 3100 4600 4600 3800 4300 3200 5900 5300	4300 5100 4700 4100 3900 4300 3900 4500 3700 3900 5100 3700 5800 6200 3300 5300 5500 6000 4700 3700	7 -22 -15 -30 -36 -19 -35 -31 23 18 -3 -17 -13 2 -15 -40 -12 -32 -22	-22	Crystalline rock at surface. Mean error: 12% (int.), 20% (cur.). Apparently the polarization contrasts do not extend downward even as far as one mile. Anomalies (2), (3) and (4) are over large topographic features.
			(2)						
			(3)						
			(4)						
			(5)						
			(6)						
			(7)						
Adak Island	Volcanic	150	(1)	4600 4500	5600 6000	5000	-8 -10	12 20	Crystalline rock at surface. Mean error: 3% (int.), 10% (cur., Anom. (3) not included in summary because of its inadequate control.
			(2)	6400	6100 5300 4500	5000	28	22 6 -10	

The two volcanic regions, Umnak and Adak islands, do not lend themselves successfully to this type of interpretation. At Umnak, the intensity and curvature methods of computation yield flight-level values that are low, by 12 and 20 per cent, respectively. Although the area has considerable topographic relief, the relief alone does not produce the large anomalies. The low estimates are attributed to a probable termination of the polarization contrasts within a depth of 1 mile. These contrasts are more than likely between lava and pyroclastic sediments and may be expected to be quite dissimilar in their structure to the contrasts extant in basement complex rock.

Adak differs from Umnak physiographically. There are two large anomalies over the southern portion of the map where the surface is an ancient terrain of essentially no relief. The computed flight levels at Adak are on the average 7 per cent too high (3 per cent from intensity and 10 per cent from curvature), which suggests that the underlying polarization contrasts are contained within sloping, and not vertical, sides.

The errors for the Maryland, Pennsylvania, and Oklahoma surveys cannot be determined as the basement's depth is unknown. It is therefore difficult to assign a probable degree of accuracy to the interpretation. At least the correct order of magnitude is obtained in each of the three areas.

As the estimated heights based on the intensity maps are in good agreement with those based on the curvature maps, they are included in the average estimated height derived for each anomaly in the Maryland, Pennsylvania, and Oklahoma areas.

In Maryland there are two anomalies, and the estimates for each anomaly agree within themselves. However, the Girdletree anomaly yields a shallower value which is contradictory to the supposed general slope of the basement's surface to the south-east; the Girdletree anomaly is southeast of the Snow Hill anomaly.

In Pennsylvania, anomalies (1), (2), and (3) are in the western portion of the surveyed area, and they give an average value of 15,400 feet for the depth of burial of the crystalline rock. Anomaly (4) is in the eastern part of the area, adjacent to the Appalachian Structural Front, and yields a greater value, 17,000 feet, which agrees with the inferred easterly slope of the basement's surface.

The Oklahoma area is surveyed at three levels so the relative accuracies of the estimates can be evaluated by comparing the actual and computed differences in flight levels. Unsatisfactory agreement is obtained for the lower levels; 1600 feet was computed for the actual value of 1000 feet. But good agreement, 4900 vs. 5000 feet, is found for the upper levels for which the flight-line control is better.

In Table 1 the mean errors for the depths computed from intensity are apparently equal to or less than the mean errors for depths based on the curvature maps. It should not be concluded that it is unnecessary to prepare the curvature maps. First, the curvature-derived values are more consistent within themselves. Secondly, the intensity-derived values are revised after the curvature is computed because the reference models are selected more accurately from the curvature maps.

SECTION 3. PROPERTIES OF MODELS

Figures A1-A83 are model charts, or maps of the total intensity and curvature of the magnetic anomaly produced by a prismatic cell. These theoretical maps are to be compared with the large anomalies commonly found on actual aeromagnetic

maps in order to study the structure of the crystalline basement. The prismatic cells, which are considered similar to large lithologic units in crystalline rock, have the following properties:

- (1) Horizontal upper surface, one unit below the plane of the map;
- (2) Vertical side walls that extend infinitely downward;
- (3) Polarization in the direction of the earth's main magnetic field;
- (4) A magnetic susceptibility, constant throughout the cell, and in contrast to the susceptibility of the rock surrounding the cell.

The prismatic cells are rectangular in plan in order to facilitate the computation of their magnetic fields. The dimensions of the rectangle are in units of the depth of burial of the top of the cell. The dimensions are always expressed herein as $n \times m$, where n is the dimension of the side that is more nearly parallel to magnetic north; n and m range from $\frac{1}{2}$ to 8 in length. In comparing the model charts to actual anomalies, measurements are not made near the corners of the models, as such corners can hardly exist in nature.

The first measurements are carried out on the intensity maps. The steepest gradients on an intensity map are caused by the shallowest and steepest contacts between lithologic units having contrasting magnetic susceptibilities. These conditions are fulfilled by the models. Therefore the horizontal extents of the steepest gradients are measured on the survey maps and on the model charts. These lengths, expressed in terms of depth of burial, are called "depth indices." The various indices have been designated by letters (E , F , G , etc.), and the key to these designations appears in Figure 3.

The horizontal extents of the gradients have been obtained from all the model charts and are plotted in Plate 1.

Depth indices also are measured on the curvature maps and are similarly designated by letters. Figure 3 also provides the key to these designations. The numerical values of the curvature indices are plotted in Plate 2. An analysis of Plate 2 reveals that several of the indices are independent of the size of the model, for the most part.

At inclination 60° , the A index is 1.25, 1.2, and 1.15 for the three $n = 6$ models, while it is 1.05, 1.1, 1.0, 1.05 for the four $m = 6$ models. Although this index is more variable at inclination 75° , it apparently decreases linearly with the increase in the models' dimensions. At 90° , the A index is almost constant for the $m = 6$ models except for the large value at $n = 2$. On the whole, the A index for the larger models varies only slightly between inclinations 60° and 90° .

The counterpart of the A index for the lower latitudes is the M index. This index is remarkably uniform for the regular⁶ models computed at inclination 30° , and slightly less uniform at inclination 20° . At the magnetic equator, however, the M index is dependent upon model size for models with one dimension less than two units.

In conclusion, the A and M indices are independent of the size of the model for the mid-latitudes, certainly between 30° and 60° inclination. At the extreme inclinations, these indices are probably constant for the larger models—those with lengths of 4 or more.

These indices, for the 4 by 6 model, are plotted in Plate 2 to illustrate the dependence upon magnetic inclination. A smooth curve can be drawn through these points.

⁶ Regular models are oriented parallel or at right angles to magnetic north.

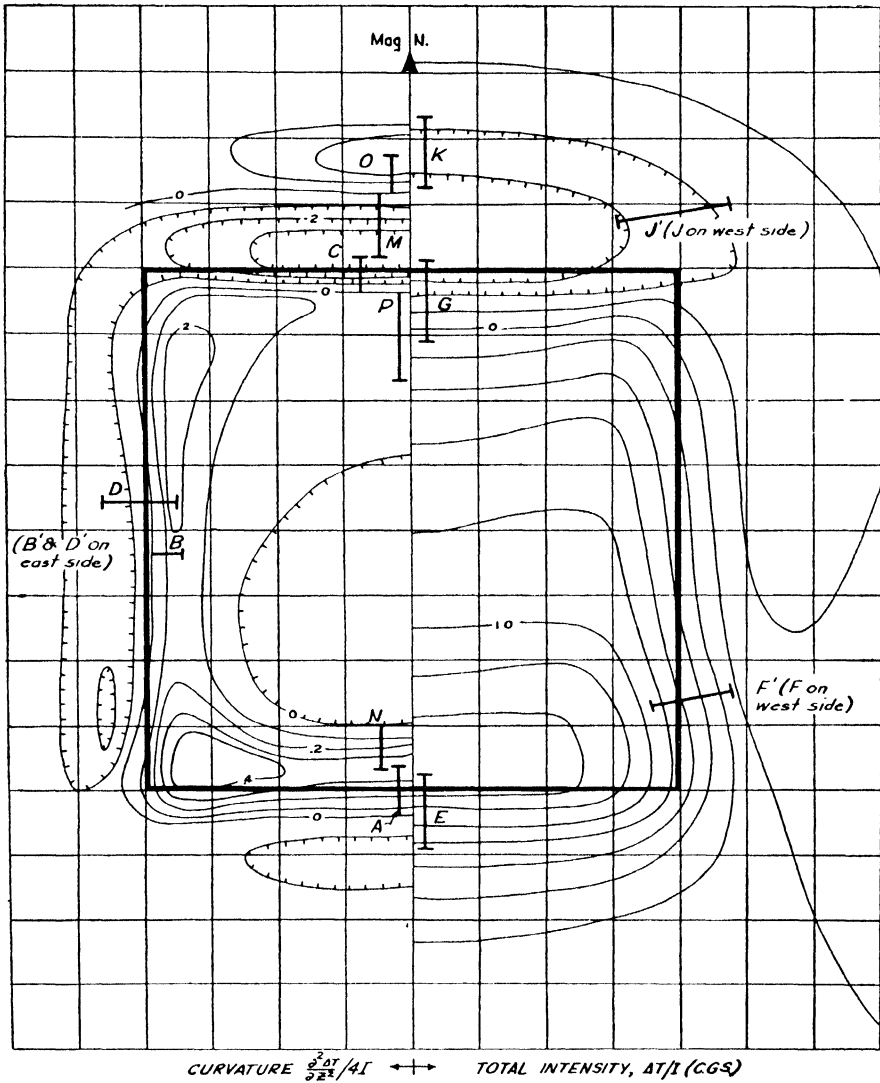


FIGURE 3.—Key to depth indices

The M index also is plotted (Pl. 2) for the 30-degree skew models⁷ at inclination 30° and is apparently unaffected by that degree of obliquity. The A index for the 45-degree skew models at inclination 75° may be taken along either the southwest (as was done) or the southeast side; in the latter case it is equivalent to the B' index on the graph. Apparently this index is approximately the same as the A index for the thin ($m < 4$) $n = 6$ models at inclination 75° . From this information, it appears that the A and M indices of the regular models may be effectively used on skewed anomalies.

⁷ Skew models are oriented obliquely to magnetic north.

In Table 2, the depth indices are listed for the special group of models computed at inclination 60° . The A index decreases from 1.3 to 0.9 as the square models increase in size from 1 by 1 to 8 by 8. This is analogous to the decrease of this index as the $n = 6$ models increase in width from 1 to 4. Such a decrease is not prohibi-

TABLE 2.—*Depth indices for square-shaped models at inclination 60°*

	Vertical thickness	A	B	C	D	E	F	G
1 $\times$ 1	infinite	1.2	—	.6	—	.8	.5	.5
2 $\times$ 2	infinite	1.3	1.4	.7	1.9	.9	—	.9
4 $\times$ 4	infinite	1.0	.8	.8	1.5	.9	.8	.9
8 $\times$ 8	infinite	.9	.7	.9	1.4	1.3	1.2	1.3
8 $\times$ 8	7	.8	.6	.9	1.6	1.3	1.3	1.4
8 $\times$ 8	3	.8	.4	.9	1.3	1.0	1.2	1.1
8 $\times$ 8	1	.7	.4	.7	1.2	.9	1.2	1.2

TABLE 3.—*Summary table of depth indices*

Inclination	Intensity					Curvature					
	E	F	G	K	J	A	B	C	M	N	O
90	1.0	1.1	1.1			0.8	1.1	0.9			
75	1.2	1.2	1.1			0.9	1.0	0.7			
60	1.2	1.1	1.1			1.0	0.8	0.7			
45			1.1			1.6			1.6		
30			1.1	1.0					1.0	1.0	0.7
20			1.1	1.1	1.4				0.8	0.8	0.7
0			1.0		1.2				1.0		0.8

tive and is in contrast with the great dependence of the intensity indices upon model size for this special group of square blocks. The A index also is constant, for practical purposes, for blocks that have a finite vertical thickness of at least one unit. The change in this index from an infinitely deep block to one only 1 unit thick is about 10 per cent for an 8 by 8 body.

A side index, B , also is plotted and is apparently useful for the larger models (4 units or more). Another remarkably uniform index is O , which unfortunately can be found only at the lower inclinations. This index is essentially independent of the size of the model and its skewness. It is dependent on the magnetic inclination, and ranges from 0.9 to 0.6 between inclinations 0° and 30° .

The indices presented in Plates 1 and 2 generally appear to become reasonably independent of the size and shape of the model when both n and m are 2 or more units. In Table 3, average values of the indices are listed so that they can be readily determined for the interpretation of those anomalies that are referable to the larger models. Each interpretation described in this chapter was made by reference to the index of a specific model in order to make the results as exact as possible. However, useful results can be obtained by recourse to the indices listed in Table 3.

It may be concluded that the depth indices are sufficiently independent of model

size and thickness to be applicable to actual geologic situations, under the conditions assumed.

SECTION 4. DESCRIPTION OF METHOD

GENERAL STATEMENT

The procedures described in this section were used in the interpretation of aeromagnetic maps by means of the prismatic models.

A. ELEMENTS OF THE GEOMAGNETIC FIELD

The average values of the total intensity, inclination, and declination of the earth's magnetic field are obtained from Vestine's (1947) work and from magnetic charts published by the U. S. Coast and Geodetic Survey.

B. REMOVAL OF GEOMAGNETIC GRADIENTS

The geomagnetic gradient is removed from the aeromagnetic intensity map by determining the total intensity from these publications at a number of points on the aeromagnetic map so that the earth's main field can be contoured over the entire map. The gradient of the earth's field can then be removed.

C. INSPECTION OF INTENSITY MAP

i. The model charts of the inclination most nearly equal to that of the area are reviewed for recognition of the general features of potentially usable anomalies. Skew models, those whose geometric axes are oriented obliquely to the magnetic meridian, are included for inclinations 30° and 75° . These skew models also should be studied for the effect of skewness on the general characteristics of the intensity pattern. At and below inclination 60° , the negative portion of an anomaly becomes important. The anomalies of large areal extent and sharp gradients are best suited for comparison with the model charts.

ii. Having selected the usable anomalies, the horizontal extent of the steepest gradients of each anomaly is measured to derive rough estimates of the depth to the crystalline rock. These lengths are depth indices and are given their appropriate letter designations in accordance with their location on the anomaly. (See key, Fig. 3.) Then a model is selected that shows a pattern of greatest similarity with the anomaly or some portion thereof. The selection of the proper model is necessarily indefinite as the intensity indices depend upon the size of the models. The G index is the best of the indices, insofar as independence of size is concerned, and should be employed first. The G index determined from the actual map is divided by the corresponding G index of the selected model, and their quotient is the estimated depth of burial. The dimensions of the actual anomaly can then be measured in units of the depth of burial to see whether they conform to the dimensions of the intensity anomaly of the selected model.

The other indices are employed to provide additional estimates of the depth of burial from the same anomaly. Often a second model must be selected, the use of which results in better agreement among the several depth estimates.

iii. Before studying further any of the anomalies on an aeromagnetic map, one

should investigate the quality of the control of each anomaly. A flight-line spacing of half the depth of burial is believed to delineate an anomaly adequately.

D. CONSTRUCTION OF THE CURVATURE MAP

After selection of particular anomalies for further study, the curvature map is prepared for the anomalies only, or for the entire map. Usually the entire map is employed because the curvature map may isolate important anomalies that were obscured on the intensity map by the mutual interference of anomalies or of large gradients.

To compute the curvature (Henderson and Zietz, 1949) a square grid is superimposed over the aeromagnetic intensity map.

It was ascertained that the spacing of the grid lines did not materially affect the location of the zero, maximum, and minimum values of curvature for the theoretical bodies. But smaller grid spacing did result in a more accurate delineation of the curvature. Actually, however, the choice of a grid size is more difficult. An aeromagnetic intensity map often contains anomalies produced by a variety of heterogeneous bodies whose depths can conceivably range from the earth's surface downward to the Curie-point geotherm. The superimposed grid acts as a filter so that a resulting curvature map retains features relating only to sources whose upper surfaces are above a certain depth. As an illustration of the screening effect of a grid, an "Aeromagnetic map of area near Curwensville, Pennsylvania" is presented (Pl. 4). This map contains three curvature plots over the same area which are computed on 1-, 2-, and 3-mile grids. The 1-mile plot illustrated the "eyes" and contour irregularities of a small grid. The small features are attributed to near-surface effects and to errors introduced during the construction of an aeromagnetic map. These small anomalies distort and obscure the large features that are to be expected on the curvature map of the Curwensville anomaly on the basis of the curvature and intensity distributions on a similar model chart. The 2-mile and 3-mile grids result in a curvature plot that the Curwensville anomaly should produce. Although the 2-mile grid still retains variations attributable to observational errors, the zero and extreme values are essentially the same on each map. This agreement indicates the degree of freedom in the selection of the grid spacing.

The spacing of the grid lines should approximately equal the depth to the crystalline rock below the level of flight of the airborne magnetometer over the area. The depth of burial obtained from the intensity map is sufficiently accurate to indicate the spacing of the grid.

The grid is superposed on the intensity map, and the intensity at each grid-line intersection is interpolated and recorded. Eight intensity values about a corner value, T_0 , are used in the curvature computation. They are A through H and are illustrated in the following diagram:

A	B	C
D	T_0	E
F	G	H

To facilitate the computation, additional values (M , N , R , S) are inserted according to the following diagram. These values are combinations of the original values, where $M = A + C$, $R = D + E$, $N = F + H$, and $S = B + G$.

A	B	C
	M	

$$\begin{array}{ccc}
 D & T_0 & E \\
 & R & \\
 & S & \\
 F & G & H \\
 & N &
 \end{array}$$

The curvature is found by means of the expression

$$0.5 (3 T_{op} - 4T_1 + T_2)$$

where

$$T_{op} = 4T_0, \quad T_1 = R + S, \quad T_2 = M + N.$$

A 1-mile grid spacing is chosen as a standard, and all curvature values are converted to gammas per mile per mile. If the grid spacing is n miles, the expression is multiplied by $1/n^2$.

The computation is restricted to the corners of the grid. However, the computation may be made for any density of points by reapplying the grid at the desired points. Ordinarily the grid is applied once over the entire map, then values at additional points are computed in areas where further information is needed for accurate contouring. The contouring of the curvature map is the final step.

The comparison of an actual anomaly with a model chart may suggest that the anomaly is two-dimensional and may be treated by considering a profile only. In such cases the curvature may be computed along a profile if a quick estimate of the depth of burial is desired. Such profiles are drawn perpendicular to intensity contours where the latter are nearly parallel, and often a composite profile is drawn as the average of several profiles. The curvature is computed along the profile at as many points as desired by using the expression $(2T_0 - B - G)$ where B and G are the values at two points equidistant from T_0 . This expression is also multiplied by $1/n^2$ when B and G are n miles from T_0 in order to express the curvature in gammas per mile per mile.

E. INSPECTION OF CURVATURE MAP

Comparison of the curvature maps and charts is much more significant than the comparison between actual maps of intensity and the model charts, as the curvature of the intensity field delineates the anomalies more clearly. This is readily seen by an examination of any of the model charts. The curvature contours, especially the zero contour, outline the prismatic cell, whereas the trends of the intensity contours do not suggest the outline of the cell.

Anomalies large in area and magnetic relief are selected for study. No exact dimensions can be given, but the anomalies should be conspicuous on the map. They are preferably well isolated from other anomalies and should have adequate flight-line control. For example, anomalies contained between flight lines or crossed by only one flight line lack sufficient control.

Certainly the anomalies selected on the intensity map must have the properties that permit an analysis for depth estimates on the curvature map. In addition, however, the curvature map will have isolated anomalies that appear on the intensity map as mere noses or variations in gradient. If these counterparts of the curvature

anomalies are clearly visible on the intensity map, and if the curvature anomalies exhibit the properties mentioned above, they may be satisfactorily employed for estimating depths.

The zero value of the curvature tends to outline the top surface of the source of the magnetic anomaly. The shape of a possible prismatic block can be estimated by comparing the zero contour to the periphery of the top surface on the model charts. One of the models can be selected as an approximate source for all or a great portion of these large magnetic anomalies. After a model is selected, the depth estimates are made by using the curvature depth indices in the same way that the intensity depth indices were used. A depth index is measured on the map and the model chart, and the quotient (map index/chart index) is the estimated depth.

At magnetic inclinations between 0° and 45° , the M index should be measured first. Similarly, the A index is used first between inclinations 45° and 90° . These two indices are apparently more independent of the size of the model than others.

Care must be exercised in the use of the A and M indices for narrow models ($n < 2$ or $m < 2$), especially at the extreme inclinations (approximately between 0° and 15° , and between 75° and 90°). This narrowness, in terms of the depth of burial, can be detected even before the depth is calculated by inspection of the models.

For example, the $n = 6$ models have a simple, circular, or oval-shaped positive curvature anomaly if m is 2. For these models the A and B indices are approximately of the same value. However, if m is less than 2, the shape of the anomaly remains the same, but the B index becomes considerably less than the A index. (See curves in Pl. 2.)

Again, the $m = 6$ models have a simple circular or oval-shaped positive curvature anomaly when n is 2 or less. At $n = 2$, the A index is equal to or less than the N index; but for $n = 2$, the A index is greater than the N index.

(The above discussion for the inclinations between 45° and 90° can be applied to the models between 0° and 45° by utilizing the negative curvature anomaly and the M index.)

After determining the depth of burial by means of the A index or M index, the selection of the model can be evaluated and changed, if necessary.

Additional depth estimates can then be made from the same anomaly, utilizing the other indices as indicated in Figure 3. The estimates should agree among themselves. If they do not, the curvature map should be inspected to determine whether any of the indices are disturbed by interference from other anomalies. Otherwise, the model has been selected incorrectly.

F. DETERMINATION OF THE MAGNETIC SUSCEPTIBILITY CONTRAST, k

The quantity k is determined from well-isolated anomalies on the intensity map. From the model selected for the anomaly, the total amplitude of the intensity anomaly, ΔT_c , is measured. One also measures the total amplitude of the actual anomaly, ΔT_m , in gammas. Then,

$$k = \Delta T_m / \Delta T_c T$$

where T = the intensity of the earth's main magnetic field in gammas, as previously determined.

The polarization, I , which appears in the model charts, is equal to the product, kT .

As the computation for k is based on a comparison with infinitely deep models, it yields the minimum susceptibility contrast.

SECTION 5. APPLICATION TO INDIVIDUAL SURVEYS

WORCESTER COUNTY, MARYLAND

General discussion.—In 1947, the U. S. Geological Survey published an aeromagnetic map of Worcester County and part of Wicomico County, Maryland (U. S. Geol. Survey, Oil and Gas Investigation, Preliminary map 46). Two anomalies, herein called the “Snow Hill” and “Girdletree”, are conspicuous on the map (Fig. 4).

Worcester County is in the coastal plain area of Maryland, and the basement complex is buried under a considerable thickness of sediments. There are no well data exactly over the anomalies that indicate the depth of burial of the crystalline rock. However, two wells in adjacent areas penetrated the basement complex. The Salisbury well, 11 miles north of the Snow Hill anomaly, encountered the basement at 5568 feet below the surface. The Berlin well, 11 miles northeast of the Snow Hill anomaly, encountered bedrock at 7148 feet (Richards, 1948). Generalized contours of the depth of the basement complex, based on all available well and seismic data (Ewing *et al.*, 1950), show that the area containing the two anomalies is bounded by the 6000-foot contour on the west and the 7000-foot contour on the east.

The intensity, inclination, and declination of the earth's magnetic field in this area are 55,900 gammas, 71°, and 9°W, respectively.

Geological setting.—The Coastal Plain sediments overlying the basement complex in Worcester County range from Lower Cretaceous to Pleistocene. In addition Richards (1948) identifies some hundreds of feet of Triassic sediments in the Salisbury and Berlin wells—mainly unconsolidated sands, clays, and marls. There is no reason to believe that they contain ferromagnetic minerals in sufficient quantity to produce detectable magnetic anomalies. The sediments are believed to be generally monoclinical and follow the regional southeasterly dip of the basement complex.

The lithology, age, and structure of the basement complex in Worcester County are practically unknown. The basement penetrated by the well at Berlin is “an igneous black rock, probably a gabbro” (Richards).

Some indications of the character of the crystalline basement may be found in an examination of the crystalline rocks where they are exposed west of the Fall Line. The Fall Line lies about 80 miles northwest of the area. A cursory examination of the geological map of Maryland (Mathews, 1933) reveals that the band of crystalline rock west of the Fall Line is 30 miles wide and strikes northeasterly. It is called the Piedmont Upland. By far the major portion of this band is Wissahickon schist. Other large constituents are the Baltimore gneiss, the Peters Creek schists, and various granitic bodies. Smaller bodies of rock, perhaps more important as causes of magnetic anomalies, are serpentine and gabbroic sills with related small bodies of pyroxenites and peridotites. The gabbro is especially prevalent along the eastern margin of the Piedmont Upland where it crops out in areas of more than 50 square miles.

Stose and Stose (1946) have examined the crystalline rocks in detail in Carroll and Frederick counties, Maryland. The Baltimore gneiss is the oldest rock in the Upland. It is an injection complex, and its original constituents represent sedimentary formations. The gneiss is considered early Precambrian. Crystalline schists, approximately 1 mile thick, overlie the gneiss and include the Wissahickon schists

which comprise the bulk of the sequence. It is an oligoclase schist in the eastern part of the Piedmont Upland and an albite schist in the western part. The Peters Creek schist occupies a syncline between the two Wissahickon types.

Small magnetic anomalies might be caused by changes in the configuration of the gneiss and schists; but the rocks would be normally characterized, magnetically, by a region of generally lower intensity. Larger anomalies might be caused by intrusive bodies in the metamorphic rocks. Besides the older intrusive pyroxenite and gabbro, Triassic diabase dikes and sills are found in pre-Triassic rocks as well as in the Triassic province west of the Piedmont Upland.

The Piedmont Upland area has topographic relief of the order of 500 feet.

If these data regarding the basement complex in the Piedmont can be applied to the bedrock of Worcester County, the general nature of the bedrock may be described as

(1) a base of injection complex consisting of granitoid layers alternating with magmatic material;

(2) a sequence, of the order of 1 mile thick, of schists with some volcanic flows and tuffs lying on the injection complex;

(3) local intrusive bodies and volcanic centers of basic rock types.

Magnetic anomalies of local character perhaps may be attributed to the intrusive bodies, either of basic rock or of granitic rock with a high ferromagnetic content.

Magnetic intensity map.—The U. S. Geological Survey prepared two aeromagnetic maps of southeastern Maryland (U. S. Geol. Survey, Oil and Gas Investigations, 1947, Map 46, Figs. 1, 2). Figure 1 of that publication is corrected for the variation of the earth's main magnetic field and contains a definite increase of intensity from west to east over an area where the basement is generally sloping to the southeast 100 feet per mile. Figure 2 is corrected for this regional magnetic gradient. Two areas of sharp magnetic relief appear on Figure 2, and they are called herein the "Snow Hill" and "Girdletree" anomalies (Fig. 4).

The horizontal extents of the sharpest gradients are measured on each of the two anomalies in order to estimate the depth to bedrock. The measurements are indicated on Figure 4, and the resulting depth estimates are included in Table 4.

The Snow Hill anomaly is compared to the 4 by 6 model at inclination 75° , largely because the anomaly is nearly square. The indices are designated E and F' because of their azimuthal direction and position on the anomaly. Similarly the Girdletree anomaly is compared to the 1 by 6 model. Its obvious skewness is neglected.

The curves for the intensity indices of the 45-degree skew models at inclination 75° (Pl. 1) exhibit rapid changes of the indices. The corresponding curves for the 30-degree skew models at inclinations 30° do not vary so markedly. One can not correct for the effect of skewness on the intensity indices. This is one of the factors that make the depth estimates based on gradients only rough approximations.

Curvature map.—A square grid with 1 mile spacing was used to compute the curvatures over the area of Figure 4. The values were contoured, and the resulting curvature map is presented in Figure 5.

The Snow Hill curvature anomaly consists of a series of positive values enclosed

by an irregularly shaped zero contour which is in turn surrounded by a series of disconnected negative anomalies. The bulk of the anomaly may be considered to be caused by a prismatic block in the crystalline rock that measures 3.9 by 4.5 miles

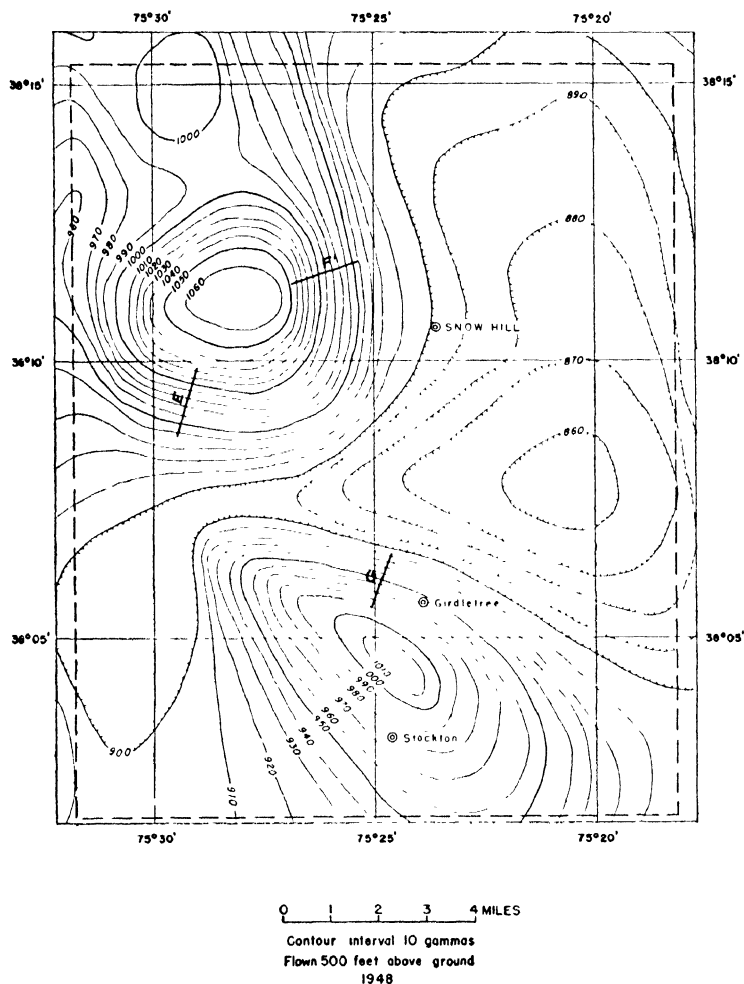


FIGURE 4.—Aeromagnetic map of part of Worcester County, Maryland, showing variations in total intensity

and is oriented N. 26° E. although such an approximation must neglect the sharp protuberances that give the anomaly its irregular shape.

The anomaly shows the depression in the middle that begins to develop, according to the models, when the source of the anomaly exceeds two units (in terms of depth of burial) in length and width. This depression is surrounded by a ring of maximum curvature, and reliable indices can be measured from the zero to maximum curvature around the anomaly wherever the features are strongly developed. These indices are indicated in Figure 5, and the resulting depth estimates are included in Table 4.

The indices are referred to the 4 by 6 model because this model exhibits the depression characteristic of the center of the areally large models.

The Girdletree curvature anomaly (Fig. 5) is similar to the curvature of a long, narrow skew model. From a study of the 1 by 6 and 2 by 6 models at inclination

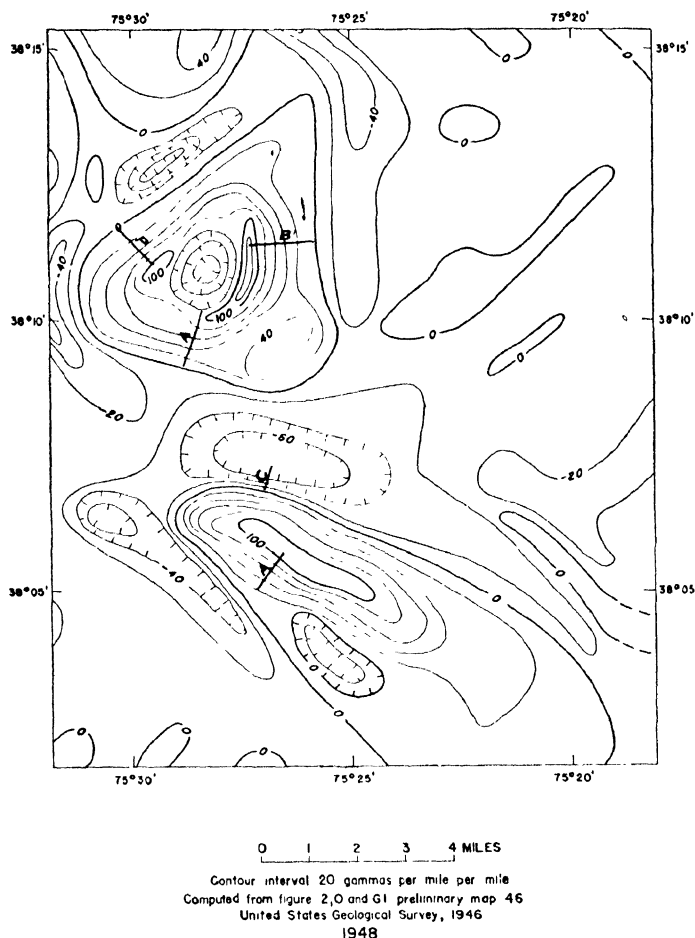


FIGURE 5.—Aeromagnetic map of part of Worcester County, Maryland, showing curvature of total intensity

75°, it can be concluded that the disturbing block is nearly 1 unit in width in terms of depth of burial. In Table 4, the disturbing block has been estimated to be 1.5 miles wide and more than 6 miles long.

Although the suggested block is oriented N. 40° E., the regular 1 by 6 model is used instead of the skewed 5.6 by 1.4 model. See previous discussion.

Two indices, *A* and *C*, can be obtained and are marked in Figure 5. The index *C* is less reliable than *A* as both a map and model index. It results in a smaller depth estimate (Table 4).

Determination of susceptibility contrasts.—Now that corresponding models are chosen for each of the two anomalies, 4 by 6 for Snow Hill and 1 by 6 for Girdletree, the susceptibility contrast of the underlying rocks can be computed. The 4 by 6 model has an intensity range of 4.0 kT , c.g.s. units. The Snow Hill anomaly has an amplitude of 160 gammas, if 900 is considered as the zero contour. As T is 55900

TABLE 4.—*Depths of burial of crystalline rock, Worcester County, Md.*

Anomaly	Location	$n \times m$ (miles)	Suggested block n -azimuth†	Ref. model	Depth index map/model	Depth of Burial* (Feet)	Avg D. B.
Snow Hill	38°11' 75°28'	3.9 x 4.5	N.26°E.	4 x 6	E, 1.5/1.3	5600	5800‡
					F, 1.5/1.3	5600	
					B, 1.4/.85	8200	
					P, 1.1/.9	6000	
Girdletree	38°05' 75°25'	1.5 x 6 (?)	N.40°E.	1 x 6	A, 1.1/.9	6000	4700
					G, 1.2/1.2	4800	
					A, 1/1	4800	
					C, 6/.65	4400	

* Height of plane, 500 feet, not included.

† Magnetic.

‡ 8200 value omitted.

gammas, the susceptibility contrast is .0007. The 1 by 6 model has an intensity range of 1.6 kT gammas, and the Girdletree anomaly, 110 gammas. The susceptibility contrast for Girdletree is then .0005.

Summary.—The depths of burial of the crystalline rock in Worcester County, Md., derived from studies of the aeromagnetic maps of the area, are summarized in Table 4. The average depth at Snow Hill is near the 6000-foot generalized contour that passes through this anomaly.

The Girdletree estimates indicate a rise in the basement floor or an underlying, anomalous block probably less than 1 mile in vertical extent. The three depth estimates agree well among themselves, and each is supported by well-defined evidence. But no definite choice can be made between the two suppositions from a study of the magnetic data alone.

The previous description of the exposed crystalline rock in the Piedmont Upland would suggest early Paleozoic intrusive bodies of basic rocks and Triassic intrusives or extrusives of diabase as possible sources of the anomalies.

Woollard (1943) has made a detailed gravity and magnetic (vertical-intensity) survey over a portion of the Coastal Plain area in New Jersey, and his map (Pl. 5) contains local anomalies of size comparable to the Snow Hill and Girdletree anomalies. In this area the basement surface slopes seaward from its exposed surface at the Fall Line and reaches a depth of approximately 2000 feet at the coast. The general magnetic intensity decreases about 300 gammas from the Fall Line to the coast. There are two noteworthy exceptions to this general decrease, about 9 and 17 miles west of the coast.

These exceptions are zones of relatively higher intensity, and each has an associated group of gravity maxima. Woollard discusses the western group in some detail.

In discussing the pronounced gravity feature, he mentions the possibility of a "cupola rising from a large intrusive at depth." He notes also that there is "an exceptionally high seismic velocity, 22,000 feet per second," for the basement rock in the area.

APPALACHIAN PLATEAU, CENTRAL PENNSYLVANIA

General discussion.—The U. S. Geological Survey, in co-operation with the School of Mineral Industries of Pennsylvania State College, has prepared an aeromagnetic map of 1800 square miles of the Appalachian Plateau, east of State College, Pennsylvania.⁸

The total intensity, inclination, and declination averages of the earth's magnetic field are 57,500 gammas, 72°, and 8°W., respectively.

Geological setting.—The larger portion of the surveyed area lies within the Allegheny synclinorium (Kay, 1942) just west of the more highly folded Appalachian Mountains. The Appalachian structural front (Price, 1931), between the synclinorium and the mountains, runs southwesterly across the southeastern corner of the area. It is approximately coincident with contour "750" of Plate 3.

Pennsylvanian sediments crop out extensively throughout the area west of the structural front. However, the older sediments, down to the Cambrian, are exposed in the sharp anticlinal folds to the east. The subsurface of the synclinorium is considered to contain sediments ranging in thickness from approximately 20,000 feet in the western part of the area to 24,000 feet at the structural front.

The thickness of the Cambrian and Ordovician section, 10,000 feet, is based on measurements of the exposed section (Swartz, 1948). The remaining thickness is derived from both well records and exposures (Price, 1931).

This sedimentary section has been subjugated to the broad, open folding of the synclinorium. The major fold axes (Pls. 3, 5) are continuous over tens of miles and are spaced approximately 5 miles apart. These axes are locally sinuous. The amplitudes of the folds, at the surface, are of the order of 500 feet, but the intensity is considered to increase with depth (Sherrill, 1941, p. 417).

Surface faults of small displacement are prevalent, and evidences of extensive faulting in the deeper formations are found in well records.

The nature of the Precambrian floor of these sediments must be conjectural, as no wells penetrate the crystalline rock. In general, the Precambrian crystalline rock is thought to have a surface of low relief (300–400 feet), and large areal variations in lithology are anticipated.

As in the Maryland example, the exposed Precambrian can be examined to ascertain the general make-up of a Precambrian area. Swartz (1948) includes comments on the structure and composition of the Precambrian in the Adirondack Mountains, eastern Pennsylvania, and the Blue Ridge province. His salient points are:

(1) In the Adirondack Mountains, "foliation . . . reflects Precambrian and not post-Cambrian regional deformation and intrusion." The mountains contain large areas of basic and acidic plutons intrusive into the Grenville metasediments. (See Swartz, 1948, Fig. 2.)

(2) The extension of the Jersey Highlands in eastern Pennsylvania is similar to the Adirondacks in that it is composed of "ancient, highly deformed gneisses of sedimentary origin, intruded by stock-like, plutonic masses of gabbro, anorthosite, and granitic rocks."

(3) The Precambrian of south-central Pennsylvania contains basaltic and acidic lavas which are conspicuously absent in the other areas.

⁸ See Joesting (1949).

There is also the possibility of post-Precambrian intrusive activity that would produce rock units detectable by the airborne magnetometer. Such igneous bodies as those near Baltimore and Philadelphia, the Cortlandt norite bodies of New York and Connecticut, and the Triassic diabases must all be considered.

The surface of the Precambrian crystalline rock has been folded along with the sediments in the easternmost Appalachians, so it is reasonable to anticipate that the basement complex is folded along with the sediments in the broad structures of the Allegheny synclinorium. However, this anticipation involves the classic question relating to the stresses active during Appalachian deformation, viz., plastic shortening of the basement.

Magnetic intensity map.—The aeromagnetic map of a portion of the Appalachian Plateau (Pl. 3) has superimposed on it the axes of the major anticlines and synclines in the area. The trends of the magnetic contours crosscut the structural axes for the most part, thereby suggesting the lack of relationship between the magnetic and the structural control. The axes and the magnetic trends agree well in the southeastern portion of the area. In this area the crystalline rock probably has been severely deformed in conformity with the overlying sediments because here the isoclinal folding and faulting of the Appalachian Mountains begin. However, the area of agreement is too small to justify the statement that the magnetic trends reflect Appalachian structure.

The intensity map is a series of flat, featureless zones separated by well-defined bands of sharp gradients. These sharp gradients represent the boundaries among the various types of rock that constitute the basement complex. Furthermore, the flat zones of higher intensity may be considered to be underlain by rock of higher ferromagnetic content than the featureless zones of low intensity. In the northeastern portion of the map, two bands of higher intensity extend southward until they join and culminate to form the broad anomaly south of Karthaus. The two bands are separated by a region of intermediate intensity. Similarly, in the western part of the map two bands of higher intensities extend outward from the broad anomaly west of Curwensville, one band trending just west of north and the other extending to the northeast.

These two large groups of anomalies at Curwensville and Karthaus each represent large lithologic units that extend over hundreds of square miles. These intrabasement bodies should most nearly possess the properties of the calculated models and are therefore likely to yield reliable depth estimates.

First, the lengths of the sharp, well-defined gradients are employed. The 13 gradients measured are indicated on the intensity map by numbers in parentheses (Table 5). The average depth of burial of the basement complex is estimated from the intensity indices to be 16,600 feet.

Curvature map.—A 3-mile grid was used for the computations of the curvature map (Pl. 5). The depth indices measured on Plate 5 are plotted on the map and listed in Table 5b. Twelve estimates of the depth of burial of the crystalline rock are obtained. The average value, 15,900 feet, agrees well with the average depth of Table 5a. Two of the values are apparently excessively large, 20,000 and 22,000 feet. These values are each measured on the broad south and southeast flanks of

TABLE 5.—*Depths of burial of basement, central Pennsylvania*

a. ESTIMATED FROM INTENSITY MAP

Gradient	Reference model	Depth index, map/model	Depth of burial* (Feet)	Avg. D. B. (Feet)
(1)	6 x 2	E, 3.5/1.3	13,000	16,600
(2)	6 x 2	G, 2.8/1	14,000	
(3)	6 x 2	F', 3.8/1	19,000	
(4)	6 x 2	E, 4.1/1.3	16,000	
(5)	6 x 2	F, 3.6/1.0	18,000	
(6)	6 x 2	F', 3.75/1.0	19,000	
(7)	1 x 6	E, 3.2/.95	17,000	
(8)	8 x 6	F, 4.3/1.1	20,000	
(9)	6 x 4	F, 3.75/1.1	17,000	
(10)	6 x 4	E, 4.4/1.5	14,000	
(11)	8 x 6	F', 3.0/1.1	13,000	
(12)	6 x 2	F, 3.2/1	16,000	
(13)	8 x 6	F', 4.4/1.1	20,000	

b. ESTIMATED FROM CURVATURE MAP

Anomaly	Location	Suggested block $n \times m$, n -azimuth* (miles)	Ref. model	Depth index map/model	Depth of burial* (Feet)	Avg. D. B. (Feet)
(1)	40°55' 78°38'	8 x 7, N.4°W.	6 x 2	A, 3.75/1.3 B', 3.75/1.2 C, 2.05/.65	14,000 16,000 16,000	15,900
(2)	41°02' 78°32'	2 x 2.75, N.8°W.	1 x 6	A, 2.4/1 N, 1.85/.6	12,000 15,000	
(3)	41°08' 78°33'	? x 6, N.16°E.	6 x 2	B or B', 3.4/1.2	14,000	
(4)	41°05' 70°10'	12 x ?, N.14°W.	4 x 6	B, 2.9/.95 A, 3.6/.9 A, 2.75/.9 B', 4.2/.95 A, 3.0/.9 A, 2.75,.9	15,000 20,000 15,000 22,000 17,000 15,000	

* Height of plane, 1,000 feet, not included.

The major difficulty in using the gradients is the choice of the proper reference model. On the Pennsylvania map, the 6 by 2 model is chosen for the anomaly west of Curwensville on the basis of the lengths of gradients (1), (2), and (3). Once selected, a model serves as a guide in the selection of other reference models.

The gradients (4), (5), and (6) are grouped around an anomaly considered to be caused by a block with a negative susceptibility contrast.

Gradients (8) and (11) are referred to an 8 by 6 model as this model most closely approximates a two-dimensional slope, and the gradients may each be considered to have such a source.

the Karthaus anomaly, and suggest that the walls of the underlying anomalous block may be less steep in these areas.

Six of the indices are measured around the Karthaus curvature anomaly. The treatment of this anomaly is somewhat different from that of the intensity anomaly. The central negative area

is again neglected, and the entire anomaly is referred to a 4 by 6 model oriented N. 14° W. The indices are designated *A* and *B* mainly because of their azimuthal direction. Additional *B* indices were not measured in the neighborhood of N. 41°10', W. 78°10' because the positive anomaly there is abnormally narrow. Furthermore the negative is overdeveloped as it is above one positive anomaly and adjacent to another.

The *B* indices of anomaly (3) are only fairly reliable because the choice of the reference model is based on the similarity to anomaly (1).

Susceptibility contrasts.—The Curwensville anomaly has magnetic relief of about 200 gammas, and the computed susceptibility contrast is .0013. The Karthaus high has relief of approximately 360 gammas, and the contrast is .0017.

Concluding remarks.—Aeromagnetic maps indicate that the basement complex in Central Pennsylvania, just west of the Appalachian structural front, is buried beneath 3 miles of sediments. The calculations are based on a study of the gradients and curvatures of large magnetic anomalies considered to arise from the juxtaposition of large intrabasement units that have dissimilar magnetic polarizations. These magnetic differences carry the added implication that the intrabasement units are different lithologic units, as for example gabbro versus granite. Furthermore the more basic rocks probably underlie the regions of higher magnetic intensity.

These intrabasement units are haphazardly arranged except in the eastern portion of the surveyed area, which is directly adjacent to the Appalachian front where the magnetic trends and geological axes are approximately parallel. This conformable unit seems to be composed of two bands that enter the area from the northeast and culminate south of Karthaus. Furthermore the two bands are separated by an area that is probably underlain by a rock type magnetically intermediate between the rock under the Karthaus anomaly and the surrounding rock.

MANGUM, OKLAHOMA

Mangum is located in Greer County in southwestern Oklahoma at latitude 34°52'N. and longitude 99°30'W. The intensity, inclination, and declination averages of the earth's magnetic field are 55,000 gammas, 65°, and 11°E., respectively, in this area.

Geological setting. (Taff, 1904; Oklahoma Geol. Survey, Bulletin 19, 1917; Hoffman, 1930).—The topography and geology of Greer County are featured by the Wichita Mountains, which enter the county from due east and trend N. 45° W. into the center of T.6 N., R.21 W., where they disappear beneath the Redbed Plains. All of the county outside of the Wichita Mountains area lies in the Redbed Plains.

The mountains are a system of scraggly hills, especially in the western part, which extend for 65 miles from Fort Sill to Granite. The system trends N.70°W. Just northeast of the area surveyed by the airborne magnetometer are Quartz Mountain and Devils Canyon Mountain. Although the mountains in the western part are small hills, they are rugged and rise abruptly from the gentle Redbed Plains. Many of the rounded knobs and peaks rise 600 to 800 feet above the plain.

The Wichita Mountains are Precambrian granophyre and gabbro with related anorthosite. The Precambrian age was established by Taff from occurrences of igneous rocks intrusive into the Meers Precambrian quartzite.

The gabbroic rocks do not crop out in the Mangum area but are extensive in the central and eastern portions of the mountains. The gabbro averages more than 80

per cent labradorite. Much of it contains 96 per cent labradorite and is classed as anorthosite. Diallage is the most common ferromagnesian mineral. Hornblende, biotite, and hypersthene also are present. The accessory minerals include magnetite, which is abundant, although the quantity varies inversely with the amount of labradorite. The magnetite is insignificant in anorthosite and as high as 6 per cent in the gabbros.

The granophyres comprise the igneous rock bodies cropping out in the Mangum area. All the high hills throughout the Wichita Mountains are composed of granophyre. Taff originally called these rocks granites, but Hoffman significantly changed the terminology. He states that the "acidic rocks of the Wichita Mountains are composed to a large extent of quartz and alkali feldspar intergrown in micropegmatitic fashion. This type of rock is referred to by Rosenbusch as granophyre."

The granophyres are almost entirely quartz and alkali feldspars. They have very small amounts of ferromagnesian minerals. In the Lugert granophyre, which constitutes most of the igneous rock in the mountains near Mangum, the ferromagnesian content is seldom as great as 8 per cent. The granophyres contain an average of 1 per cent magnetite.

The western Wichita Mountains were formed during late Mississippian diastrophism (Bucher, 1941, p. 370). The earlier Paleozoic geosyncline of the Wichita-Arbuckle region, primarily a series of thick Cambro-Ordovician limestones, was transformed into a pair of basins separated by high blocks of Precambrian rock. The basin to the north is the Anadarko basin, and that to the south is the Red River basin. The Anadarko basin is a foreland basin, and the sedimentary rocks dip steeply into the basin. The dips on the southern side, or in the Mangum area, are more gentle. It is unreasonable to assume a uniform regional dip away from the exposed crystalline rocks. A southwest dip of 500 feet per mile may be used for the general attitude of the Precambrian basement in the Mangum area (Moss, 1936, p. 948).

Of the sedimentary rocks, only the Permian crop out in the Mangum area, and the underlying rocks must be studied from drill logs. The mountains were formed along geosynclinal axes as the greatest thicknesses of early Paleozoic sediments occur in or adjacent to the mountains. The Cambro-Ordovician series is about 8500 feet thick, of which approximately 6000 feet is the Arbuckle limestone. The Silurian, Devonian, Mississippian, and lower Pennsylvanian are not found in the Wichita area. A thin layer of upper Pennsylvanian clastics is the next younger sediment. The Permian beds overlap the older rocks and lie adjacent to the flanks of the mountains. These beds are products of the erosion of the Wichita Mountains, and the strata thicken considerably into the Anadarko and Red River basins.

No igneous rock crops out in the area surveyed by the airborne magnetometer although granite is exposed in sec. 18, T.5 N., R.20 W. (Pl. 6), which directly adjoins the area under consideration. Data could be found for only two wells in the immediate area, and these data indicate only total depths. It is assumed that the wells are entirely in sedimentary rock. Gahrtz (1922) lists a well of 1300 feet, total depth, in T.5 N., R.21 W.; and Trout (1915) lists one of 900 feet, total depth, in sec. 28, T.5 N., R.21 W.

Intensity maps.—Mangum was one of the first areas surveyed by an airborne mag-

netometer. One reason for choosing the Mangum area was that a map of vertical magnetic intensity had already been prepared by the Gulf Research and Development Co., and therefore the maps of vertical and total intensity could be compared. The area was flown at elevations of approximately 300, 1300, and 6300 feet above the ground. The resulting maps were published by the U. S. Geological Survey. The four maps are included here as Plate 6.

The vertical-intensity map and the total-intensity map for the 300-foot level are very similar. Both exhibit the zone of higher intensities flanked by parallel bands of steep gradients in the northeastern and central-eastern area, undoubtedly related to the buried flank of the Wichita Mountains which crop out in sec. 18, T.5 N., R.20 W. The apex of the large high in the zone is located in almost exactly the same position on both maps.

The maximum of the total intensity anomaly is theoretically offset south of the vertical anomaly although the offset would not be discernible from a near-by source of the anomaly. Roman (1946) estimates this offset to be one- to two-tenths of the distance from the source to the place of observation for a horizontal line of poles lying magnetically east-west.

Both the large positive anomaly and the entire zone of high intensities parallel the strike of the Wichita Mountains on the east. The large anomalies in the high zone are confined to the west edge. They cause three polarization contrasts, in general, between the large zone and the outlying rock, between the large zone and its own western rim, and between the western rim and the outlying rock.

Granite crops out as a small hill within the negative anomaly on the east edge of Plate 6 (sec. 18, T.5 N., R.20 W.). Evidently the zone of higher intensities is caused by a change in lithology and not by a change in the slope of the Wichita Mountains. Probably a band of gabbro about 3 miles wide lies buried on the southwest slope. Furthermore this band probably has a larger development of magnetite along its western rim.

The lengths of the sharpest gradients were measured and labeled on the three aeromagnetic intensity maps (Pl. 6). Two measurements on the eastern margin of the high zone yield an estimated depth of burial of 600 feet. Four estimates along the western margin indicate that this edge is buried to a depth of 2300 feet although the range of values is from 1800 to 2900 feet (Table 6a). The zone is 3 miles wide, and the computed slope of 600 feet per mile is reasonable.

Curvature.—The curvature of the Mangum intensity fields was computed first over the area of Plate 6, but the curvature map did not prove useful, because the irregularities of the intensity map were magnified too much.

The curvature was computed along profile *AB*. (Point *A* is NW. corner sec. 1, T. 4 N., R. 22 W. Point *B* is NW. corner SE. $\frac{1}{4}$ sec. 12, T. 5 N., R. 21 W.; see Pl. 6.) The field along this profile was considered representative of the normal or undisturbed portion of the zone of high intensity. This computation was made for each of the three altitudes, and the curvature profiles are plotted in Plate 7a. The estimated depths for the western margin (Table 6b) agree with the average value, 2300 feet, determined from the intensity maps.

In addition three curvature maps (Pl. 7) were prepared for the small area embrac-

ing the large positive anomaly along the western rim of the zone of higher intensity for each of the three flight levels. The maps at the lower two altitudes delineate the western border of the apparently more highly polarized rock of the zone. This zone

TABLE 6.—*Depth of burial, Mangum, Oklahoma*

a. AS ESTIMATED FROM INTENSITY MAPS

Pl	Gradient	Ref. model	Depth index, map/model	Depth of burial* (Feet)	Avg. D. B. (Feet)
6	(1)	2 x 6	E, 0.40/1.05	1800	600 (east slope) 2300 (west slope)
	(2)	8 x 6	F', 0.23/1.4	500	
	(3)	6 x 2	F, 0.35/1.05	1800	
6	(4)	6 x 4	F', 0.40/1.0	800	
	(5)	6 x 2	F, 0.80/1.05	2800	
6	(6)	6 x 2	F, 1.8/1.05	2900	

b. AS ESTIMATED FROM CURVATURE PROFILES

Pl.	Curve	Ref. model	Depth index map/model	Depth of burial* (Feet)	Avg D. B. (Feet)
7	(1)	8 x 6	A, .54/1.05	2400	2300 (west slope)
	(2)	6 x 4	A, .63/.9	2400	
	(3)	6 x 2	A, 1.6/1.0	2100	

c. ESTIMATED HEIGHT OF AIRPLANE ABOVE CRYSTALLINE ROCK FOR "WEST SLOPE" AREA

Source of data	Estimated height (Feet)	Avg estimated height (Feet)	Estimated height differences (Feet)	Actual height differences (Feet)
Pl. 6 Grad. (1)	2100	2300	1600	1000
Pl. 6 Grad. (3)	2100			
Pl. 7 Curve (1)	2700			
Pl. 6 Grad. (5)	4100	3900	4900	5000
Pl. 7 Curve (2)	3700			
Pl. 6 Grad. (6)	9200	8800		
Pl. 7 Curve (3)	8400			

* Height of plane is not included.

is long and narrow (about 0.7 mile) compared to the depth of burial and is not useful for determinations of the depth of burial as the available *B* indices are actually a measure of the width of the underlying block.

The curvature map for the highest level (Pl. 7) does not contain the small features peculiar to the other two curvature maps but has one broad anomaly, the product of the entire zone of high intensities. This zone, 3 miles in width, is also long and narrow compared to its depth of burial, 8600 feet; and again the available *B* index cannot be used to estimate depths.

The depth to crystalline rock is unknown in the surveyed area, but maps were

prepared for three flight levels—300, 1300, and 6300 feet above the ground. The differences between the estimated heights above the crystalline rock should equal the actual differences in flight level of 1000 and 5000 feet. These data are summarized in Table 6c, and the average estimated differences are 1600 and 4900 feet. The better agreement for the upper levels may be ascribed to the relatively better coverage that the same flight-line pattern gives at the higher altitudes.

Determination of susceptibility contrasts.—The magnetic susceptibility contrasts, as determined from Plate 6, are .004 between the high zone in general and the outlying rock and .015 between the western border of the zone and the outlying rock.

Concluding remarks.—The study of the magnetic surveys around Mangum and of the geological setting of the Wichita Mountains suggests that a narrow band of gabbrolite rock lies in the buried flank of the mountains. This suggestion is made more plausible by the fact that gabbro, where exposed in the Wichita Mountains, is always at lower elevations than the granitic rocks.

The evidence available to evaluate the estimates of the depth of burial is the comparison of the estimated and actual differences between the flight levels. The comparison for the difference between the two upper levels is excellent, 4900 vs. 5000 feet. The discrepancy between the estimated and actual values for the two lower levels, 1600 vs. 1000 feet, may be attributed to insufficient flight-line control.

The consistency of the estimate of depth of burial based on the flight at 6300 feet, in the two-dimensional analysis, suggests that the band of gabbrolite rock extends approximately to a depth of a mile or more.

BAGDAD, ARIZONA

Bagdad is located in western-central Arizona. The intensity, inclination, and declination of the earth's magnetic field are 52,900 gammas, 62°, and 15°E., respectively, in this area.

Geological setting.—Here the crystalline rocks crop out (Pl. 8).⁹ The rock is predominantly Precambrian; other portions consist of late Cretaceous (?) to Tertiary (?) intrusives of rhyolite and quartz monzonite and later basalt flows. Anderson states that the complex includes "units of the Yavapai schist, intrusive rhyolite, small areas of gabbro and related rocks, alaskite porphyry, granodiorite gneiss, and small areas of granite."

Magnetic intensity map.—The aeromagnetic intensity map of Bagdad (Pl. 9) is not ideally suited to the model method of interpretation, because the anomalies are only 1 or 2 square miles in area. It will be shown that the anomalies are controlled by local bodies of igneous rocks. These blocks can reasonably extend downward for 1000 feet, which justifies the use of the models in interpretation.

The map has two conspicuous features, a magnetic low centering just west of the town of Bagdad and a series of highs trending N-NE. along the central-western portion of the map. In addition, the intensity map contains a large area just north of the center of the map, which is noteworthy because of the lack of anomalies.

This central flat area is underlain by Precambrian granite, and Anderson (1948)

⁹ The generalized geologic map of Bagdad was generously provided by Charles A. Anderson and the U. S. Geological Survey together with an unpublished preliminary "Summary Statement." The geologic information for the Bagdad area is drawn almost entirely from these sources.

believes that the granite occurs "beneath most of the amphibolites and schists". The granite must have a low content of ferromagnetic minerals, as the intensity over this extensive area is lower than that over the remaining regions on the map, except for the low centering west of Bagdad. The contrast between an extensive area of low magnetic relief and the adjacent magnetically disturbed areas is sometimes of importance in prospecting. The discovery of the Snowshoe granodiorite plug is attributed to such circumstances (Koulomzine and Brossard, 1947).

The magnetic low west of Bagdad is over the mineralized quartz monzonite stock. Of the two other large monzonite stocks, in the central-eastern portion of the map, one has a sharp gradient of magnetic intensity associated with it, and a magnetic high occurs over the second. All of the monzonite stocks crop out in a belt that trends approximately N.70° E., but the mineralized stock is in an area where the belt is transected by a fracture system trending SE. The stock is appreciably fractured and is mineralized by hypogene alteration, according to Anderson. The alteration has apparently destroyed the ferromagnetic minerals in the stock either by removing the iron oxides in solution or by altering them to pyrite and chalcopyrite.

The alteration of magnetite to iron sulfides is not without precedent. Lindgren (1933) in his discussion of the hydrothermal action on the gold-bearing conglomerates of the Witwatersrand district says "black sand was once present in the deposits and 2 to 3 percent does not seem unreasonable. . . . It seems probable that much water, partly or wholly of magmatic origin, certainly containing hydrogen sulfide . . . accompanied . . . igneous outbursts. These waters . . . transformed the iron oxides to sulfide. . . ."

Igneous and metamorphic rocks invariably contain at least a small percentage of magnetite, so the removal of the iron oxides in the mineralized monzonite stock results in a conspicuous negative anomaly. Therefore the areal limits of the anomaly probably delineate the borders of the mineralized area now concealed beneath the adjoining Precambrian rock intruded by the monzonite and lying beneath the basaltic flow north of Bagdad.

The series of magnetic highs and steep gradients in the central-western area of the intensity map are clearly associated with the large gabbroic body of Anderson's map. In his description of the gabbro, Anderson notes a high percentage of disseminated magnetite and large dikes of magnetite. The conformity between the outlines of the gabbro and the area of high anomaly is so consistent that the extension of the gabbro northward under the basalt flows can be estimated from the magnetic intensity map.

The horizontal lengths of six gradients are measured on the flanks of the positive anomalies in the central-western area (Pl. 9 (2-7)). As they are all F indices, they are averaged together and yield an estimated flight level of 1010 feet for an actual value of 1000 feet (Table 7a).

Three other F indices are employed ((1), (8), and (9) on Pl. 9), and the nine gradients give rise to an excellent estimated flight level, 1000 feet.

One G index is measured, north of a long eastward-trending slope ((10) on Pl. 9). The flight level estimated from (10) is 1460 feet. This slope is probably caused by a contact between granite and quartz monzonite (Pl. 8), which is buried beneath a basalt cap, approximately 400 feet thick. The monzonite is exposed beneath the

basalt in the floor of a deep ravine (Pl. 9).¹⁰ As the flight level was not adjusted to these small topographic features, the estimated height should be greater than 1000 feet in this case.

Other possible *G* (and *E*) indices (northwest of gradient (1), for example) are not included because of inadequate flight-line coverage. The lines run east-west and are spaced about every quarter-mile, which is not sufficient to define gradients running north-south and about a quarter of a mile in length.

Curvature map.—A square grid of a quarter of a mile spacing was used to compute the curvature map (Pl. 10). The curvature map, like the intensity map, has a flat zone of no anomalies over the granite area which is surrounded by many small anomalies, the larger of which are again associated with the gabbro.

A zero contour clearly delineates this north-south band of gabbro. The southern portion of this band is erratic and not easily adapted to comparison with the models. A simple positive anomaly (Pl. 10 (1)) is located in the northern portion, and a good flight level, 900 feet, is obtained by using the *B'* index (Table 7b).

A group of anomalies is situated north of (1). They are too small in area for adequate control by the flight-line coverage of a quarter of a mile.

The proposed monzonite-granite contact is located under anomaly (2) which is again approximated by the 8 by 6 model at inclination 60°. The distance between the minimum and maximum is essentially constant and is used to compute the flight level. The value of 1200 feet which is obtained is again excessive, as expected after the discussion of the related intensity anomaly (Pl. 9 (10)).

The anomaly southeast of (2) is too narrow and erratic to warrant a dependable interpretation.

Anomaly (3) of Plate 10 is nicely shaped, but the magnetic data are meager. An excellent estimate of the flight level, 1000 feet, is obtained by use of the *A* index. This anomaly is coincident with an intrusive body of rhyolite included on the geologic map. The apparent relationship may not be real as the rhyolite has no unusual amount of ferromagnetic minerals. It is underlain, however, by a diabase body (C. A. Anderson, personal communication).

Anomaly (4) is undoubtedly related to the band of metavolcanics of the southwestern portion of Plate 8. A good *A* index can be measured, and the resulting estimate of the flight level is 1100 feet. This anomaly is further developed to the northeast and east but is less simple in form and would have to be approximated by an arrangement of several models, a questionable procedure in itself.

Anderson particularly identified this metavolcanic unit of the Precambrian schists. In his Summary Statement, he writes that

"one unit of metavolcanic rocks in the Yavapai schist contains sufficient magnetic minerals to warrant separation on the generalized map. This unit crops out in two bands in the southern half of the area. The rocks were originally andesitic and basaltic lava flows. . . . The lava flows in the eastern belt have recrystallized to massive dark greenish-black amphibolites. . . . Ilmenite is indicated as an original accessory because in some (thin) sections granular sphene is abundant where black opaque minerals are absent. . . . The western belt of metavolcanics is of lower metamorphic grade than the eastern belt".

¹⁰ The topographic map of the Bagdad quadrangle, U. S. Geol. Survey, should be consulted.

This description attributes the higher susceptibility to ilmenite, a ferromagnetic mineral. On both the intensity and curvature maps, however, sizable anomalies exist in the western belt, but only magnetic trends are present over the eastern belt. The greater metamorphism of the eastern belt has destroyed much of the ferromagnetic content.¹¹ Harker (1932, p. 280) describes this type of alteration.

Anomaly (5) on the curvature map provides a good estimate, 1100 feet, of the 1000-foot flight level. The *A* index is used. This anomaly is in an area of undifferentiated Precambrian rock. Anderson differentiated the rocks by sketching a small map for the authors. Quartz diorite, somewhat mafic, underlies the central area of the anomaly, and gabbro, the eastern portion.

The narrow anomaly adjacent to the east side of (5) is too small areally for adequate coverage and lacks a well-developed counterpart on the intensity map.

Similarly, the anomaly in the southeastern corner of Plate 10 is not utilized as the flight lines are widespread in relation to the area of this anomaly.

Determination of susceptibility contrasts.—The following magnetic susceptibility contrasts (*k*) are assigned to the Bagdad area from computations based on the intensity map:

Rock Types	Minimum Susceptibility Contrast
Gabbro vs. granite	.006
Sulfide ore body vs. granite	.003
Quartz monzonite vs. granite	.004
Metavolcanic schists vs. ?	.004

Summary.—The most significant fact from this survey is that the computed altitudes are in most cases close to the actual one. From the geologic map it is reasonable to postulate that the magnetic anomalies used for the computations originated in a band of igneous and metamorphic rocks surrounding a body of homogeneous granite. The granite is indicated by the featureless low area in the middle of the map. Ordinarily, or when the crystalline rocks are buried under 5000 or 10,000 feet of sediments, these magnetic anomalies would lose their individuality, and the map would merely be the product of the contrast between the granite and the more ferromagnetic rocks that surround it.

The small anomalies, however, clearly indicate the several units within the crystalline rocks—the gabbro, granite, quartz monzonite, and metavolcanic schists. It is unlikely that these bodies extend downward to the Curie point geotherm. The fact that they do give the flight level, however, indicates the existence of boundaries between the various rocks that extend downward to depths greater than 1000 feet. The structure of the igneous outcrop is thus roughly prospected in depth, giving a third dimension to the areal geology of igneous exposures.

ALEUTIAN ISLANDS

Northern Adak Island is in the Andreanof Islands, a group in the middle of the chain of Aleutian Islands. Northeastern Umnak Island is in the Fox Islands, the eastern third of the Aleutian Islands.

¹¹ Anderson, in a personal communication, recalled that ilmenite was altered to sphene in the eastern belt

The U. S. Geological Survey in collaboration with the Naval Ordnance Laboratory has a geologic project underway in the Aleutian Islands entitled "Alaskan Volcano Investigations". These investigations are described in Alaskan Volcano Investigation Report No. 2. The Survey has kindly made a copy of this report available

TABLE 7.—*Depths of burial, Bagdad, Arizona*

a. AS ESTIMATED FROM INTENSITY MAP

Gradient	Reference model	Depth index, map/model	Depth of burial (Feet)	Avg. D. B. (Feet)
(1)	4 x 6	F', .23/1.2	1000	1000†
(2)–(7)	6 x 2	F, .21*/1.05	1100	
(8)	6 x 2	F, .19/1.05	1000	
(9)	6 x 2	F, .20/1.05	1000	
(10)	8 x 6	G, .28/1.05‡	1500	

b. AS ESTIMATED FROM CURVATURE MAP

Anomaly	n x m, Suggested block n-azimuth§	Ref. model	Depth index map/model	Depth of burial¶ (Feet)	Avg. D. B. (Feet)
(1)	1.0 x .5 mi., N.10°W.	6 x 2	B', .2/1.2	920	1000
(2)	two-dimensional slope	8 x 6	C + P, .34/1.5	1200	
(3)	.2 x .5, N.45°W.	1 x 6	A, .20/1.05	1000	
(4)	.25 x .2, N.45°W.	2 x 6	A, .22/1.1	1060	
(5)	.3 x .5, N.40°W.	2 x 6	A, .22/1.1	1060	

* Avg. of gradients (2–7).

† Avg. based on gradients (1–9). The "depth of burial" is the flight level in this example.

‡ This value is extrapolated from the curve in Pl. 1.

§ Magnetic.

¶ In this case, the depth of burial is the flight level.

|| (2) value omitted.

to the authors prior to its publication, and all the geologic information of this section is taken from Parts III (Umnak) and V (Adak) of this Report.

NORTHEASTERN UMNAK ISLAND, ALASKA

Umnak Island is in the Fox Islands group, the eastern third of the Aleutian Islands. The intensity, inclination, and declination of the earth's magnetic field are 50,000 gammas, 65°, and 15°E., respectively, in this area.

Geological setting (Byers *et al.*, 1946).—Northeastern Umnak Island is almost covered by lava flows and fragmental deposits of igneous rocks. The few sedimentary rocks represent reworking of the igneous rocks by glacial, stream, and wave action. (Plate 11 illustrates the distribution of lava, fragmental, and sedimentary deposits as generalized from Plate III of Alaska Volcano Investigations Report No. 2.)

The source of most of the rock is Okmok Volcano which now contains Okmok-caldera, a circular depression, $7\frac{1}{2}$ miles in maximum diameter, centered about the point 53° 25.5' N. and 168° 08' W. The rim of the caldera rises to 3000 to 3500 feet, whereas the floor is between 1500 and 2500 feet. Sheer cliffs, 1000 to 1800 feet high, form the inside wall of the rim.

Mount Idak is another important center of volcanism. It is centered about $53^{\circ} 28.5' \text{ N.}$ and $167^{\circ} 54' \text{ W.}$ and attains an altitude of almost 2000 feet.

Mount Tulik ($53^{\circ} 22.5' \text{ N.}$, $168^{\circ} 03.5' \text{ W.}$), the highest peak in the area (4111 feet), is considered a parasitic vent on the southeast flank of Okmok Volcano.

All the lava flows are basalt. No detailed mineralogical analyses are included in the Byers' report, so there is no means to detect lithologic variations that might affect the magnetometer. Evidence is given to support equivalences of time relationships among the major lava flows. Later Idak flows are contemporaneous with the oldest exposed Okmok flows, the Ashishik basalt. The oldest exposed flows of Mount Tulik interfinger with the flows that overlie the Ashishik basalt. Mount Tulik is further characterized by the lack of pyroclastics cropping out on its slopes. The mountain is considered to have been formed of viscous lavas, and the steep sides of the cone are attributed to high viscosity.

The topography of northeastern Umnak has a maximum relief of 4111 feet. The surface slopes gradually upward (200 feet per mile) from the Pacific Ocean and Bering Sea to the flanks of Okmok, Tulik, and Idak. Then the slopes steepen. The slope is 800 feet per mile around Okmok Volcano, 2000 feet per mile at Mount Tulik, and 1200 feet per mile at Mount Idak. Other noteworthy features are the sheer cliffs forming the inner walls of the rims around Okmok caldera and the sea cliffs along the shore line east of Mount Idak. (Plate 12 illustrates also generalized topography.)

Magnetic intensity map.—Plate 11 is the aeromagnetic map of total intensity for northeastern Umnak Island. The aeromagnetic map extends 6 miles farther west than the geologic map prepared by Byers.

Anomaly (1) on Plate 11 lies wholly within Okmok caldera. Anomaly (2) is located on the rim of the caldera. (3) is on a spur extending westward from the rim, and (4) is directly over Mt. Tulik. It may be argued that these conspicuous anomalies are caused by topographic relief and are not analogous to the prismatic models. However, closer examination of the anomalies and the underlying topography reveals that:

1. The large anomaly (1) is located over a depression. The cliffs of the caldera's rim rise 1500 feet above the floor.

2. Anomaly (2) is on the rim, which attains an elevation of 3000 feet directly under the anomaly. However, the rim continues almost completely around the caldera (*see* dotted contours on Pl. 11), but the anomaly is restricted to the northwest portion of the rim. A lithologic contrast also must be developed within this portion of the rim.

3. Anomaly (3) is definitely associated with Mt. Tulik which rises to 4000 feet, or about 2000 feet above its surrounding territory. In addition, Mt. Tulik has steep slopes. The mountain itself could conceivably be the source of anomaly (3) but would be amenable to comparison with a model as its height is almost equal to the level of flight above the mountain peak, 2500 feet.

On the other hand, Mt. Idak (at $53^{\circ} 28'$, $167^{\circ} 54'$) rises to 1800 feet, about 1400 feet above its surroundings. Its peak is almost 5000 feet below the flight level. This peak has no expression on the magnetic intensity map.

4. Anomaly (4) is related to a spur that has more than 1000 feet relief. However, a similar spur, $3\frac{1}{2}$ miles to the southeast, has a slight negative anomaly over it.

There is therefore no direct correlation between these large anomalies and topographic form. This discussion does not affect the interpretational procedure. If Umnak Island were buried under a sedimentary cover so that the topography were unknown, the interpretations would be effected without regard to topography.

Fifteen gradients were measured on Plate 12; 11 of them were on the flanks of the anomalies (1) to (4). Two were on the flanks of anomaly (5). These measurements are not so reliable as the others because anomaly (5) is not well controlled by flight lines. Two additional gradients were measured along the southern portion of the caldera rim.

Several F indices were omitted because they were inadequately controlled by flight lines. For example, the F index on anomaly (2) and the F' index of the "high" east of anomaly (1) were not included.

The average flight level computed from the 15 gradients is 6000 feet, or 500 feet less than the actual level. (See Table 8a and Plate 12.)

Curvature map.—The curvature map (Pl. 11) was computed on a half-mile grid. The computation isolated anomalies (1) to (5) that are on the intensity map, and these anomalies are numbered identically on the curvature map.

Eight depth indices were measured on Plate 11, and they are included on the map and in Table 8b. The flight levels computed from the curvature indices yield an average value of 5500 feet, which is 1000 feet below the actual level.

The intensity indices produced a flight level that was 500 feet too low, and the curvature indices have accentuated that error. The curvature indices are reliable for anomalies (1), (2), and (4). On (3), only B indices are available, and they are very dependent on the size of the reference model. Therefore they demand some knowledge of the flight level beforehand. Anomaly (5) is unreliable because of inadequate control, as was pointed out in discussing Plate 11.

Possibly bottom effects cause the low estimates of flight level. The average estimate based on curvature indices is almost 25 per cent too low, assuming an average ground elevation of 2000 feet. This would suggest that the polarization contrasts extend less than a mile downward.

Determination of susceptibility contrasts.—The caldera anomaly (1) has a susceptibility contrast of .005 when compared to the 4 by 4 model. Anomalies (2–4) have computed contrasts of .01 when compared to their reference models. If the rocks producing contrasts are magnetically similar throughout the area, the block under the caldera must have less depth than the other suggested blocks. This conclusion is not substantiated by the flight-level estimates which are no lower for anomaly (1) than for the other anomalies.

Concluding remarks.—The significant inference resulting from the study of the aeromagnetic maps is that the polarization contrasts terminate within a mile of the surface. These contrasts exist around centers of volcanic activity—Mt. Tulik and Mt. Okmok, for example. The contrasts may be between pyroclastics and volcanic plugs. If so, the pyroclastics must be less than a mile in thickness.

The term "plug" as here used does not mean the narrow, pipelike feed illustrated in many geologic sections through volcanoes. The "plugs" under discussion are large

bodies (see "Suggested blocks", Table 8b) of congealed lava or magma that are surrounded by less ferromagnetic material which may be pyroclastic.

TABLE 8.—*Depth of burial, northeastern Umnak Island*

a. AS ESTIMATED FROM INTENSITY MAP

Anomaly	Ref. model	Depth index map/model	Ground elevation (Feet)	Depth of burial* (Feet)	Avg. D. B. (Feet)
(1)	4 x 4	E, .7/.8 F, .6/.8 F', .6/.8 G, .5/.9	2200 1400 1800 2400	6800 5400 5800 5300	
(2)	1 x 6	G, .6/1.2	2600	5200	
(3)	6 x 1	E, .7/1.2 F, .7/.8 F', .7/.8 G, .8/1.1	2000 2800 2600 2600	5100 7400 7200 6400	
(4)	1 x 6	E, .9/1.1 G, .6/1.0	1400 2800	5700 6000	
(5)	4 x 4	F, .9/.8 G, .9/.9	700 300	6600 5600	
(6)	8 x 6	E, .9/1.4	1800	5000	
(7)	8 x 6	E, .8/1.4	2800	5700	6000

b. AS ESTIMATED FROM CURVATURE MAP

Anomaly	Suggested block $n \times m$ n -azimuth† (Miles)	Ref. model	Depth index map/model	Ground elevation (Feet)	Depth of burial* (Feet)	Avg. D. B. (Feet)
(1)	3 x 2.5, N.14°E.	4 x 4	A, .5/1.05 B, .6/.8	2600 1400	5100 5400	
(2)	1 x 2, N.30°W.	1 x 6	A, .7/1.05	2200	5700	
(3)	2 x 1, N.15°W.	6 x 1	B, .5/.8 B', .6/.8	2600 2600	5900 6600	
(4)	1 x 2, N.5°E.	1 x 6	A, .8/1.05	1400	5400	
(5)	3 x 3, N.15°W.	4 x 4	B, .5/.8 B', .8/.8	1000 500	4300 5800	5500

* The flight level, in this case.

† Magnetic.

NORTHERN ADAK ISLAND, ALASKA

The total intensity, inclination, and declination of the earth's magnetic field are 49,000 gammas, 64°, and 90°E., respectively.

Geological setting.—The island can be roughly divided into two provinces, differing physiographically and geologically, by a line drawn from north shore of Shagak Bay on the west to north shore of Clam Lagoon on the east.

In the area south of this line, the terrain has low relief with the greatest elevations approximately 1000 feet. The rocks of the area are the folded, faulted, and highly altered Mesozoic (?) Finger Bay volcanics. These volcanic rocks are intruded by a mass of gabbro, which is about 2 square miles in area and which extends for 2 miles southeast of Finger Bay.

The area north of the imaginary line is featured by high relief and younger volcanic rocks. The highest elevation is 3876 feet, the peak of Mount Moffet in the northwest portion. Mount Adagdak in the northeast has a maximum elevation of 2115 feet.

These two volcanoes, together with Andrew Bay Volcano, a hypothetical vent that was located west of the present eastern shore of Andrew Bay, are designated as the sources of the volcanic material that have built up the northern province on top of the former terrain.

The Andrew Bay volcanics lie along the western shore of the Adagdak peninsula. They consist of olivine-, hypersthene-, and hornblende-bearing basalts in the form of flows and tuff breccias. Magnetite is mentioned as a mineral in the groundmass of some of the breccia and as an accessory mineral of other breccia.

The Andrew Bay Volcano was destroyed before the advent of Adagdak activity. The oldest volcanic rocks of Mt. Adagdak lie against a cliff cut into the Andrew Bay volcanics. The first Adagdak rocks built up a shield volcano of which only the southern half remains. The rocks of the Adagdak shield volcano probably exceed 1000 feet in thickness. Two later composite cones built up Mount Adagdak at least to its present elevation of 2115 feet. All the flows, tuffs, and breccia contain magnetite in their groundmass; and the youngest rocks have magnetite as a common accessory mineral.

The large northwestern area of Northern Adak Island is Mt. Moffet. Mt. Moffet is a large composite cone centering about its peak of 3876 feet altitude. A large parasitic cone on the northeastern flank of Mt. Moffet reaches an altitude of 3250 feet. Both the parent and the parasitic cone are composed of basaltic flows and tuff-breccia with the breccia subordinate in the parasitic cone. In these rocks, magnetite is again mentioned as a constituent of the groundmass as well as an accessory mineral.

Magnetic intensity map.—Plate 13 is a copy of the aeromagnetic intensity map of Northern Adak Island prepared by the U. S. Geological Survey in co-operation with the Office of Naval Research. This map extends farther south than the area covered by the geologic survey of Northern Adak Island. The magnetic intensity anomalies in general follow the outline of the land. Four positive anomalies are obvious. The northern two are located just south of the peaks of Mt. Moffet's parasitic cone and of Mt. Adagdak. The parasitic cone's anomaly is too small areally for the flight-line coverage. The anomaly over Mt. Adagdak ((3), Pl. 13), on the other hand, is broad and is associated with the entire peninsula. The two southern anomalies ((1) and (2), Pl. 13) are outside the geologic map but appear to lie over topographically low areas.

The horizontal lengths of four of the steep gradients were measured (Pl. 13; Table 9a). The computed average flight level is identical with the actual level. However, three of the four values are approximately 4600 feet, and only the presence of the long gradient (G of (2)) produces the excellent average value.

Only one F index was used. These east-west indices are not sufficiently crossed by the north-south flight lines.

The E indices are weakly developed, as they are on the model charts, and erratic. As previously mentioned, E indices are very dependent on model size and are very long for the larger models.

Curvature map.—Plate 14 is the curvature map of the magnetic intensity of Northern Adak Island computed on a half-mile grid. This map delineates sharply

the four anomalies that appear on the intensity map. It resolves the Finger Bay anomaly into two parts.

Table 9b summarizes the data concerning the suggested blocks that might cause the three prominent anomalies, and the estimated flight levels.

TABLE 9.—*Depth of burial, Northern Adak Island, Alaska*

a. AS ESTIMATED FROM INTENSITY MAP

Anomaly	Ref. model	Depth index map/model	Ground elevation (Feet)	Depth of burial† (Feet)	Avg. D. B. (Feet)
(1)	6 x 1	F, .7/.8	0	4600	5000
	2 x 6	G, .9/1.05	0	4500	
(2)	2 x 2	G, 1.2/.95	0	6400	
(3)	2 x 6	G, .8/1.05	700	4700	

b. AS ESTIMATED FROM CURVATURE MAP

Anomaly	Suggested block $n \times m$, n azimuth* (Miles)	Ref. model	Depth index, map/model	Ground elevation (Feet)	Depth of burial† (Feet)	Avg. D. B. Feet
(1)	2.5 x 1.2, N.9°W. & 1.5 x ?, N.9°W.	6 x 1	B, .9/.85	0	5600	
		2 x 6	A, 1.25/1.1	0	6000	
(2)	2.2 x 2.5, N.30°W.	2 x 2	B', 1.5/1.3	0	6100	
			C, .6/.6	0	5300	
			P, 1.1/1.3	0	4500	
(3)	1.8 x 3, N.20°E.	2 x 6	A, 1.25/1.1	700	6700	5700

* Magnetic.

† The flight level, in this case.

Six estimates are given, ranging from 4500 feet to 6700 feet with an average of 5700 feet. The actual level is 5000 feet. The excessive values may be the result of the presence of less steep slopes than the vertical sides assumed for the prismatic models.

Anomaly (3) probably suffers from this effect. The curvature index is measured over the southern flank of Mt. Adagdak which rises to 2115 feet. Furthermore, this anomaly has inadequate flight-line control.

The *B* index for anomaly (1) is compared to a 6 by 1 model, and this selection presupposes a knowledge of the depth of burial. As for anomaly (2), its *A* index is too erratic to be utilized, and the three indices used (*B'*, *C*, *P*) are very dependent on the size of the selected model.

Determination of susceptibility contrasts.—A contrast of .006 is computed for the three Adak intensity anomalies by comparing them to the magnetic fields of their reference models.

Concluding remarks.—The Adak anomalies are not suitable for comparison with the model charts, but they represent conditions over a volcanic terrain and therefore merit inclusion. Satisfactory estimates of the flight level are obtained, however, by judicious choice of anomalies and depth indices.

The estimates of the flight level are obtained from the intensity map by selecting

anomalies of large area having adequate flight-line control and by using only the steepest gradients. The average of these estimates, 5000 feet, agrees perfectly with the actual flight level only because of the presence of the large value of 6400 feet. The three other values yield an average of 4600 feet which, similar to the findings at Umnak, is somewhat low.

The average of the flight levels based on the curvature map is too high, on the other hand. This is mainly caused by the two values obtained with the *A* index. Inspection of the intensity map reveals that the *A* index was in each case measured in an area of not the steepest gradients.

CHAPTER IV. CALCULATION OF TOTAL MAGNETIC INTENSITY ANOMALIES DUE TO IDEALIZED BODIES

BY V. VACQUIER

I. COMPUTATION OF ANOMALIES DUE TO VARIABLE POLARIZATION OF A FLAT BASEMENT

Magnetic anomalies of geologic origin are usually due to extended bodies that cannot be represented by isolated poles or linear arrays of poles and dipoles. In this book, the idealized bodies for which anomalous total magnetic intensity is computed are prisms of infinite length with vertical sides. The upper surface of the prisms is horizontal, and the total magnetic intensity is computed on a horizontal plane above it. The polarization of the prism is uniform and is directed along the earth's magnetic field. Because the polarization is constant with depth, one can express the anomalous magnetic intensity as a surface integral of the product of two functions of position, the polarization $I(\alpha, \beta)$ which is assigned, and an irrational algebraic function $U(\alpha, \beta, \delta)$ (Tables 11-26). The total magnetic intensity due to the prism can be written:

$$\Delta T = \iint I(\alpha, \beta) U(\alpha, \beta, \delta) d\alpha d\beta, \quad (1)$$

where α and β are respectively the north and east co-ordinates on a plane containing the upper surface of the prism, and δ the complement of the dip angle which is assumed constant over the area of any one map. The magnetic intensity ΔT is computed at a height $h = 1$ immediately above the origin $\alpha = \beta = 0$. The co-ordinates α and β are measured in terms of the depth of burial h which is taken as unity.

The integral can be evaluated approximately as a finite sum by dividing the α, β plane into small squares, estimating the average values of the functions I and U for each square and summing up the individual products:

$$\Delta T \cong \Sigma \Sigma \bar{I}(\alpha, \beta) \bar{U}(\alpha, \beta, \delta). \quad (2)$$

On Figure 6, the function $U(\alpha, \beta, \delta)$ is contoured on a square grid. The contours are shown dashed, and the grid is shown light. Average values of the U function for each square are inserted. The grid so constructed can be traced on a transparent template and placed on a plot of the polarization function $I(\alpha, \beta)$ shown in heavy contours. The map of the polarization is divided into squares of the same size as the squares on the template. They are drawn heavy in Figure 6. An average value for the polarization can be assigned each square. To compute the total magnetic intensity on a plane a unit distance above the surface of the polarization map, the template is oriented so that the α axis points north on the polarization map; then, having matched the squares, the products of $\bar{I}$ and $\bar{U}$ for each square are computed and added. To compute the magnetic intensity at the next grid corner the template is moved and the procedure repeated.

To compute the magnetic intensity for a prism of finite length, the computation can be carried out for two prisms of infinite length and same cross section buried at

two different depths. As the grids are laid out in terms of the depth of burial, the grid spacing will differ for the two computations.

The process illustrated in Figure 6 is greatly simplified if the polarization of the prism is uniform, and if the prism has a rectangular cross section made up of an in-

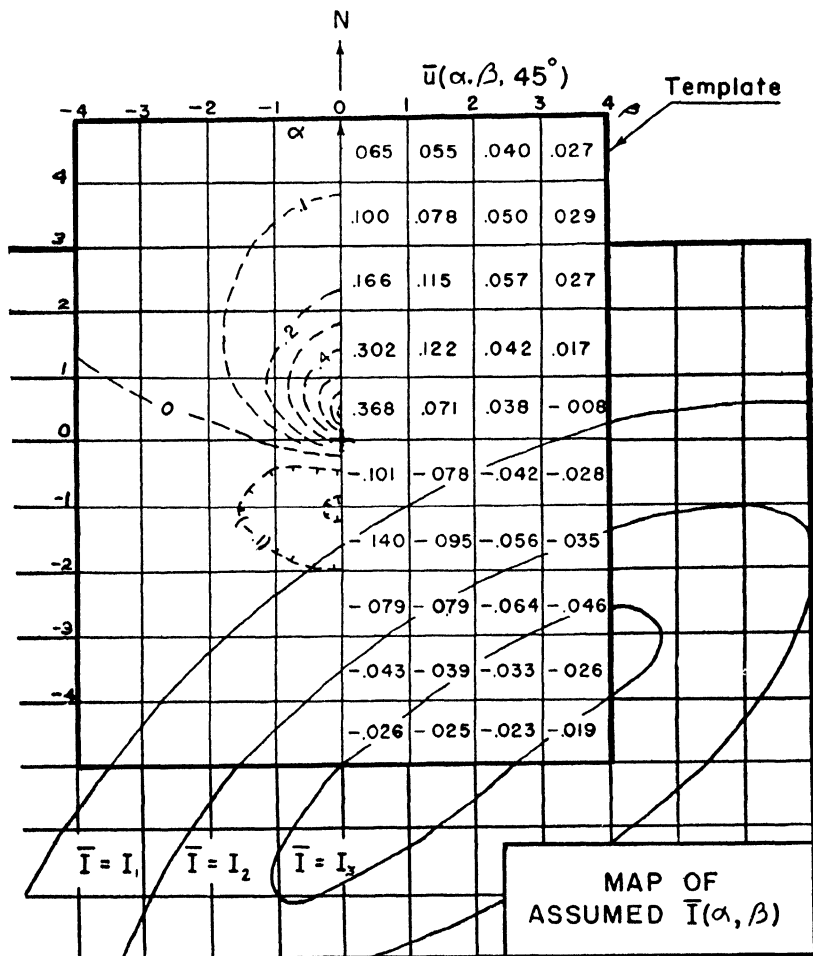


FIGURE 6.—Method for approximate calculation of total magnetic intensity

tegral number of grid squares. A mask with a rectangular hole of dimensions corresponding to the cross-sectional area of the prism is laid over the grid of the $\bar{U}$ function, and the values of the $\bar{U}$ contributions of all the squares are added. To compute the intensity at the next point, the mask is moved one square. One row of squares is thus added, and the subtotal of one row is subtracted from the previous sum. This calculation is rapid once the $\bar{U}$ function has been charted.

When the sides of the prism are at an angle with respect to magnetic north, a new U function grid has to be constructed that will strike in the same direction as the prism.

In this manner magnetic intensity shown on the right-hand side of Figures A1 to A83 has been computed. Tabular values of $\bar{U}(\alpha, \beta, \delta)$ are given in Tables 11 to 26.

The derivation of the explicit expression for the surface integral giving the total anomalous magnetic intensity will now be given.

It is required to compute the total magnetic intensity at a height h above the surface of the basement complex, the upper surface of which is a horizontal plane. The magnitude of the polarization may vary with the horizontal co-ordinates but is constant in direction with depth. The bottom of the magnetic rocks is at infinity. The polarization vector is assumed to be directed along the earth's total magnetic intensity. The latter is assumed to be a vector quantity, the direction of which is invariant over the area of the map. This is admissible because the anomalous field is very small, generally less than one-hundredth of the earth's field. The anomalous magnetic intensity measured by the airborne magnetometer is taken as the sum of the projections of the north and vertical components of the actual anomalous magnetic intensity on the direction of the total magnetic intensity. The east (y) component of the magnetic intensity is zero, since the α axis is directed north.

Let α, β, γ be the co-ordinates of the volume element $d\alpha d\beta d\gamma$ the polarization of which is $I(\alpha, \beta)$. The magnetic potential at a point (x, y, z) is

$$\Delta V(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_h^{\infty} I \frac{\partial}{\partial s} \left(\frac{1}{r} \right) d\alpha d\beta d\gamma, \quad (3)$$

where

$$I \frac{\partial}{\partial s} = I_{\alpha} \frac{\partial}{\partial \alpha} + I_{\gamma} \frac{\partial}{\partial \gamma} = I \left[\sin \delta \frac{\partial}{\partial \alpha} + \cos \delta \frac{\partial}{\partial \gamma} \right], \quad (4)$$

and

$$r^2 = (\alpha - x)^2 + (\beta - y)^2 + (\gamma - z)^2. \quad (5)$$

The quantity, δ is the complement of the magnetic dip, x is directed north, and z is positive downward. The north and the vertical magnetic intensities are

$$\left. \begin{aligned} \Delta X &= - \frac{\partial \Delta V}{\partial x} \\ \Delta Z &= - \frac{\partial \Delta V}{\partial z} \end{aligned} \right\} \quad (6)$$

Differentiation under the integral sign of (3) gives:

$$\Delta X = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_h^{\infty} I(\alpha, \beta) \left[\sin \delta \frac{\partial^2}{\partial \alpha^2} \left(\frac{1}{r} \right) + \cos \delta \frac{\partial^2}{\partial \alpha \partial \gamma} \left(\frac{1}{r} \right) \right] d\alpha d\beta d\gamma \quad (7)$$

$$\Delta Z = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_h^{\infty} I(\alpha, \beta) \left[\sin \delta \frac{\partial^2}{\partial \alpha \partial \gamma} \left(\frac{1}{r} \right) + \cos \delta \frac{\partial^2}{\partial \gamma^2} \left(\frac{1}{r} \right) \right] d\alpha d\beta d\gamma, \quad (8)$$

since

$$\frac{\partial \left(\frac{1}{r} \right)}{\partial x} = - \frac{\partial \left(\frac{1}{r} \right)}{\partial \alpha}, \quad \text{and} \quad \frac{\partial \left(\frac{1}{r} \right)}{\partial z} = - \frac{\partial \left(\frac{1}{r} \right)}{\partial \gamma}.$$

As previously mentioned, the airborne magnetometer measures

$$\Delta T = \Delta X \sin \delta + \Delta Z \cos \delta. \quad (9)$$

Using (7) and (8) and reducing, we obtain

$$\Delta T = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_h^{\infty} I(\alpha, \beta) \left[\sin \delta \frac{\partial}{\partial \alpha} + \cos \delta \frac{\partial}{\partial \gamma} \right]^2 \left(\frac{1}{r} \right) d\alpha d\beta d\gamma. \quad (10)$$

Since I is independent of γ , (10) can be transformed into a surface integral by integration with respect to γ . When this is done, the magnetic intensity at the origin $x = y = z = 0$ becomes

$$\begin{aligned} \Delta T(0, 0, 0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(\alpha, \beta) \left\{ \frac{\sin^2 \delta}{\alpha^2 + \beta^2} \left[-\frac{\alpha^2 h}{R^3} + \frac{2\alpha^2}{\alpha^2 + \beta^2} - \frac{2\alpha^2 h}{(\alpha^2 + \beta^2)R} + \frac{h}{R} - 1 \right] \right. \\ \left. + \frac{2\alpha \sin \delta \cos \delta}{R^3} + \frac{h \cos^2 \delta}{R^3} \right\} d\alpha d\beta, \end{aligned} \quad (11)$$

where

$$R^2 = \alpha^2 + \beta^2 + h^2.$$

When $I = \text{constant}$ and α and β are measured in terms of h ,

$$\Delta T = \pi I (2 \cos^2 \delta - \sin^2 \delta). \quad (12)$$

Equation (11) can be reduced to more convenient form by measuring α and β in terms of the depth of burial h . Doing this and setting $\rho^2 = \alpha^2 + \beta^2$ (11) becomes:

$$\Delta T = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(\alpha, \beta) \left\{ \left[\left(\frac{1}{R} - 1 \right) \left(1 - \frac{2\alpha^2}{\rho^2} \right) - \frac{\alpha^2}{R^3} \right] \frac{\sin^2 \delta}{\rho^2} + \frac{2\alpha \sin \delta \cos \delta}{R^3} + \frac{\cos^2 \delta}{R^3} \right\} d\alpha d\beta. \quad (13)$$

From the values of the algebraic terms listed in Table 10, $U(\alpha, \beta, \delta)$ can be computed for any magnetic latitude.

Tables 11–26 give values of $U(\alpha, \beta, \delta)$ for various specific values of δ .

II. COMPUTATION OF ANOMALIES DUE TO STRUCTURES OF SMALL RELIEF, CONSTANT POLARIZATION

The total magnetic intensity is to be computed on a horizontal plane at a height h_0 above the basement surface. The latter departs from the depth h by $\iota(\alpha, \beta)$ which represents undulations of the basement surface. It will be assumed that $\iota(\alpha, \beta)$ is small with respect to h_0 so that terms in ι of higher power than the first can be neglected. The polarization is constant and is directed along the earth's total field.

Equation (11) is a good starting point. Write it twice, once for

$$h = h_0 - \iota(\alpha, \beta)$$

$$R^2 = \alpha^2 + \beta^2 + [h_0 - \iota(\alpha, \beta)]^2$$

and once for

$$h = h_0 + \iota(\alpha, \beta)$$

$$R^2 = \alpha^2 + \beta^2 + [h_0 + \iota(\alpha, \beta)]^2.$$

The difference is the quantity we are after. Only the terms in which h or R occur are significant, so it is convenient to rewrite (11) thus:

$$\Delta T(0, 0, 0) = I \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{h}{R^3} \left(c - \frac{a\alpha^2}{\rho^2} \right) + \frac{ha}{R\rho^2} \left(1 - \frac{2\alpha^2}{\rho^2} \right) + \frac{2\alpha b}{R^3} + \left(\frac{2\alpha^2}{\rho^3} - 1 \right) \frac{a}{\rho^2} \right\} d\alpha d\beta, \quad (14)$$

where

$$\begin{aligned} a &= \sin^2 \delta \\ b &= \sin \delta \cos \delta \\ c &= \cos^2 \delta \\ \rho^2 &= \alpha^2 + \beta^2 \\ R^2 &= \rho^2 + h^2. \end{aligned}$$

Taking the difference for the two depths $h_0 - t(\alpha, \beta)$ and $h_0 + t(\alpha, \beta)$,

$$\begin{aligned} \Delta T(0, 0, 0) = I \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} & \left\{ \left(c - \frac{a\alpha^2}{\rho^2} \right) \left(\frac{h_0 - t}{[\rho^2 + (h_0 - t)^2]^{3/2}} - \frac{h_0 + t}{[\rho^2 + (h_0 + t)^2]^{3/2}} \right) \right. \\ & + \frac{a}{\rho^2} \left(1 - \frac{2\alpha^2}{\rho^2} \right) \left(\frac{h_0 - t}{[\rho^2 + (h_0 - t)^2]^{1/2}} - \frac{h_0 + t}{[\rho^2 + (h_0 + t)^2]^{1/2}} \right) \\ & \left. + 2\alpha b \left(\frac{1}{[\rho^2 + (h_0 - t)^2]^{3/2}} - \frac{1}{[\rho^2 + (h_0 + t)^2]^{3/2}} \right) \right\} d\alpha d\beta. \end{aligned} \quad (15)$$

Neglecting terms in t^2 and higher,

$$\rho^2 + (h_0 - t)^2 = R^2 - 2h_0 t$$

and

$$\rho^2 + (h_0 + t)^2 = R^2 + 2h_0 t.$$

Expanding the denominators in the integrand of (15) in powers of $\frac{2h_0 t}{R^2}$ and collecting terms one obtains

$$\begin{aligned} \Delta T = 2I \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} & \left\{ \frac{\sin^2 \delta}{R\rho^2} \left[\frac{\alpha^2}{R^2} \left(1 - \frac{3h^2}{R^2} \right) - \left(1 - \frac{2\alpha^2}{\rho^2} \right) \left(1 - \frac{h^2}{R^2} \right) \right] \right. \\ & \left. - \frac{\cos^2 \delta}{R^3} \left(1 - \frac{3h^2}{R^2} \right) + \frac{6\alpha h}{R^6} \sin \delta \cos \delta \right\} t(\alpha, \beta) d\alpha d\beta. \end{aligned} \quad (16)$$

In this expression the subscript is dropped from h_0 for the sake of brevity.

When α and β are measured in terms of the depth of burial h , (16) is not simplified much; to wit:

$$\begin{aligned} \Delta T(0, 0, 0) = 2I \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} & \left\{ \frac{\sin^2 \delta}{R\rho^2} \left[\frac{\alpha^2}{R^2} \left(1 - \frac{3}{R^2} \right) - \left(1 - \frac{2\alpha^2}{\rho^2} \right) \left(1 - \frac{1}{R^2} \right) \right] \right. \\ & \left. - \frac{\cos^2 \delta}{R^3} \left(1 - \frac{3}{R^2} \right) + \frac{6\alpha}{R^6} \sin \delta \cos \delta \right\} t(\alpha, \beta) d\alpha d\beta. \end{aligned} \quad (17)$$

This integral can be evaluated in the same manner as the one in Equation (13) for computing the total magnetic intensity over assumed geologic structures of arbitrary shape.

Equation (17) permits the evaluation of the magnetic effect of a thin magnetic plate of strength Ih . It is likely that the depth indices discussed in Chapter III will be different for the thin plate, and that anomalies due to thin bodies will give shallower answers for the maximum depth, when the interpretation is made on the basis of infinitely long prisms. To investigate this question one could construct a series of model anomalies from Equation (17). This may constitute a subject for future investigation.

CHAPTER V. TABLES AND CHARTS FOR COMPUTATION OF MAGNETIC EFFECTS

BY V. VACQUIER, N. C. STEENLAND, ROLAND G. HENDERSON, AND ISIDORE ZIETZ

The function $U(\alpha, \beta, \delta)$ derived in Chapter IV forms the basis of the calculation of the total magnetic intensity due to polarization contrasts in a horizontal basement complex. This function is given in Equation (13). It is

$$U(\alpha, \beta, \delta) = \left\{ \left(\frac{1}{R} - 1 \right) \left(1 - \frac{2\alpha^2}{\rho^2} \right) - \frac{\alpha^2}{R^3} \right\} \frac{a}{\rho^2} + \frac{2\alpha b}{R^3} + \frac{c}{R^3},$$

where

$$\begin{aligned} a &= \sin^2 \delta & R^2 &= \alpha^2 + \beta^2 + 1 \\ b &= \cos \delta \sin \delta & \rho^2 &= \alpha^2 + \beta^2. \\ c &= \cos^2 \delta \end{aligned}$$

The quantity δ is the complement of the magnetic dip angle; α and β are measured in depths of burial.

The quantities

$$\begin{aligned} A &= \{ (1/R - 1)(1 - 2\alpha^2/\rho^2) - \alpha^2/R^3 \} 1/\rho^2 \\ B &= 2\alpha/R^3 \\ C &= 1/R^3 \end{aligned}$$

are tabulated for discrete values of α and β in Table 10. By means of Table 10 tables of the U functions can be calculated for specific values of δ .

This procedure was carried out for $\lambda = 0^\circ, 20^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$ where $\lambda = 90^\circ - \delta$. Tables 11 to 26 give the U function for these magnetic latitudes.

Tables 11 to 19 give average values of the U function for squares one-half depth of burial on the side, for the above-mentioned magnetic latitudes except for latitude 45° , in which case squares 1 depth of burial on the side are given. These values were obtained by contouring U as given in Tables 20 to 26. The values for the squares near the origin were calculated by adding the contributions of the areas between contours as measured by a planimeter.

Tables 11 to 19 have been used for computing the total magnetic intensity produced by the infinitely long rectangular prisms of Figures A1-A83. The magnetic intensity is contoured on the right side of the figures. The polarization contrast was taken as unity. The computed magnetic intensity is in oersteds. The magnetic effect of other shapes consisting of an integral number of squares can be computed by cutting out the appropriate template and superposing it on the table.

A few calculations were made for prisms striking at an angle to the magnetic meridian. The average values of U for squares of grids inclined to the magnetic meridian are given in Tables 18 and 19.

The curvature or the second vertical derivative of the total magnetic intensity is contoured on the left side of Figures A1 to A83 except for the skewed models. Because of the asymmetry associated with the skewed models, the curvature for these models is given on separate plates. The curvature for all models is computed by the method described in Section 4 of Chapter III. The unit of curvature is $\frac{1}{4}$ oersted per depth of burial squared.

TABLE 11.—Average values of $U \times 10^3$, Inclination 0° , for squares of one-half depth of burial on the sideThe α and β values are the co-ordinates of the centers of squares.

$\alpha \backslash \beta$	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	5.25	5.75	6.25
0.25	-100	-79	-56	-39	-29	-22	-16	-13	-10	-9	-7	-6	-6
0.75	-75	-41	-36	-29	-23	-18	-15	-12	-10	-8	-7	-6	-5
1.25	-4	-10	-15	-17	-16	-14	-12	-10	-8	-7	-6	-6	-5
1.75	8	4	-4	-7	-8	-9	-8	-8	-7	-6	-6	-5	-4
2.25	11	8	3	-1	-4	-5	-6	-6	-5	-5	-4	-4	-4
2.75	11	9	6	2	0	-2	-3	-4	-4	-4	-4	-4	-3
3.25	10	8	6	2	2	0	-1	-2	-2	-3	-3	-3	-3
3.75	9	8	6	4	3	1	0	-1	-2	-2	-2	-2	-2
4.25	8	7	6	4	3	2	1	0	0	-1	-1	-2	-2
4.75	6	6	5	4	3	2	1	1	0	0	-1	-1	-1
5.25	6	6	5	4	3	2	2	1	0	0	0	0	-1
5.75	5	5	4	4	3	2	2	1	1	0	0	0	0
6.25	4	4	4	4	3	2	2	2	1	0	0	0	0
6.75	4	4	4	3	3	2	2	2	1	1	0	0	0
7.25	4	3	3	3	2	2	2	2	1	1	1	0	0
7.75	3	3	3	2	2	2	2	2	1	1	1	0	0
8.25	3	3	2	2	2	2	2	2	1	1	1	0	0
8.75	2	2	2	2	2	2	2	2	1	1	1	0	0
9.25	2	2	2	2	2	2	2	2	1	1	1	0	0
9.75	2	2	2	2	2	2	2	1	1	1	1	0	0

$\alpha \backslash \beta$	6.75	7.25	7.75	8.25	8.75	9.25	9.75
0.25	-5	-4	-4	-3	-3	-3	-2
0.75	-4	-4	-4	-3	-3	-3	-2
1.25	-4	-4	-3	-3	-3	-2	-2
1.75	-4	-4	-3	-3	-2	-2	-2
2.25	-4	-3	-3	-2	-2	-2	-2
2.75	-3	-3	-2	-2	-2	-2	-2
3.25	-2	-2	-2	-2	-2	-2	-2
3.75	-2	-2	-2	-2	-2	-2	-2
4.25	-2	-2	-2	-2	-2	-2	-1
4.75	-1	-1	-1	-1	-1	-1	-1
5.25	-1	-1	-1	-1	-1	-1	-1
5.75	-1	-1	-1	-1	-1	-1	-1
6.25	0	0	0	-1	-1	-1	-1

(Remaining values are 0)

TABLE 14.—Average values of $U \times 10^3$, inclination 45° , for squares one depth of burial on the side
 The α and β values are the co-ordinates of the centers of the squares.

$\alpha \backslash \beta$	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
11.5	11	11	10	9	8	7	6	6	5	4
10.5	14	13	12	11	9	8	7	6	5	4
9.5	15	15	14	12	10	9	8	7	6	4
8.5	19	18	16	14	12	10	8	7	5	4
7.5	25	24	20	16	14	11	8	6	5	3
6.5	33	31	25	20	16	12	9	6	4	3
5.5	46	38	32	24	17	12	8	6	4	2
4.5	65	55	40	27	16	11	7	4	3	1
3.5	100	78	50	29	16	9	5	2	1	0
2.5	166	115	57	27	12	5	2	0	-1	-1
1.5	302	144	42	17	5	-1	-2	-2	-2	-3
0.5	368	71	33	-8	-9	-7	-6	-5	-4	-4
-0.5	-101	-78	-42	-28	-19	-13	-10	-7	-6	-5
-1.5	-140	-95	-56	-35	-24	-16	-12	-9	-7	-5
-2.5	-79	-64	-46	-33	-23	-16	-10	-9	-7	-6
-3.5	-43	-39	-33	-26	-20	-15	-12	-9	-8	-6
-4.5	-26	-25	-23	-19	-14	-13	-11	-9	-7	-6
-5.5	-18	-17	-16	-14	-12	-11	-9	-8	-7	-5
-6.5	-12	-12	-11	-11	-11	-9	-8	-7	-6	-5
-7.5	-9	-9	-9	-8	-8	-8	-7	-6	-5	-4
-8.5	-7	-7	-7	-6	-7	-6	-6	-5	-4	-3
-9.5	-6	-6	-5	-5	-5	-5	-4	-4	-3	-3
-10.5	-5	-5	-5	-4	-4	-4	-4	-3	-3	-3

TABLE 17.—Average values of $U \times 10^3$, inclination 90° The α and β values are the co-ordinates of the centers of the squares.

For squares of one-half depth of burial on a side

$\pm\alpha \backslash \pm\beta$	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25
3.75	0	1	0	1	0	0	0	0	0
3.25	1	0	1	0	1	0	1	0	1
2.75	0	1	0	1	0	1	0	1	0
2.25	1	0	1	0	1	0	1	0	1
1.75	1	1	1	0	1	0	0	1	0
1.25	1	1	1	1	1	1	1	0	1
0.75	1	1	1	1	1	1	1	1	1
0.25	2	2	2	1	1	1	1	1	1
4.75	2	2	2	2	2	1	1	1	1
4.25	3	3	3	2	2	2	2	1	1
3.75	5	4	4	3	3	2	2	1	1
3.25	7	6	6	5	4	3	3	2	2
2.75	11	10	9	8	5	5	3	2	2
2.25	17	14	12	9	7	5	4	3	2
1.75	37	26	19	13	9	8	5	3	2
1.25	60	46	31	19	12	9	6	4	3
0.75	120	82	46	26	14	10	6	4	3
0.25	197	120	60	31	17	11	7	5	3

$\pm\alpha \backslash \pm\beta$	4.75	5.25	5.75	6.25	6.75	7.25	7.75	8.25	8.75
8.75	0	0	0	0	0	0	0	0	0
8.25	0	1	0	1	0	1	0	1	0
7.75	1	0	0	0	0	0	0	0	0
7.25	0	1	0	1	0	1	0	1	0
6.75	1	0	1	0	0	0	0	0	0
6.25	0	1	0	1	0	1	0	1	0
5.75	0	0	1	0	1	0	0	0	0
5.25	1	1	0	1	0	1	0	1	0
4.75	1	1	0	0	1	0	1	0	0
4.25	1	1	1	1	0	1	0	1	0
3.75	1	1	1	0	1	0	1	0	0
3.25	1	1	1	1	0	1	0	1	0
2.75	1	1	1	1	0	0	1	0	0
2.25	2	1	1	1	1	1	0	1	0
1.75	2	1	1	1	0	0	1	0	1
1.25	2	2	1	1	1	1	0	1	0
0.75	2	2	1	1	1	0	1	0	1
0.25	2	2	1	1	1	1	0	1	0

For squares of one depth of burial on a side

$\pm\alpha \backslash \pm\beta$	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
11.5	1	1	1	1	1	0	0	0	0	0	0	0
10.5	1	1	1	1	1	1	1	0	0	0	0	0
9.5	1	1	1	1	1	1	1	1	1	0	0	0
8.5	2	2	1	1	1	1	1	1	1	0	0	0
7.5	2	2	2	2	2	1	1	1	1	1	0	0
6.5	4	3	3	2	2	2	1	1	1	1	0	0
5.5	6	5	4	4	3	2	2	1	1	1	1	0
4.5	10	9	7	5	4	3	2	2	1	1	1	1
3.5	22	18	12	8	5	4	2	2	1	1	1	1
2.5	52	38	22	12	7	4	3	2	1	1	1	1
1.5	163	92	38	18	9	5	3	2	2	1	1	1
0.5	520	163	52	22	10	6	4	2	2	1	1	1

TABLE 22.— $U \times 10^4$, Inclination 30°

$\alpha \backslash \beta$	0.00	0.25	0.50	0.75	1.00	1.25
1.25	3222	3069	2664	2025		1143
1.00	3490	3276	2729	2056	1426	
0.75	3432	3154	2471	1693		597
0.50	2689	2382	1676	940	379	
0.25	1000	767	276	-181		-602
0.00		-1306	-1379	-1387	-1298	
-0.25	-2954	-2862	-2605	-2271		-1620
-0.50	-3508	-3378	-3034	-2608	-2187	
-0.75	-3218	-3115	-2852	-2500		-1804
-1.00	-2638	-2571	-2403	-2167	-1708	
-1.25	-2057	-2022	-1926	-1784		-1440

$\alpha \backslash \beta$	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	10.0
10.0					136							76			30
8.0	226				199				140			83		47	
7.0			277				203				119		59		
6.0	383				309				176			81		32	8
5.0	530		490		393				186			115	68	38	18
4.5	637	622	582	516	437	368	299	237	161		105	57	27	10	-16
4.0	777		691		500		311	177				42		5	
3.5	969	937	834	700	557	424	314	235	176	108		24	-6	-12	-21
3.0	1232		1014		608	420	314		126			-1	-16	-25	
2.5	1680	1501	1234	917	632	411	255	149	80	34	5	-25	-39	-39	-35
2.0	2138	1938	1472	980	595		172		15			-55	-52	-52	-42
1.5	2848	2452	1633	910	944	181									
1.0	3490	2729	1426	555	124	-61	-134		-157		-138		-94		
0.5	2689	1676	379	-189	-347	-358	-325								
0.0		-1379	-1298	-1058	-813	-627	-491		-319			-163		-98	
-0.5	-3508	-3054	-2187	-1512	-1066	-779	-589								
-1.0	-2633	-2403	-1708	-1424	-1053	-792	-608		-384		-262		-142		
-1.5	-1588	-1515	-1335	-1104	-867	-706									
-2.0	-959	-940	-883	-793	-587		-489		-345			-196		-110	-74
-2.5	-610			-562	-516	-462	-406	-354	-307	-267	-231	-178	-140	-110	-74
-3.0	-410		-409		-355		-347		-264		-210	-165	-132	-107	
-3.5	-288	-285	-293	-294	-239		-264	-255		-205	-176	-152	-124		-73
-4.0	-211				-220		-211		-189			-137			-93
-4.5	-159	-161	-161	-163	-180	-173	-170	-165	-162	-151	-141	-123	-106	-90	
-5.0	-123		-127		-134		-137		-132		-122	-109	-96	-83	
-6.0	-79				-87				-94			-85		-70	-57
-7.0			-56				-65				-68		-62		
-8.0		-39			-43			-49				-54		-47	
-10.0					-25							-32			-31

TABLE 23.— $U \times 10^3$, inclination 45°

$\alpha \backslash \beta$	0	1	2	3	4	5	6	7	8	9	10
10	15	13	13	12	11	9	8	7	6	5	4
9	18	16	16	14	12	10	9	8	6	5	3
8	22	21	20	16	14	11	9	8	6	4	3
7	27	28	25	21	16	13	10	7	5	3	2
6	38	36	31	25	19	14	10	7	5	3	2
5	55	50	40	31	21	14	10	6	4	3	
4	81	75	54	36	22	12	8	5	2	1	
3	133	112	71	41	20	10	5	2	1		
2		179	83	34	13	4	1	0	-1	-2	-2
1				12	-3	-4	-4	-4	-3	-3	
0				-22	-17	-12	-9	-7	-6	-5	
-1		-144	-76	-43	-29	-18	-14	-10	-7	-6	
-2	-110	-94	-65	-42	-28	-20	-14	-11	-8	-6	-5
-3	-57	-53	-44	-35	-25	-18	-14	-11	-9	-7	
-4	-33	-30	-29	-24	-20		-13	-10	-8	-7	
-5	-22	-21	-20	-18		-13	-11	-9	-8	-6	
-6	-15		-14		-13		-9	-8	-7	-6	-5
-7		-11		-10		-9		-7	-6	-5	
-8	-8		-8		-7		-6		-5		
-9											
-10			-5				-4				-3

TABLE 25.— $U \times 10^4$, Inclination 75°

$\alpha \backslash \beta$	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
2.00	1762	1728	1633	1492	1326	1154	987	836	704
1.75	2236	2184	2039	1829	1618	1349	1127	933	769
1.50	2891	2807	2578	2259	1909	1574	1279	1032	831
1.25	3796	3657	3289	2795	2283	1820	1433	1124	884
1.00	5026	4794	4194	3434	2693	2065	1571	1197	918
0.75	6592	6208	5252	4114	3085	2272	1669	1237	927
0.50	8269	7674	6258	4682	3358	2380	1697	1226	901
0.25	9368	8740	6783	4990	3390	2336	1622	1153	840
0.00		8200	6393	4539	3102	2275	1459	1029	742
-0.25	7087	6645	5120	3683	2546	1748	1207	855	621
-0.50	4691	4349	3636	2633	1876	1320	933	668	435
-0.75	2752	2587	2178	1693	1257	914	662	483	355
-1.00	1491	1418	1231	996	768	578	430	318	234
-1.25	749	718	639	532	424	328	299	197	140
-1.50	330	319	287	244	197	153	116	86	63
-1.75	99	95	85	70	80	37	24	13	5
-2.00	-27	-28	-30	-32	-35	-36	-37	-38	-37

$\alpha \backslash \beta$	0	1	2	3	4	5	6	7	8	10	12
12	44	43	42	39	37	33	30	27	24	18	14
10	63	63	59	55	50	45	39	33	29	21	14
8	102	100	92	82	72	58	50	41	34	22	15
7	135	131	120	103	87	70	57	45	35	23	15
6	198	180	159	132	105	82	64	48	37	23	14
5	276	260	219	171	128	95	68	50	37	21	12
4	441	402	315	224	153	104	71	50	35	19	11
3	799	688	470	290	176	108	70	47	32	16	10
2				350	184	104	62	40	26	13	7
1				354	161	83	47	28	18	8	3
0				244	101	48	25	14	9	3	0
-1				80	30	12	4	1	-1	-2	-3
-2				-32	-24	-18	-14	-10	-9	-6	-4
-3	-150	-134	-103	-72	-50	-37	-26	-19	-15	-10	-6
-4	-130	-122	-101	-78	-58	-43	-33	-25	-20	-13	-9
-5	-101	-96	-85	-70	-56	-42	-34	-27	-22	-14	-11
-6	-78	-76	-70	-60	-51	-41	-32	-27	-22	-14	-11
-7	-63	-61	-56	-51	-44	-38	-31	-26	-22	-15	-11
-8	-51	-49	-47	-44	-38	-36	-29	-25	-21	-16	-11
-10	-36	-34	-34	-32	-29	-25	-23	-21	-18	-14	-11
-12	-25	-25	-24	-24	-22	-21	-19	-17	-16	-13	-10

TABLE 26.— $U \times 10^4$, inclination 90°

$\frac{1}{2}\beta$	0.000	.125	.250	.375	.500	.625	.750	.875	1.00	1.25	1.50	1.75	2.00
2.000	894	990	978	858	831	799	762	722	680	595	512	437	370
1.750	1221	1214	1194	1160	1117	1064	1005	943	878	750	630	526	437
1.500	1707	1694	1659	1602	1527	1440	1343	1243	1191	947	775	630	512
1.250	2438	2416	2351	2250	2120	1970	1810	1647	1487	1194	947	750	595
1.000	3536	3494	3376	3193	2963	2705	2438	2178	1924	1487	1141	878	680
0.875	4262	4206	4046	3800	3494	3158	2815	2483	2174	1647	1243	943	722
0.750	5120	5044	4827	4499	4098	3664	3228	2815	2438	1910	1343	1005	762
0.625	6098	5997	5709	5278	4759	4206	3664	3158	2705	1970	1440	1064	799
0.500	7155	7023	6650	6098	5443	4759	4098	3494	2963	2120	1527	1117	831
0.375	8209	8043	7578	6895	6098	5278	4499	3800	3193	2250	1602	1160	858
0.250	9131	8933	8380	7578	6650	5709	4827	4046	3376	2351	1659	1194	878
0.125	9770	9549	8933	8043	7023	5997	5044	4206	3494	2416	1694	1214	890
0.000	10000	9770	9131	8209	7155	6098	5120	4262	3536	2438	1707	1221	894

$\frac{1}{2}\beta$	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
16	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1
15	3	3	3	3	3	3	3	2	2	2	2	2	1	1	1	1	1
14	4	4	4	3	3	3	3	3	2	2	2	2	2	1	1	1	1
13	5	4	4	4	4	4	3	3	3	3	2	2	2	2	1	1	1
12	6	6	6	5	5	5	4	4	3	3	3	2	2	2	2	1	1
11	7	7	7	7	6	6	5	4	4	3	3	3	2	2	2	2	1
10	10	10	9	9	8	7	6	5	4	4	3	3	3	2	2	2	1
9	13	13	13	12	10	9	8	7	6	5	4	3	3	2	2	2	2
8	19	19	17	16	14	12	10	8	7	6	5	4	3	3	2	2	2
7	28	27	25	22	19	15	13	10	8	7	5	4	4	3	3	2	2
6	44	43	38	32	26	20	16	13	10	8	6	5	4	3	3	2	2
5	75	71	61	48	37	27	20	15	12	9	7	6	5	4	3	3	2
4	143	131	104	75	53	37	26	19	14	10	8	6	5	4	3	3	2
3	316	274	191	121	75	48	32	22	16	12	9	7	5	4	3	3	2
2	894	686	370	191	104	61	39	25	17	13	9	7	6	4	4	3	2
1				274	131	71	43	27	19	13	10	7	6	4	4	3	2
0				316	143	75	44	28	19	13	10	7	6	5	4	3	2

TABLE 27.—*Susceptibility of magnetic minerals**

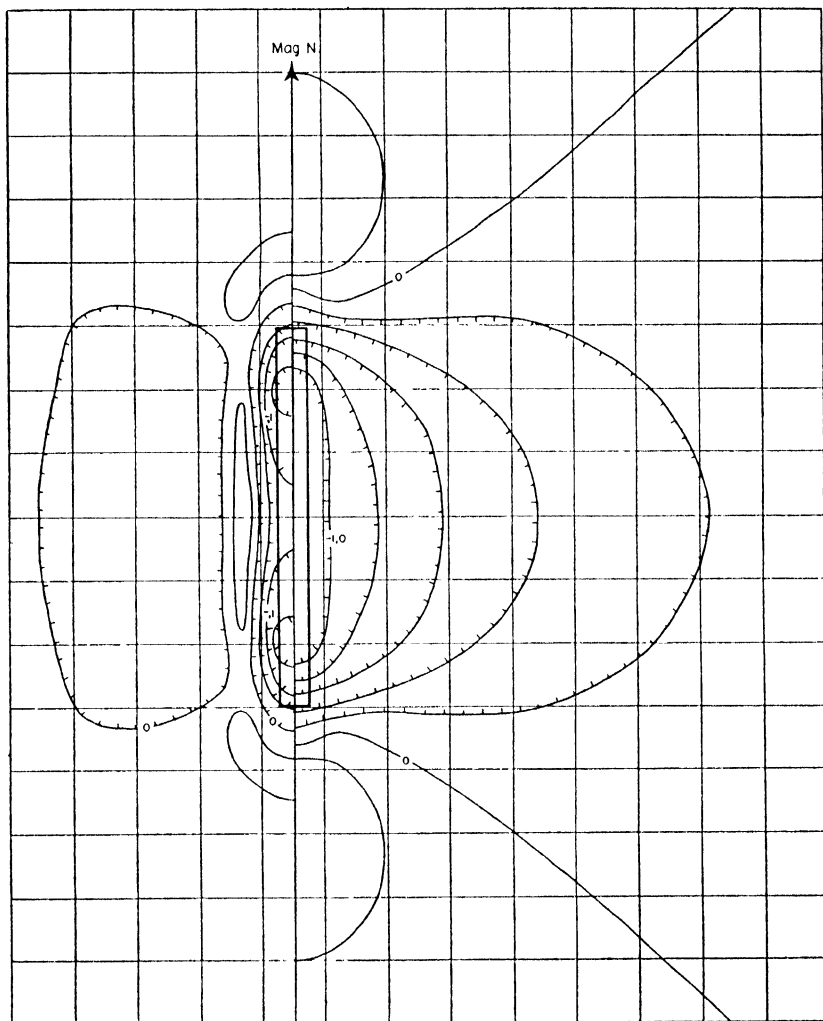
Mineral	Susceptibility (e.m.c.g.s.) (per cm. ³)	Field strength (Oersted)
Magnetite	.3 to .8	.6
Pyrrhotite Sudbury, Ont.	.028	.6
Pyrrhotite	.007	—
Ilmenite	.031	—
Ilmenite	.044	.6
Specularite	.004	.6
Specularite	.003	—
Franklinite	.036	—

* Reprinted from Birch *et al.* (1942, p. 296).TABLE 28.—*Range of magnetic susceptibility in major rock types**Susceptibility in electromagnetic c.g.s. units per cm.³

Rock type	Number of samples	Percentage of samples with susceptibility			
		Less than 10 ⁻⁴	Between 10 ⁻⁴ and 10 ⁻³	Between 10 ⁻³ and 4 × 10 ⁻³	Greater than 4 × 10 ⁻³
Basic effusives	97	5	29	47	19
Basic plutonics	53	24	27	28	21
Granites and allied rocks	74	60	23	16	1
Gneisses, schists, slates	45	71	22	7	0
Sedimentary rocks	48	73	19	4	4

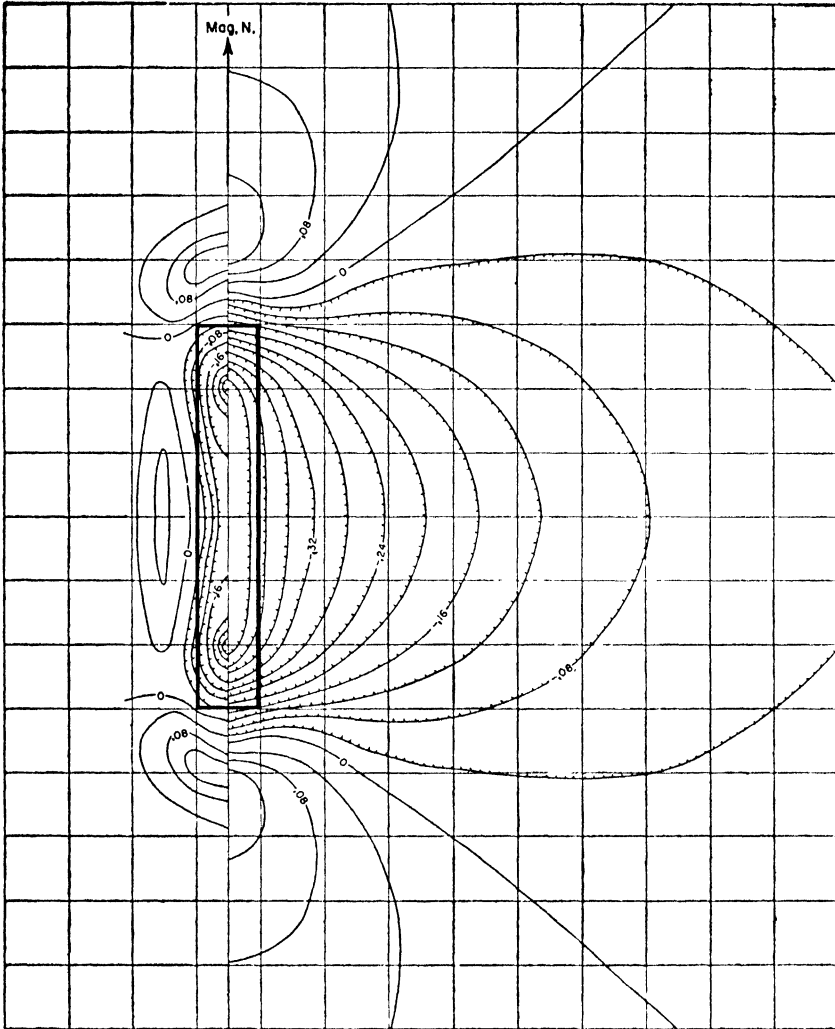
* Reprinted from Birch *et al.* (1942, p. 296).

FIGURE A1



CURVATURE $\frac{\partial^2 I}{\partial x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta T/I$ (CGS)
 INCLINATION 0° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A2

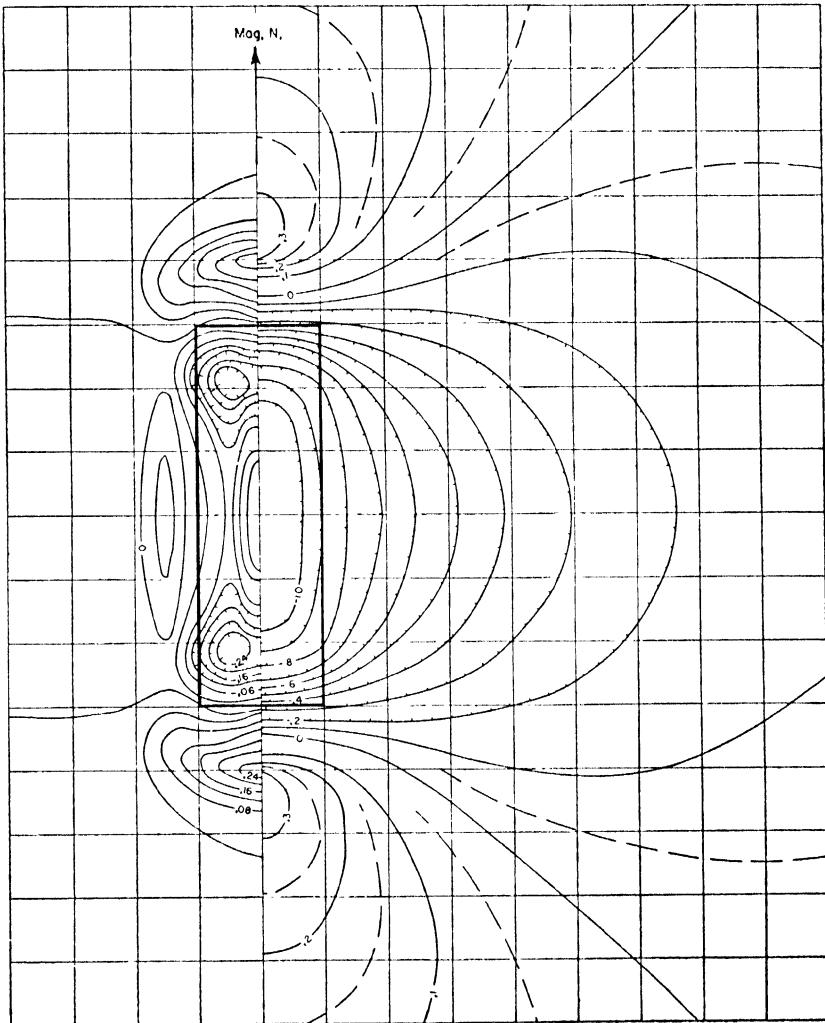


CURVATURE, $\frac{d^2I}{dx^2}/4I \rightarrow$ TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 0°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A3

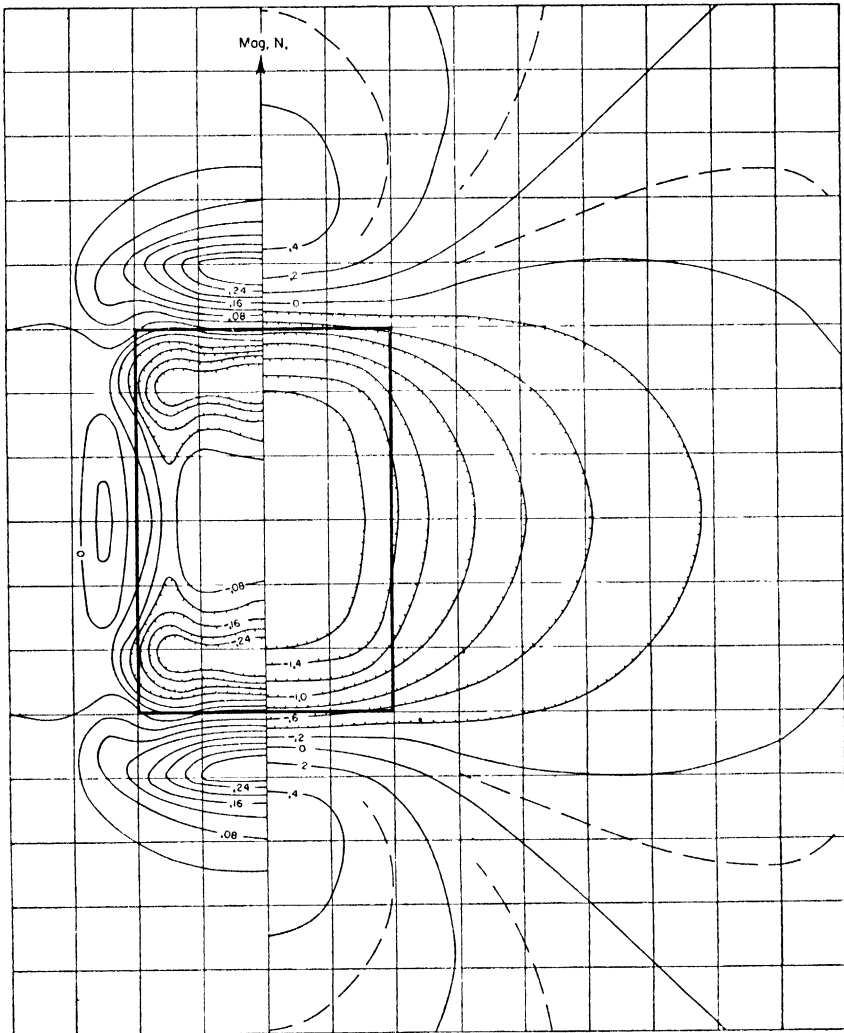


CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 0°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A4

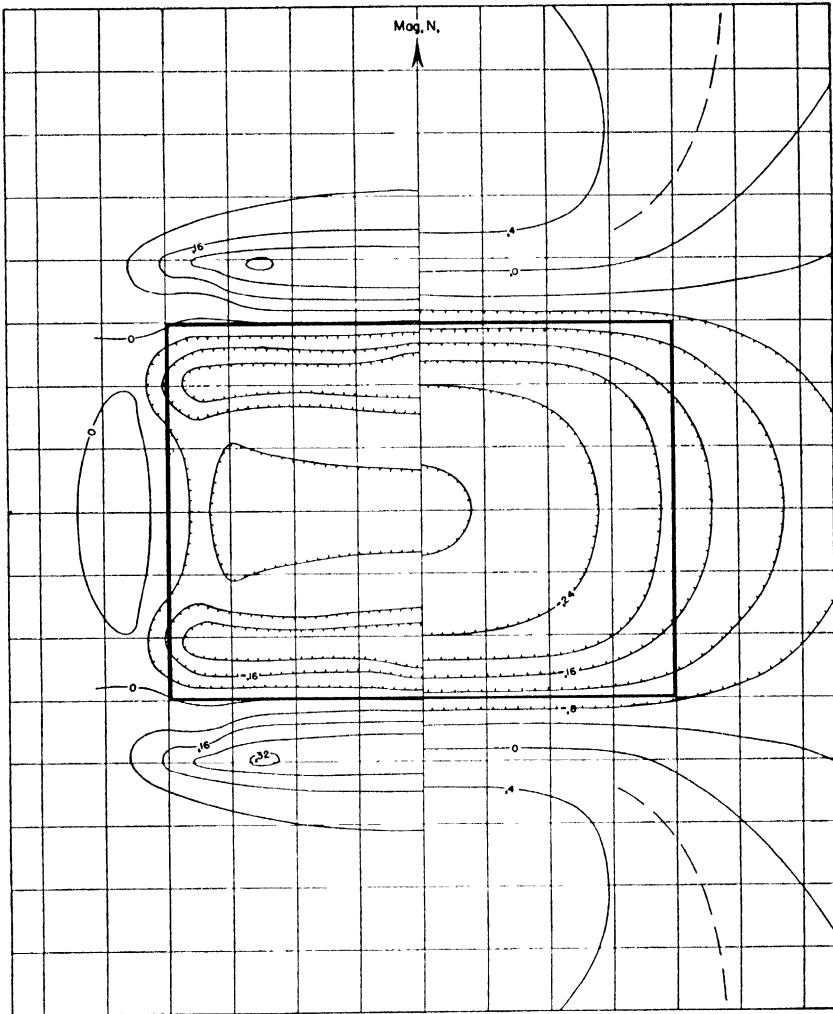


CURVATURE, $\frac{\Delta T}{I} / 4I \rightarrow \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 0°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A5

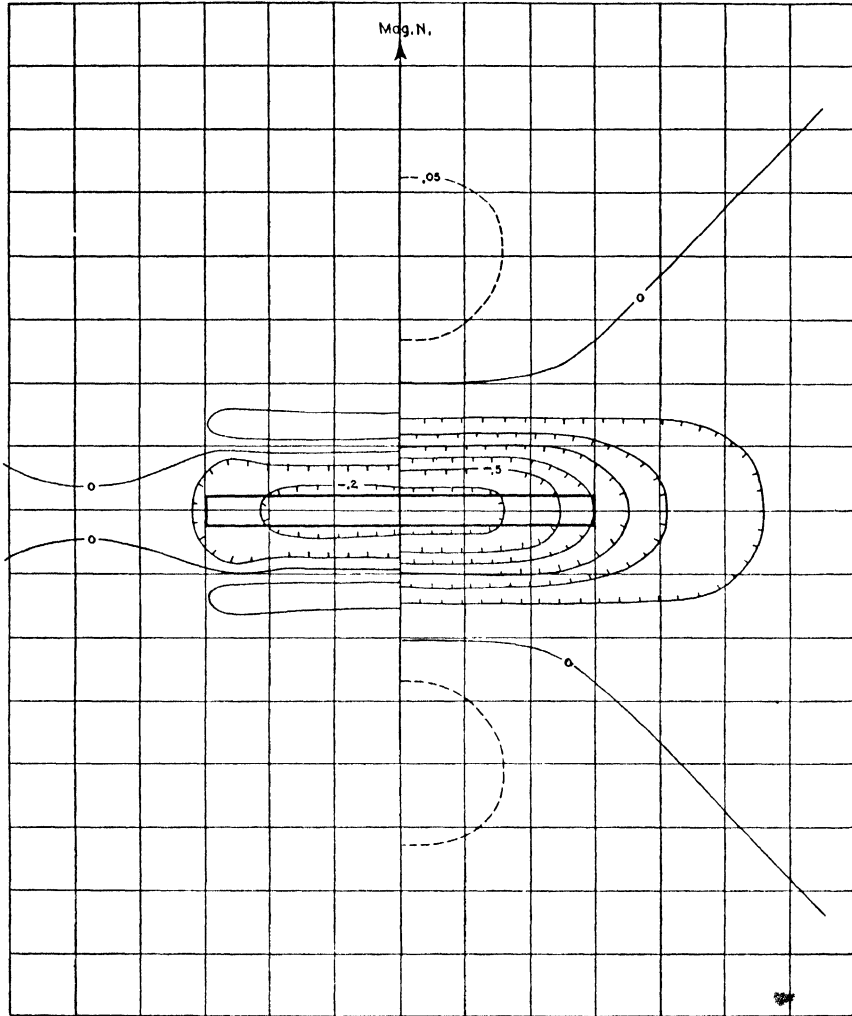


CURVATURE, $\frac{\Delta I}{\Delta r} / 4I \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 0°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A6



CURVATURE $\frac{\partial^2 I}{\partial x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)
 INCLINATION 0° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A7

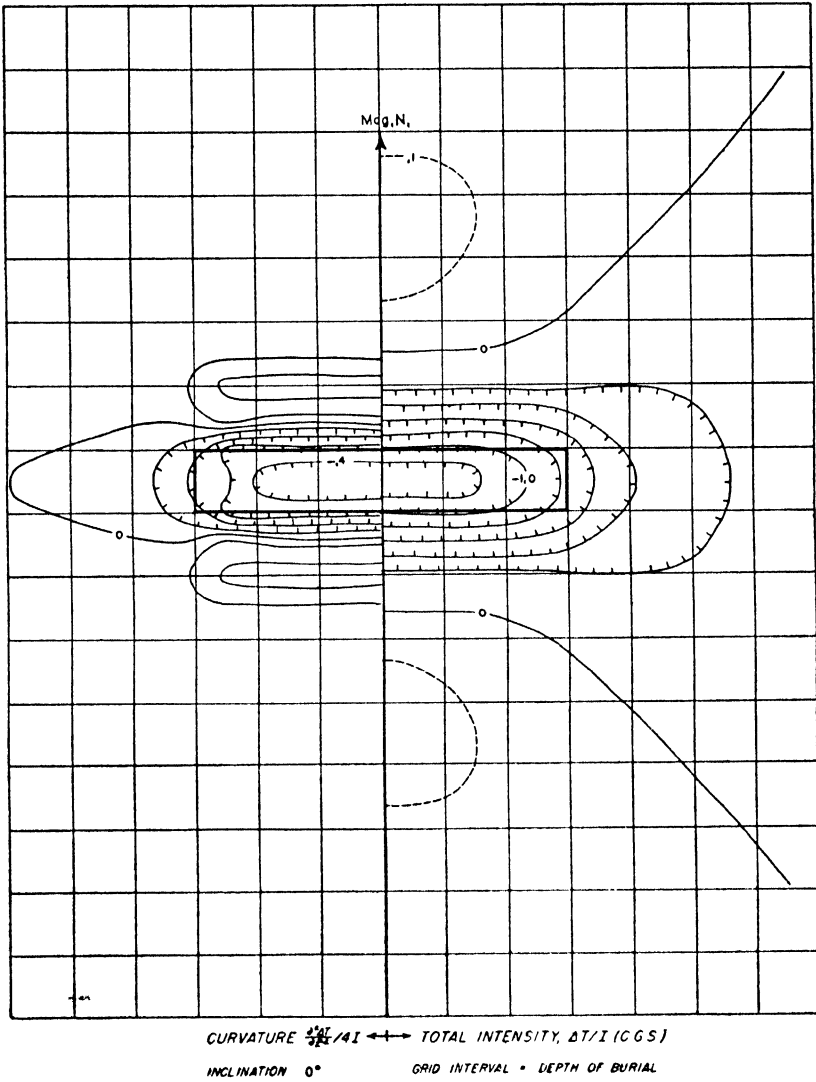
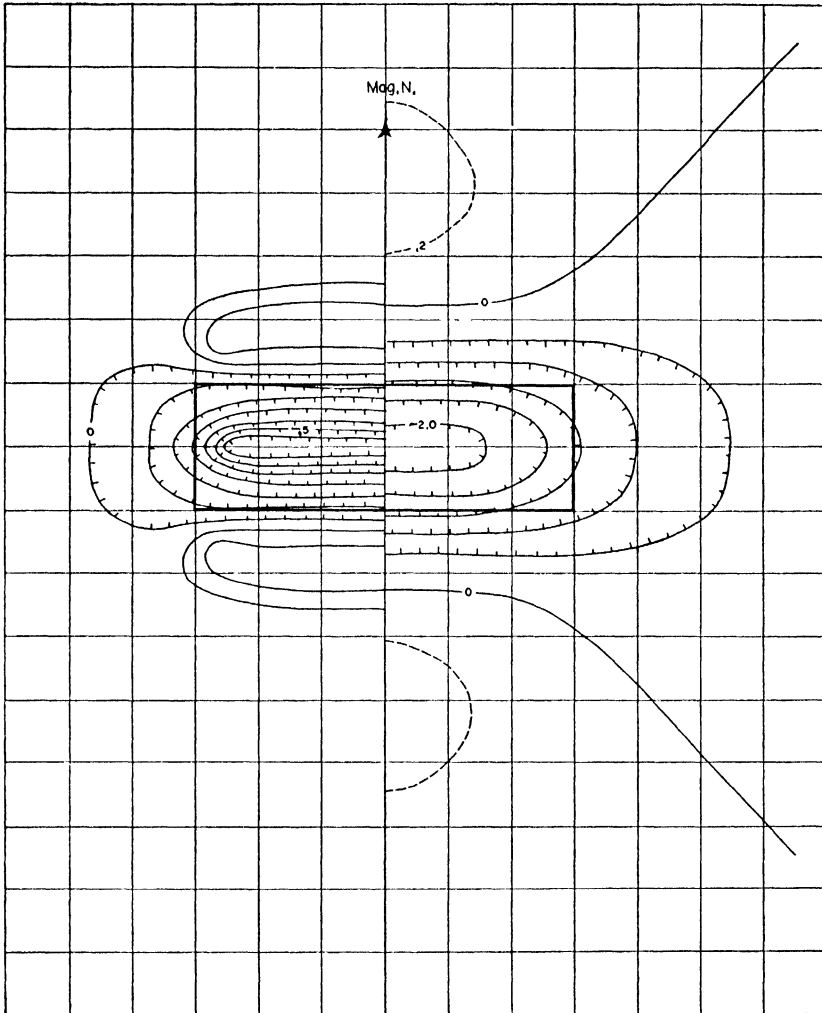


FIGURE A8



CURVATURE $-\frac{\partial^2 I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)
 INCLINATION 0° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A9

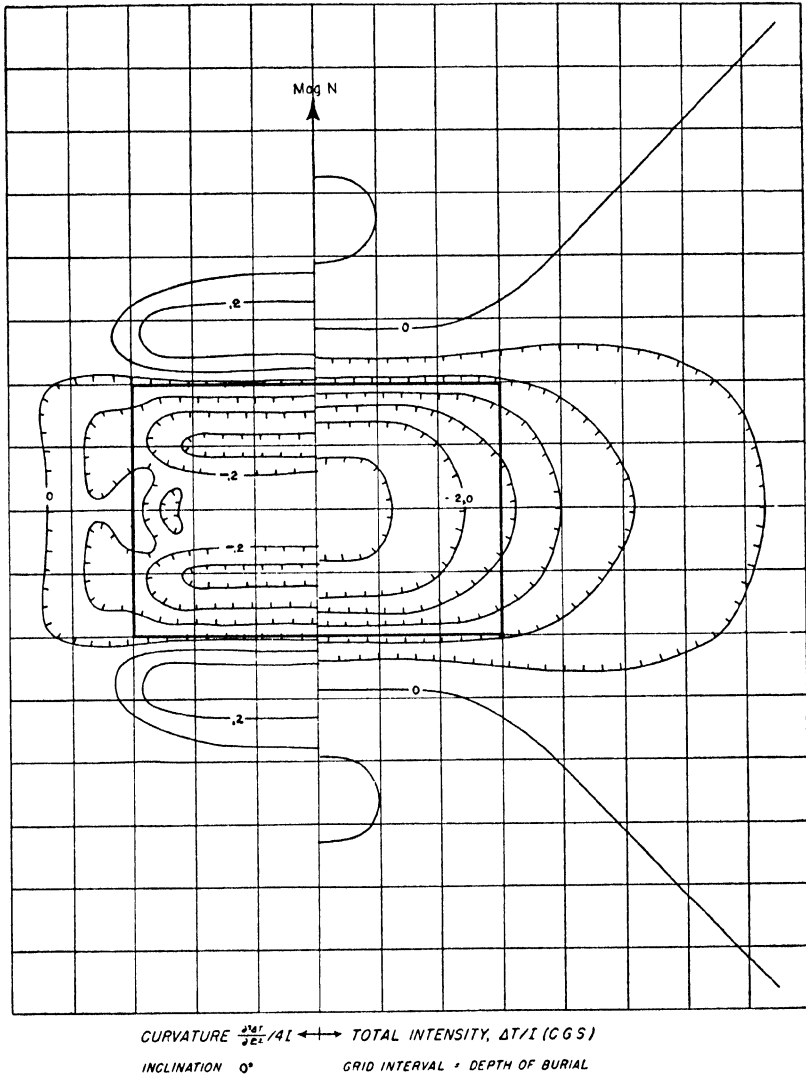
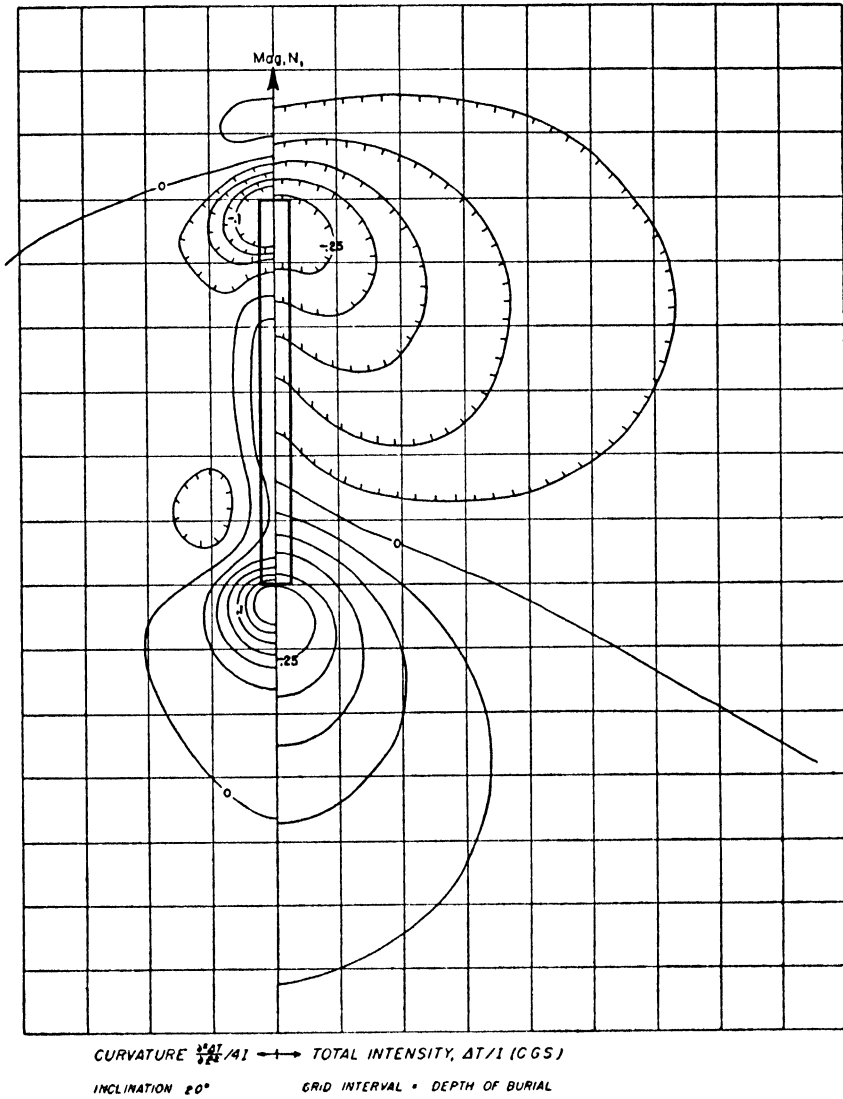


FIGURE A10



INCLINATION 20° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A13

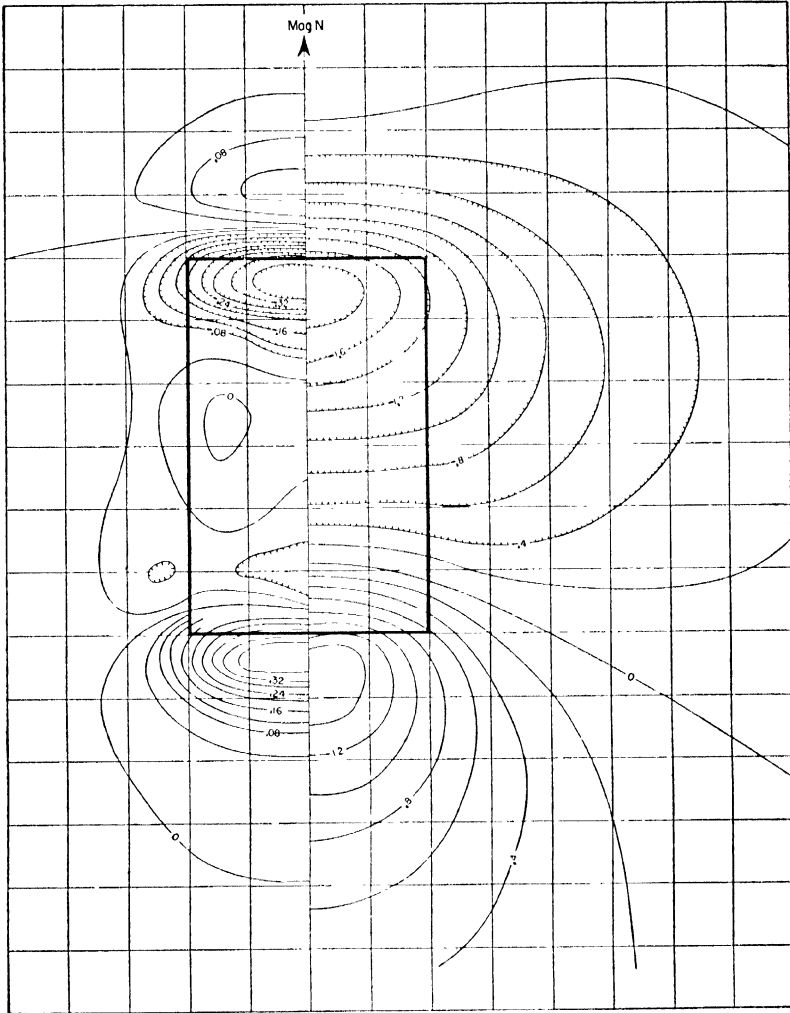
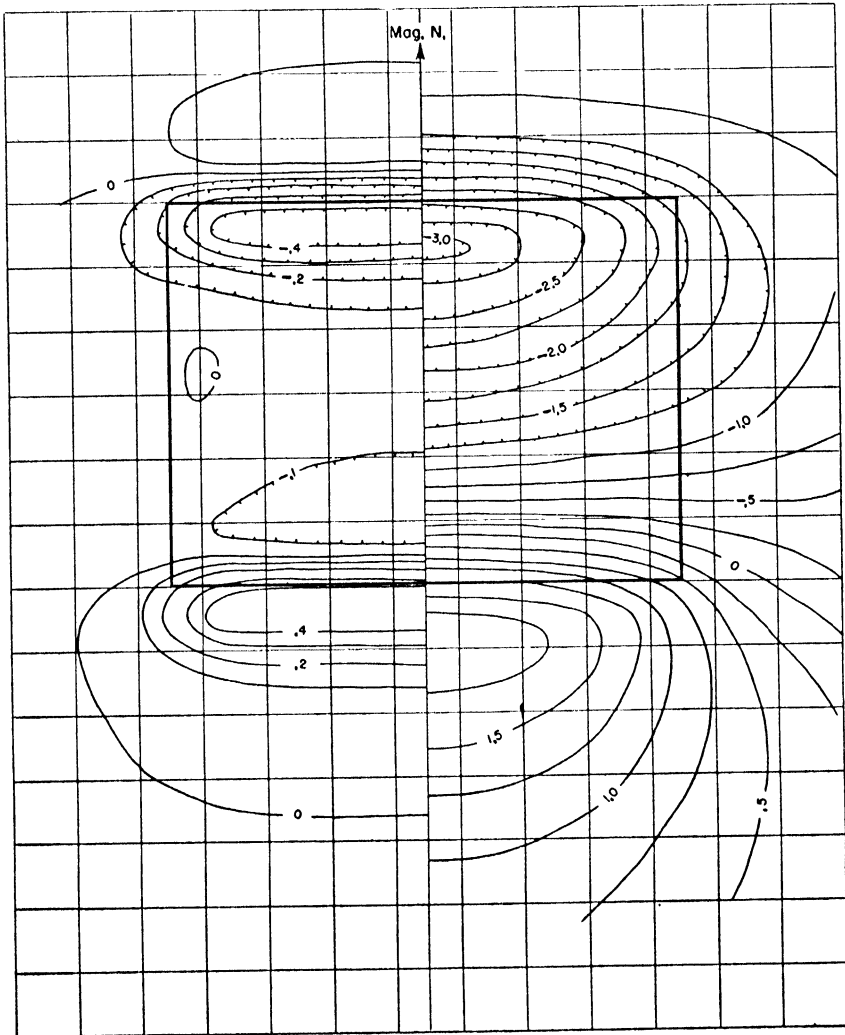


FIGURE A14



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \rightarrow \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (GGS)
 INCLINATION 20° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A15

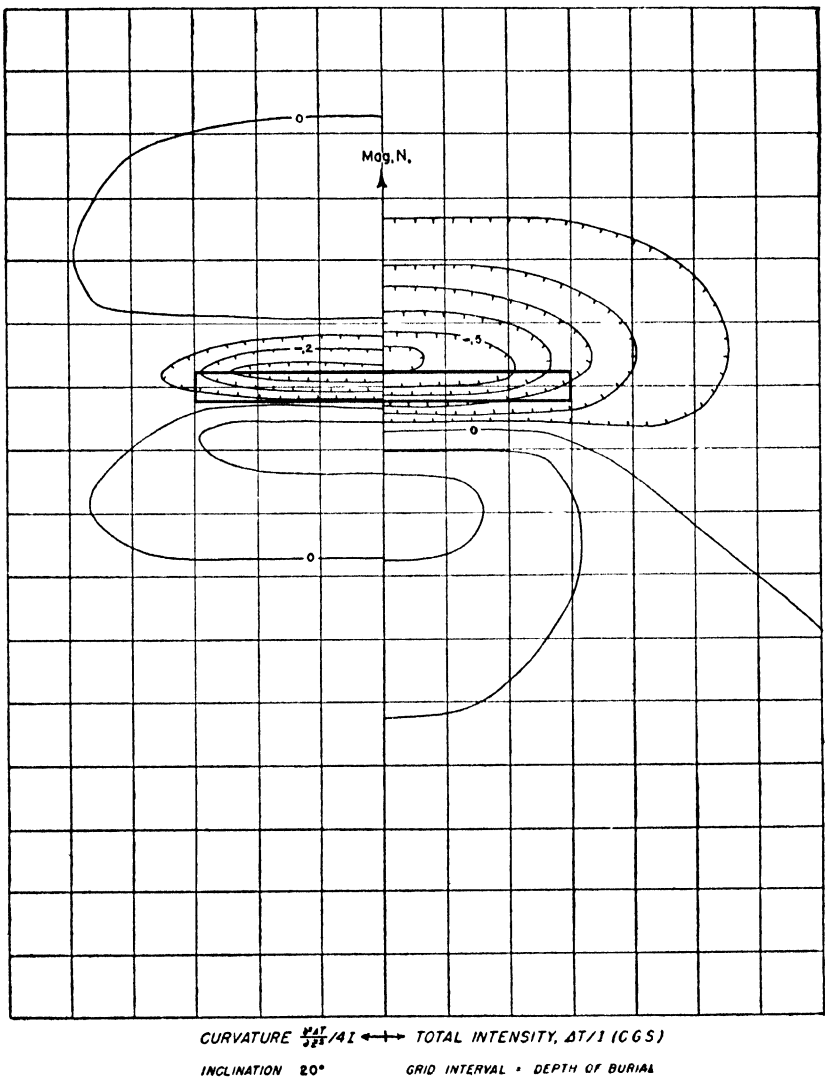
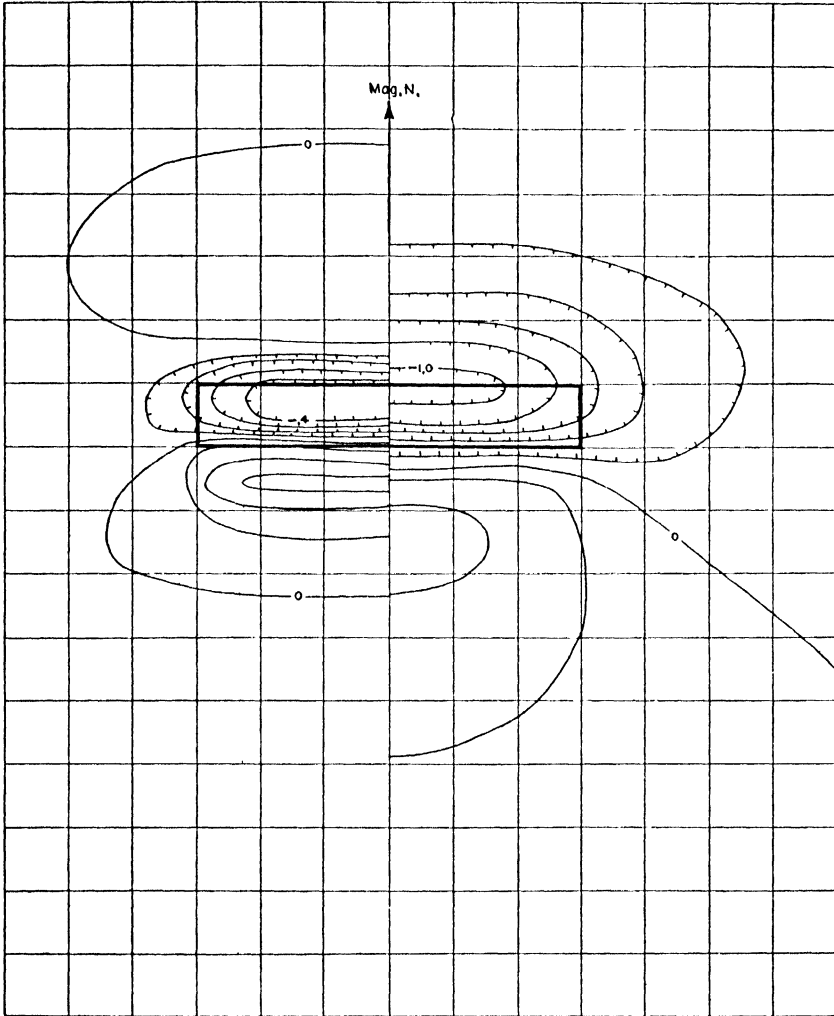


FIGURE A16



CURVATURE $\frac{\partial^2 \Delta I}{\partial x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 20°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A17

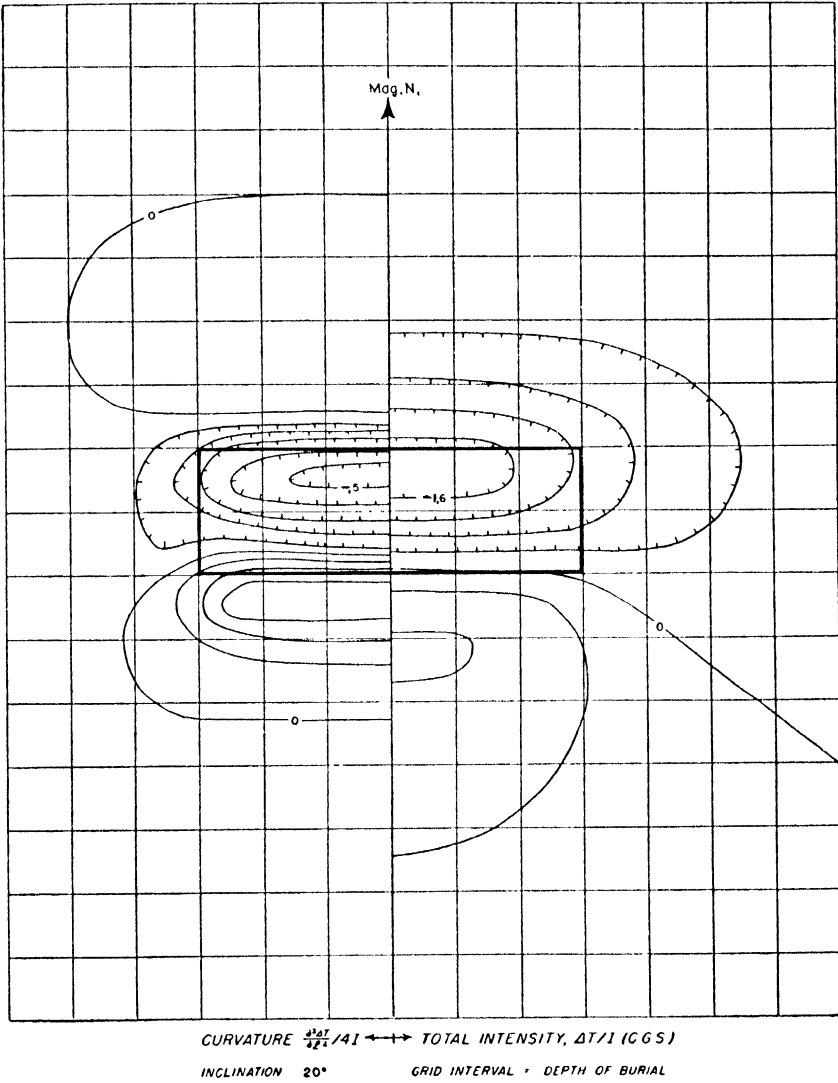
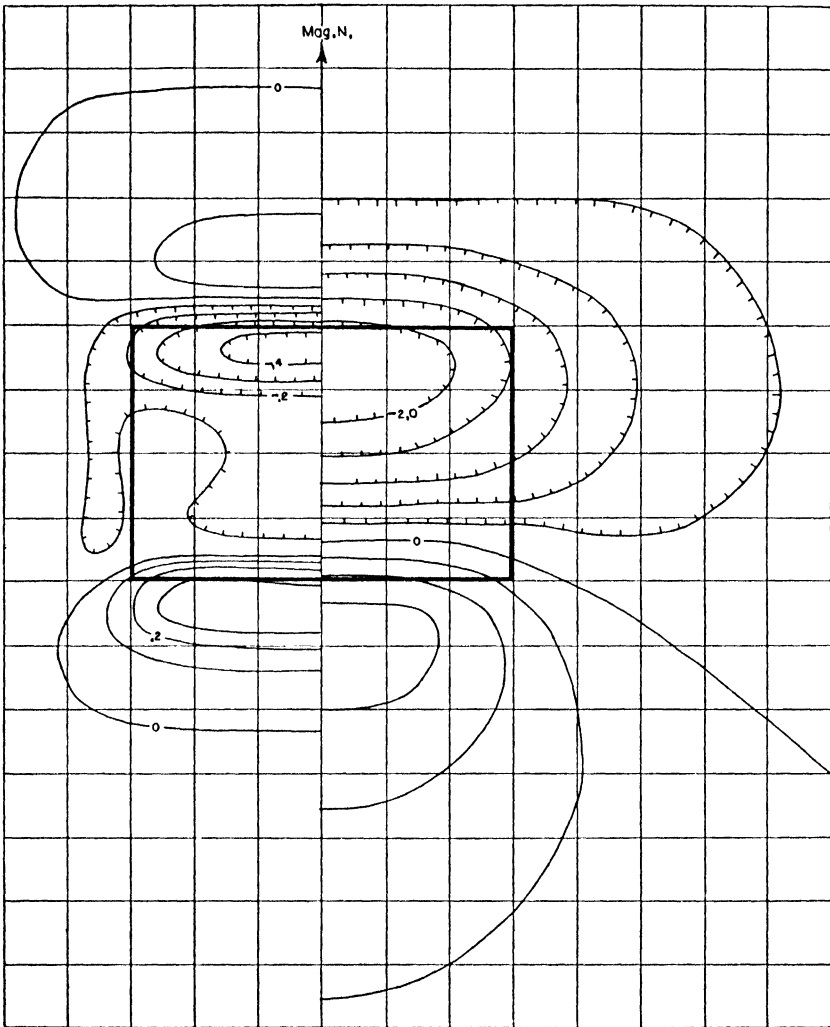


FIGURE A18

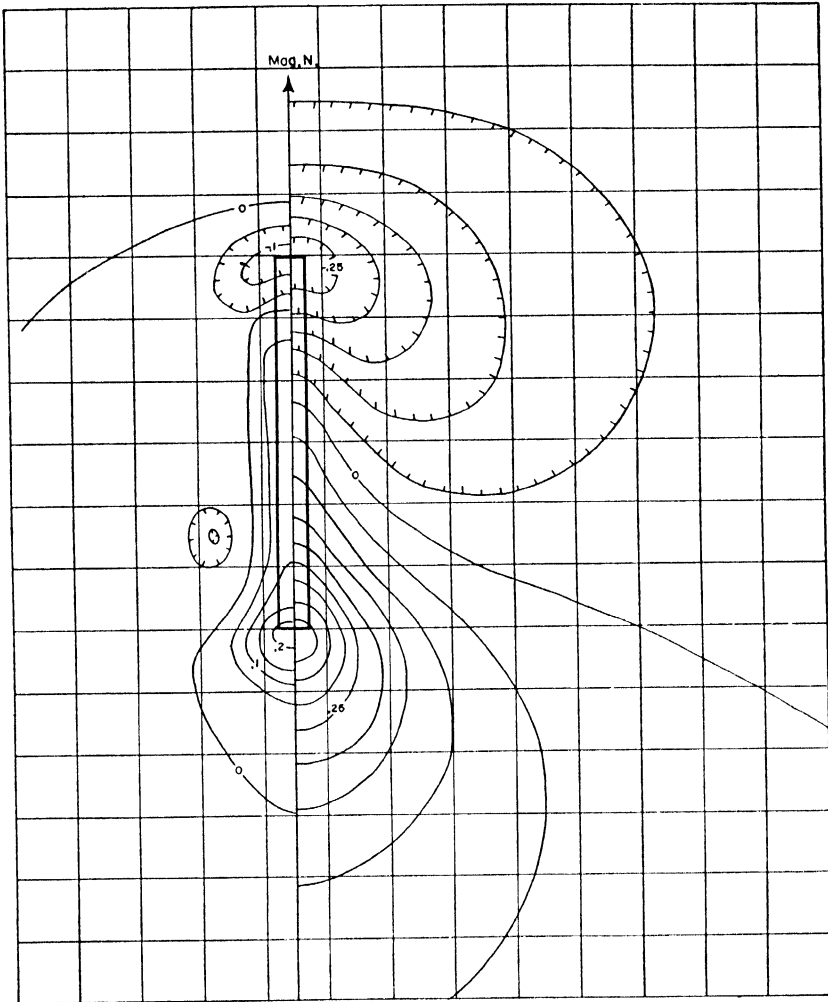


CURVATURE $\frac{\partial^2 \Delta T}{\partial x^2} / \Delta T \leftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 20°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A19

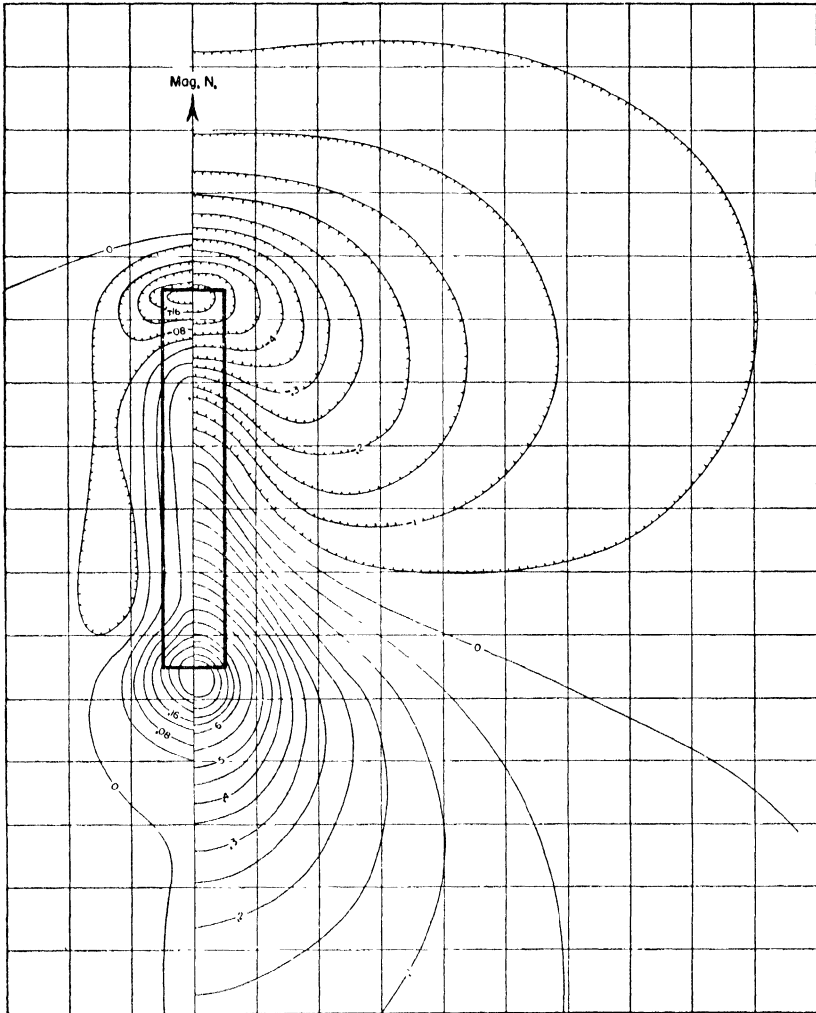


CURVATURE $\frac{\partial^2 I}{\partial x^2} / 4I \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A20

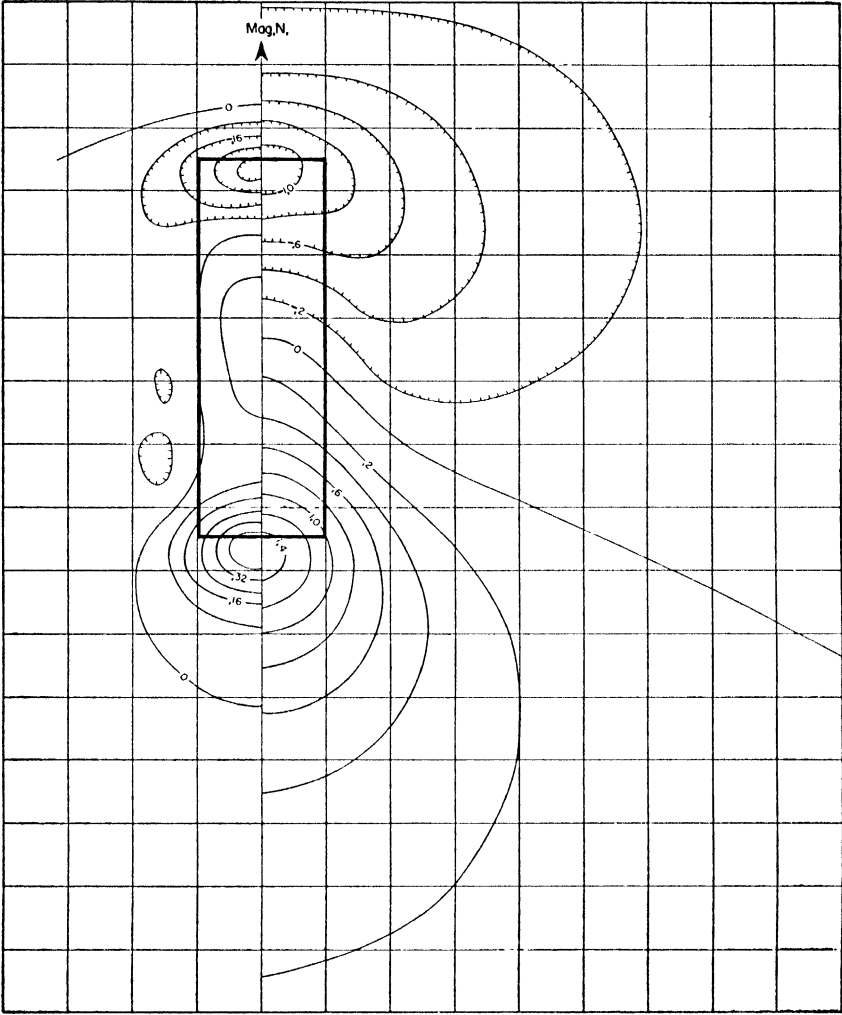


CURVATURE, $\frac{\partial^2 I}{\partial x^2} / \Delta I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 30°

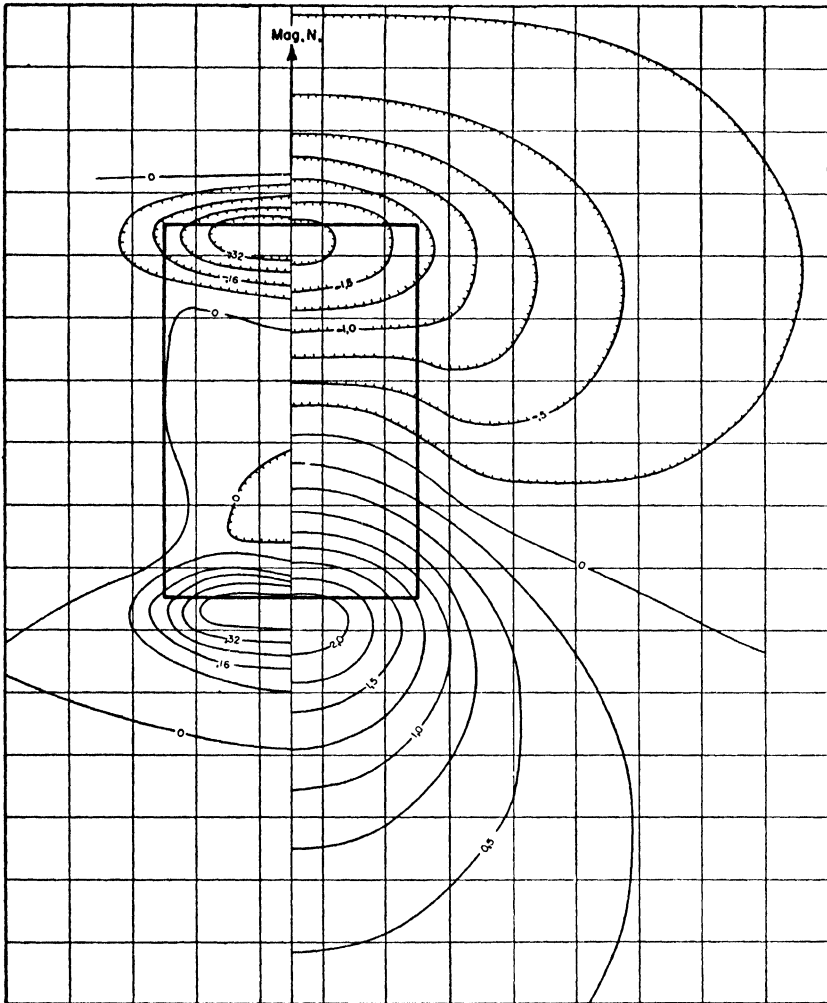
GRID INTERVAL = DEPTH OF BURIAL

FIGURE A21



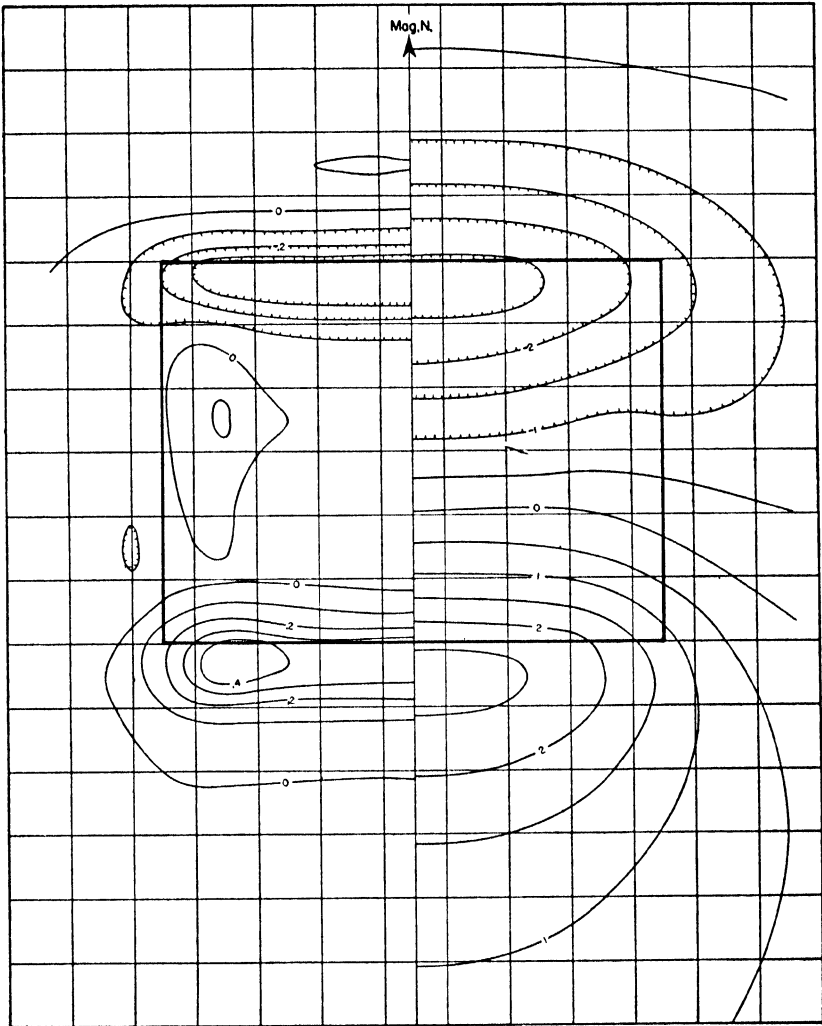
CURVATURE, $\frac{\partial^2 I}{\partial x^2}$ ↔ TOTAL INTENSITY, $\Delta I/I$ (CGS)
INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A22



CURVATURE, $\frac{\Delta T}{I^2}/41 \longleftrightarrow$ TOTAL INTENSITY, $\Delta T/I$ (CGS)
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A23



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I$ $\longleftrightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A24

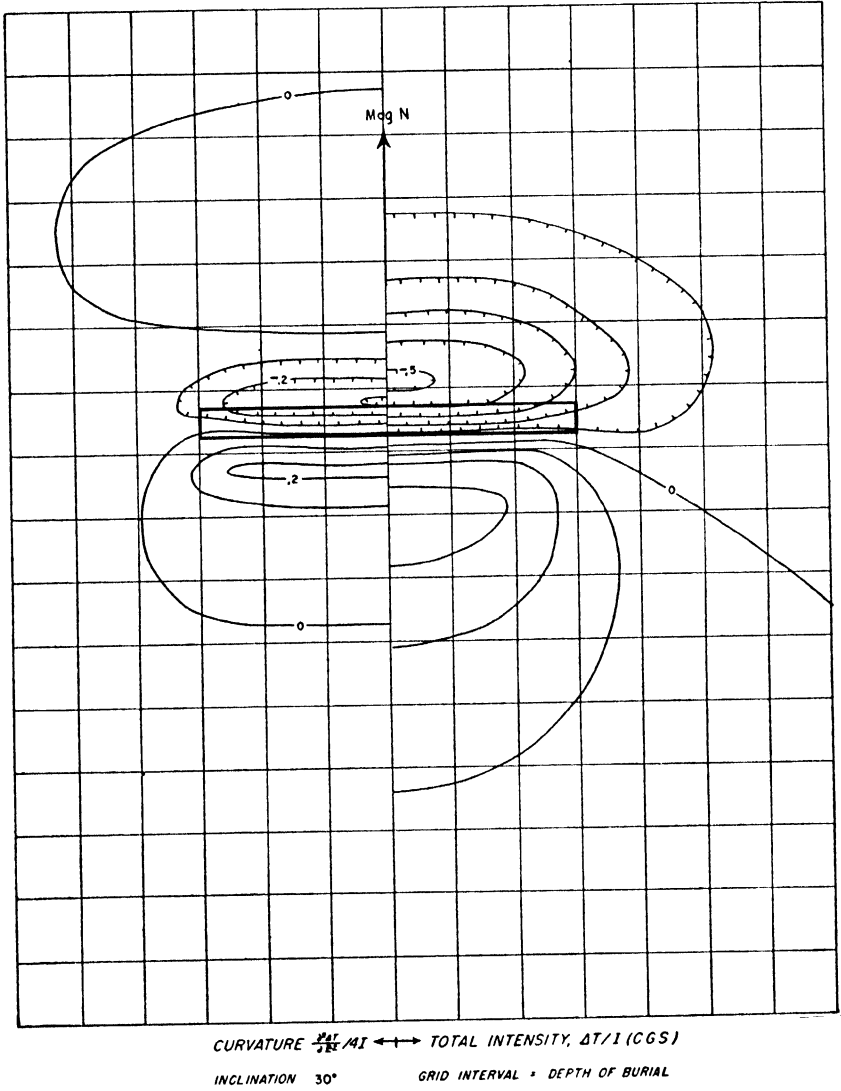
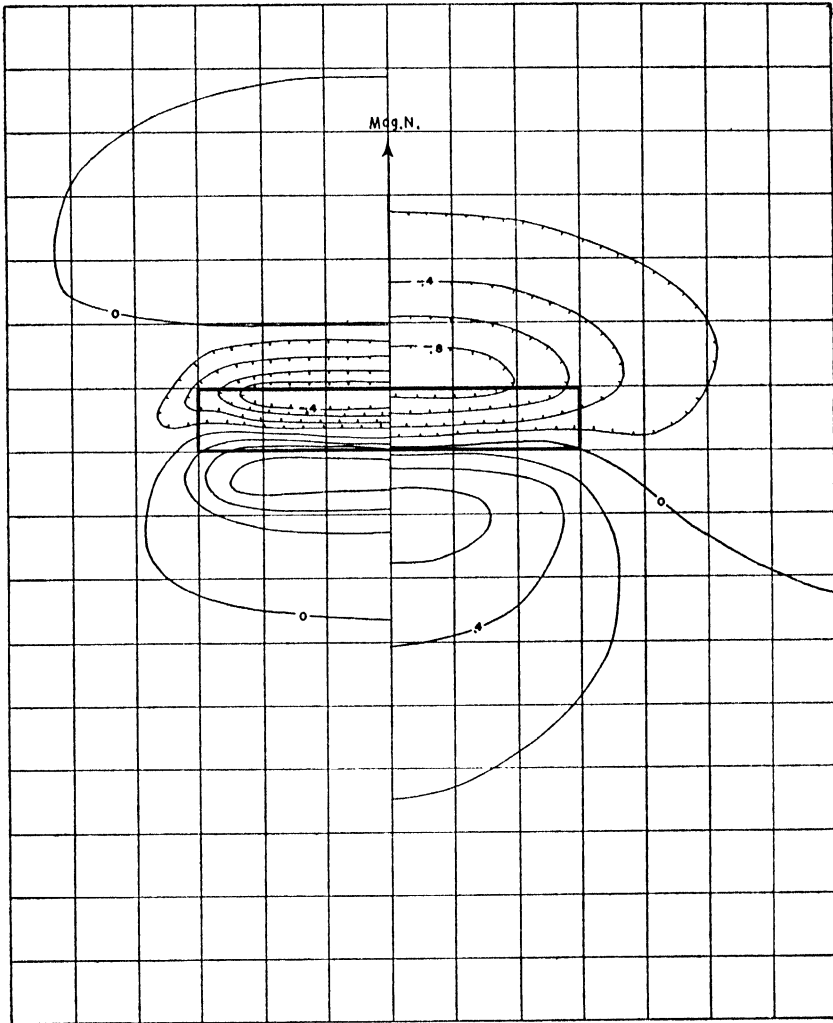
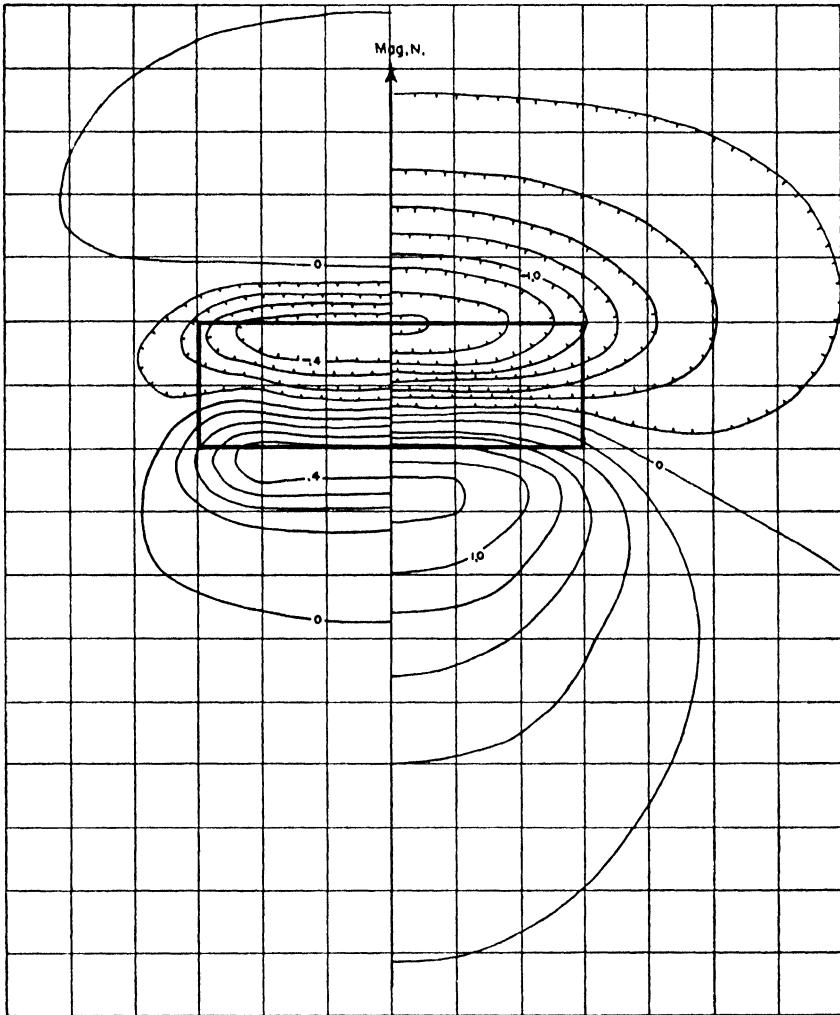


FIGURE A25



CURVATURE $\frac{\Delta^2 I}{\Delta x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A26



CURVATURE $\frac{\partial^2 I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta T/I$ (CGS)
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A27

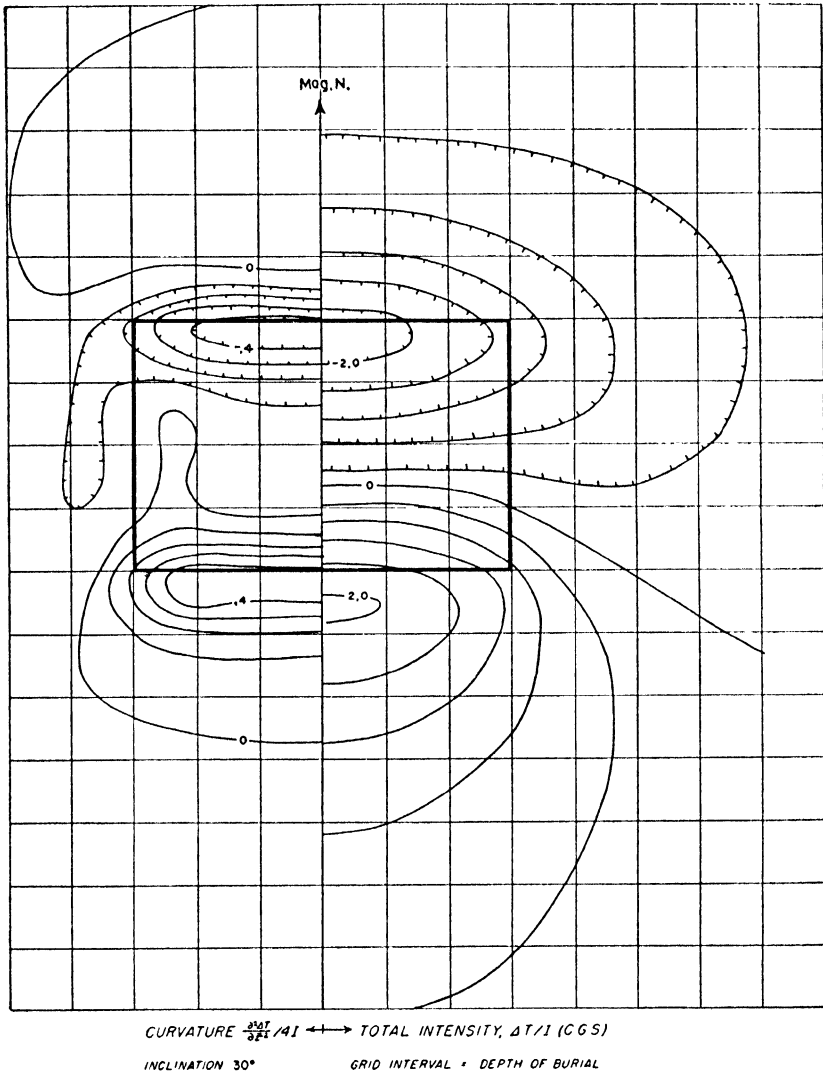
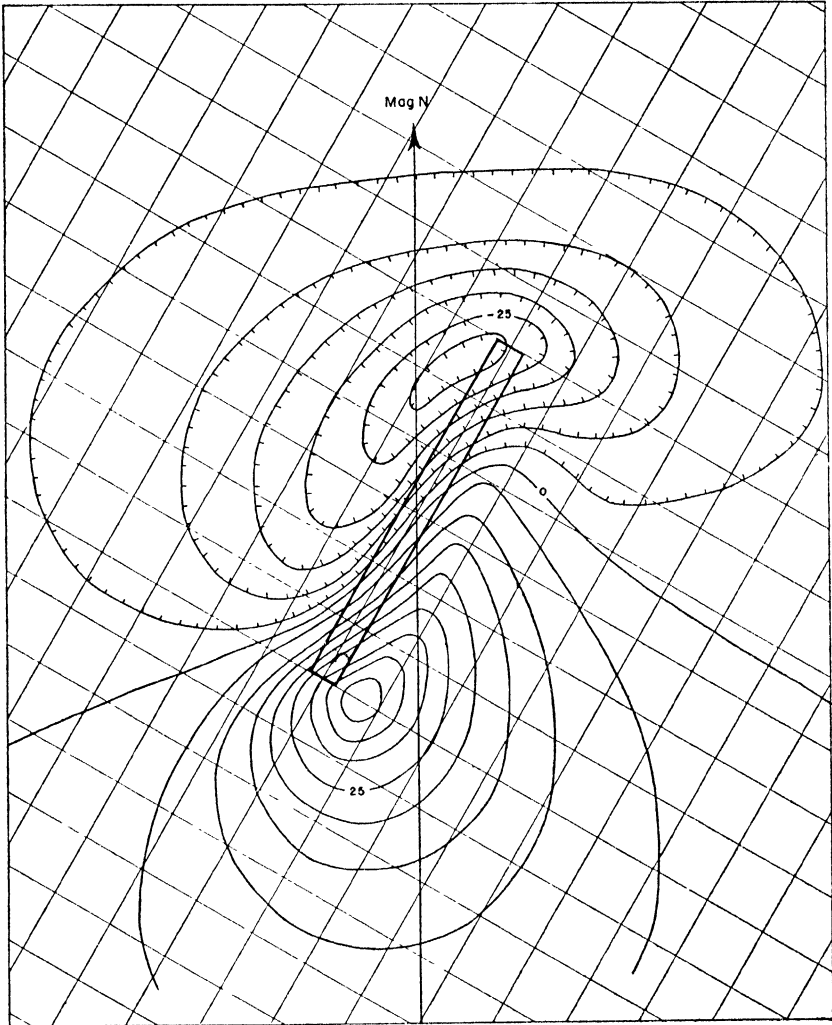


FIGURE A28



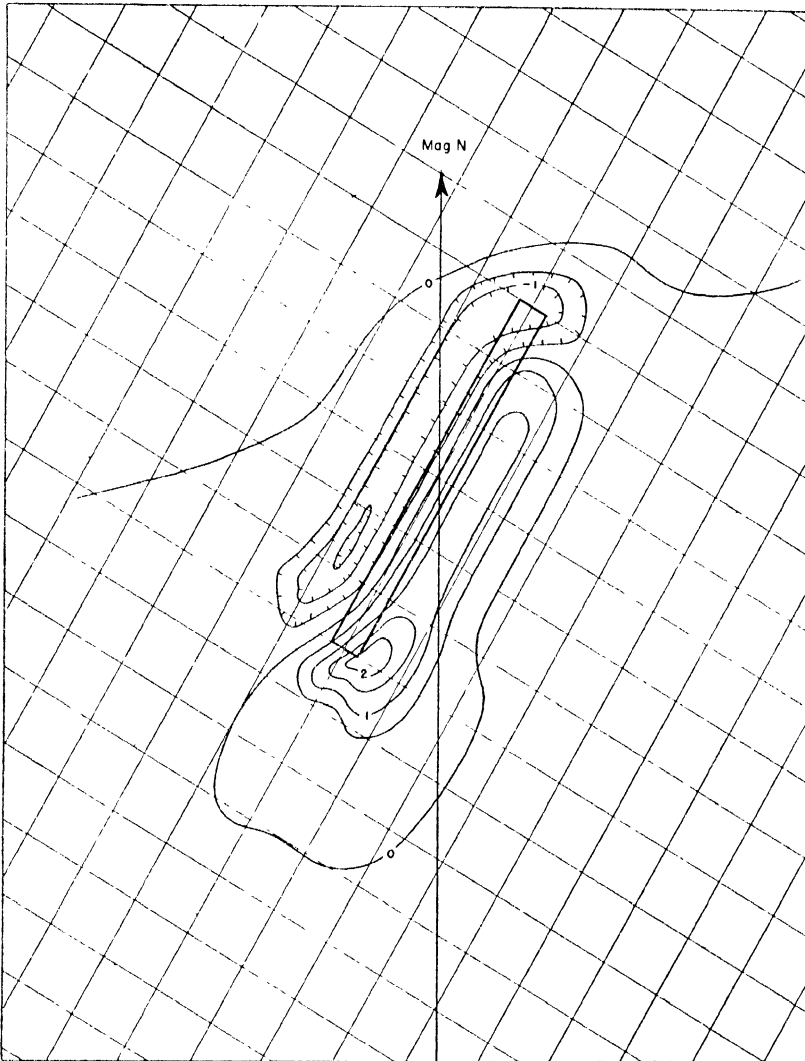
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

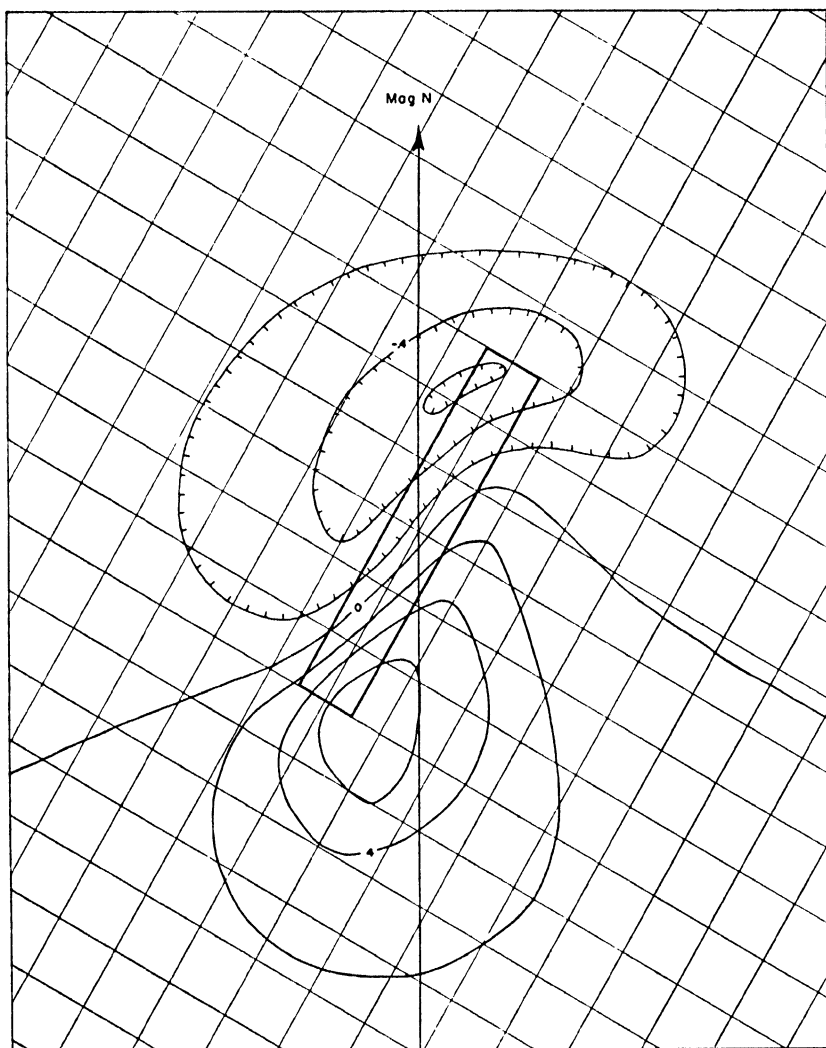
STRIKE = $N 30^\circ E$ or W (Mag)

FIGURE A29



$\text{CURVATURE, } \frac{\Delta^2 I}{\Delta Z^2} / 41$
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL
 STRIKE = N 30° E or W (Mag)

FIGURE A30



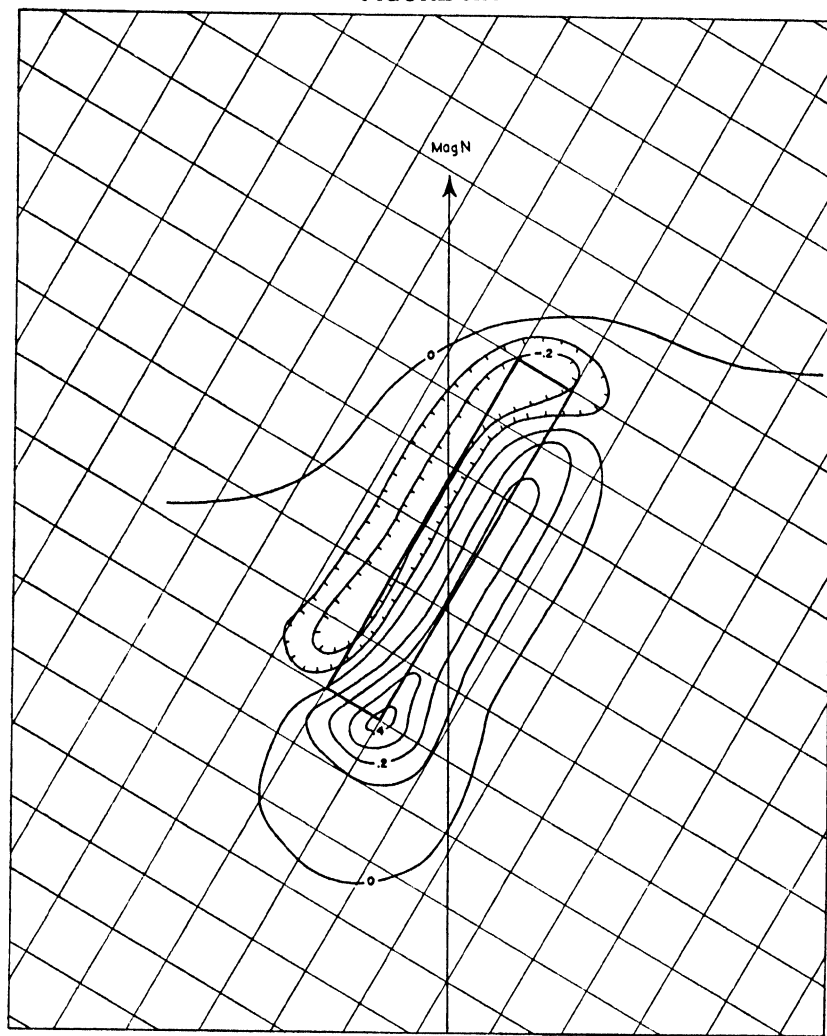
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

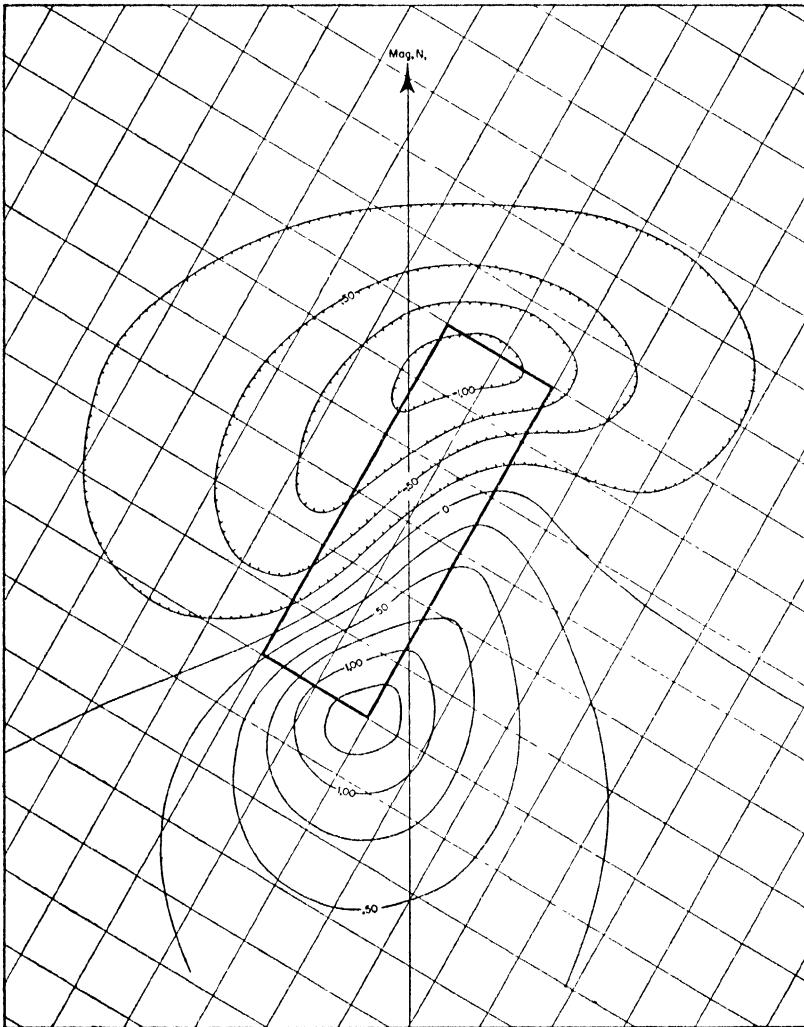
STRIKE = N 30° E or W (Mag)

FIGURE A31



CURVATURE $\frac{\partial^2 I}{\partial x^2} / 4I$
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL
 STRIKE = N 30° E or W (Mag)

FIGURE A32



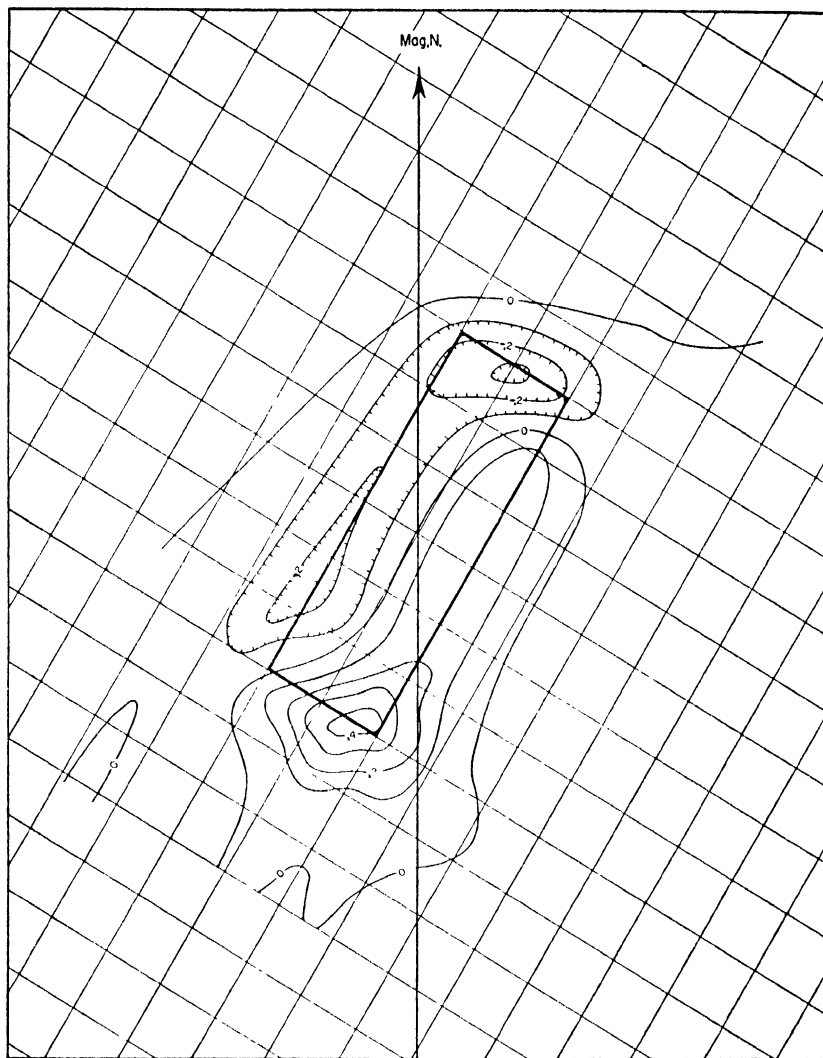
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

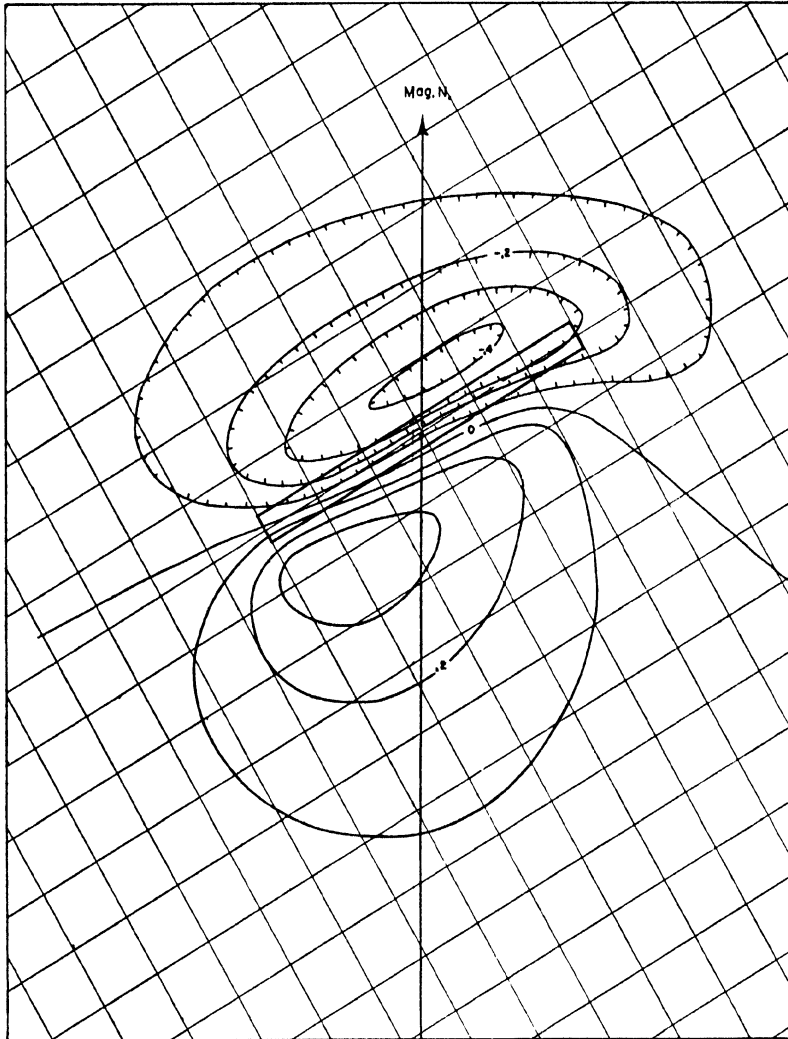
STRIKE = $N 30^\circ E$ (Mag)

FIGURE A33



INCLINATION 30°
GRID INTERVAL = DEPTH OF BURIAL

FIGURE A34



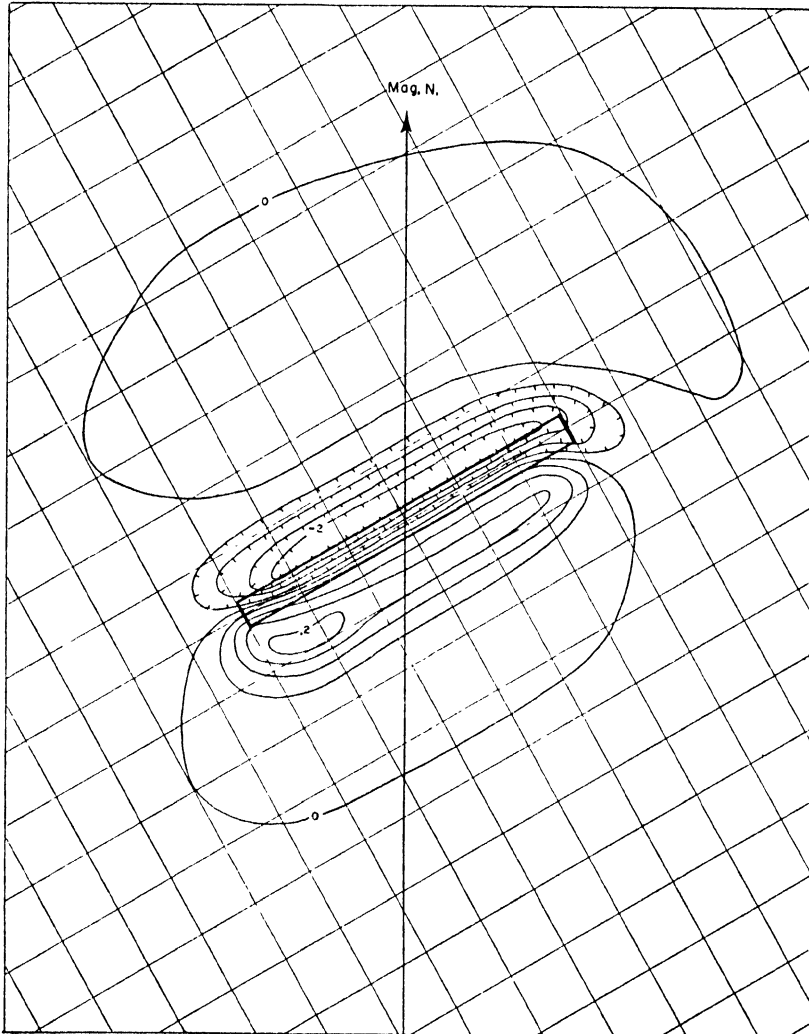
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

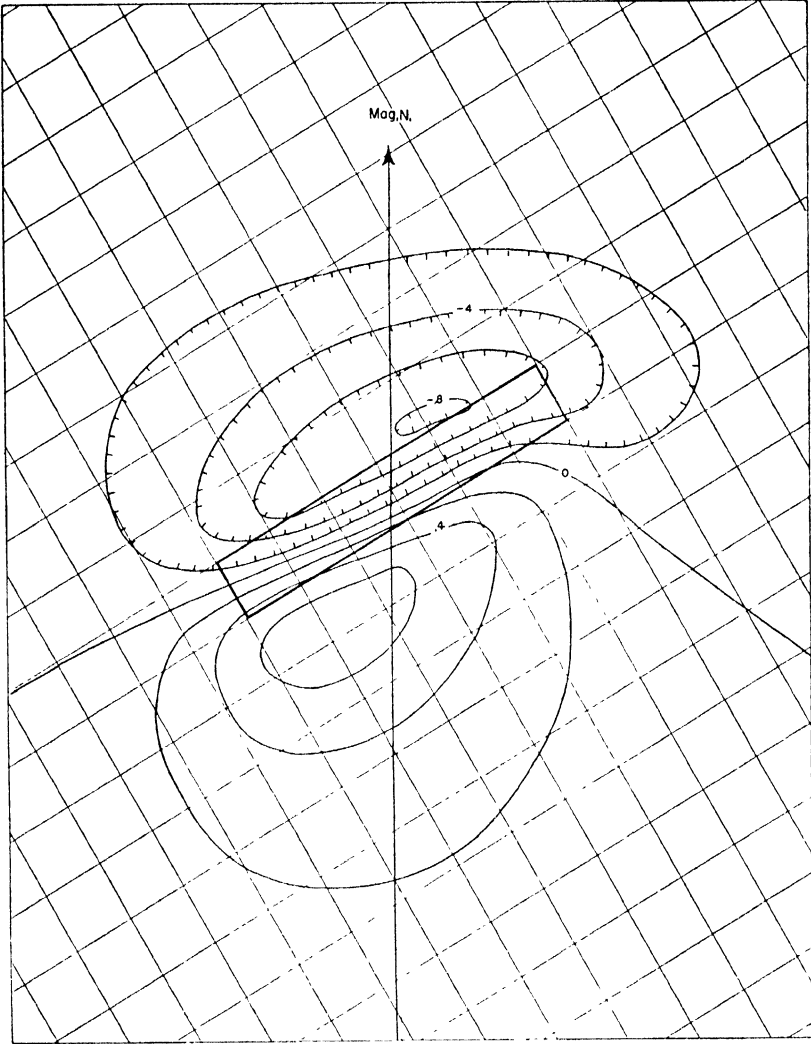
STRIKE = N. 60° E or W (Mag)

FIGURE A35



CURVATURE, $\frac{\partial^2 I}{\partial z^2} / 4I$
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL
 STRIKE = N 60° E or W (Mag)

FIGURE A36



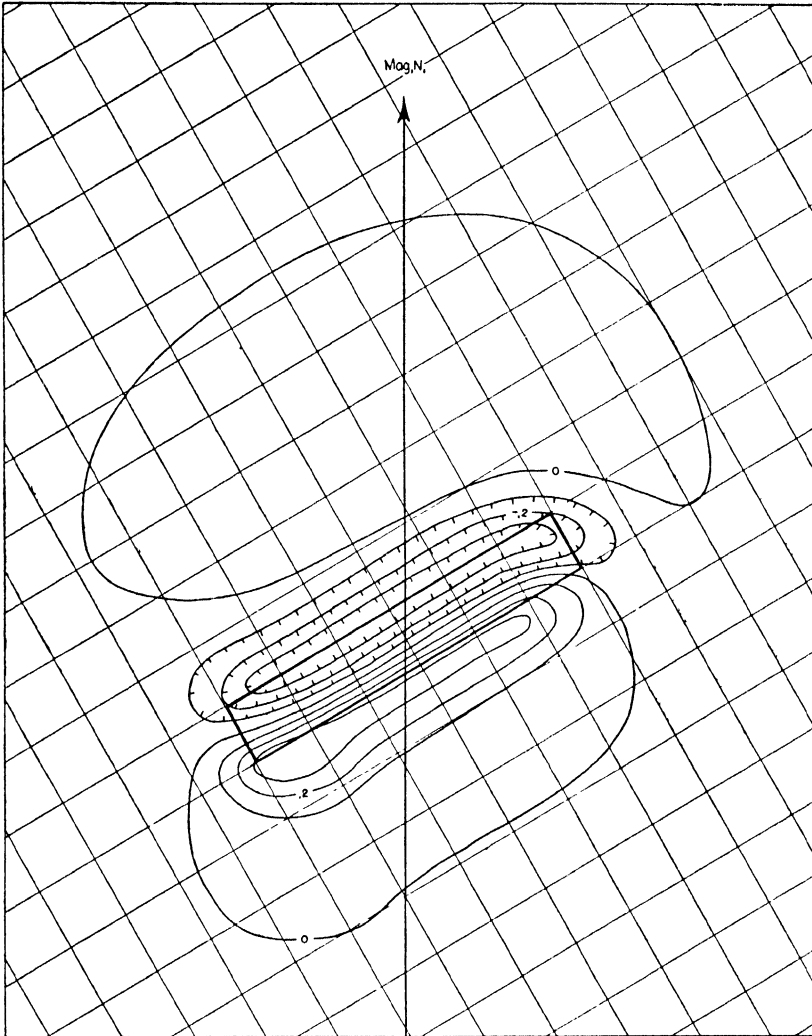
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

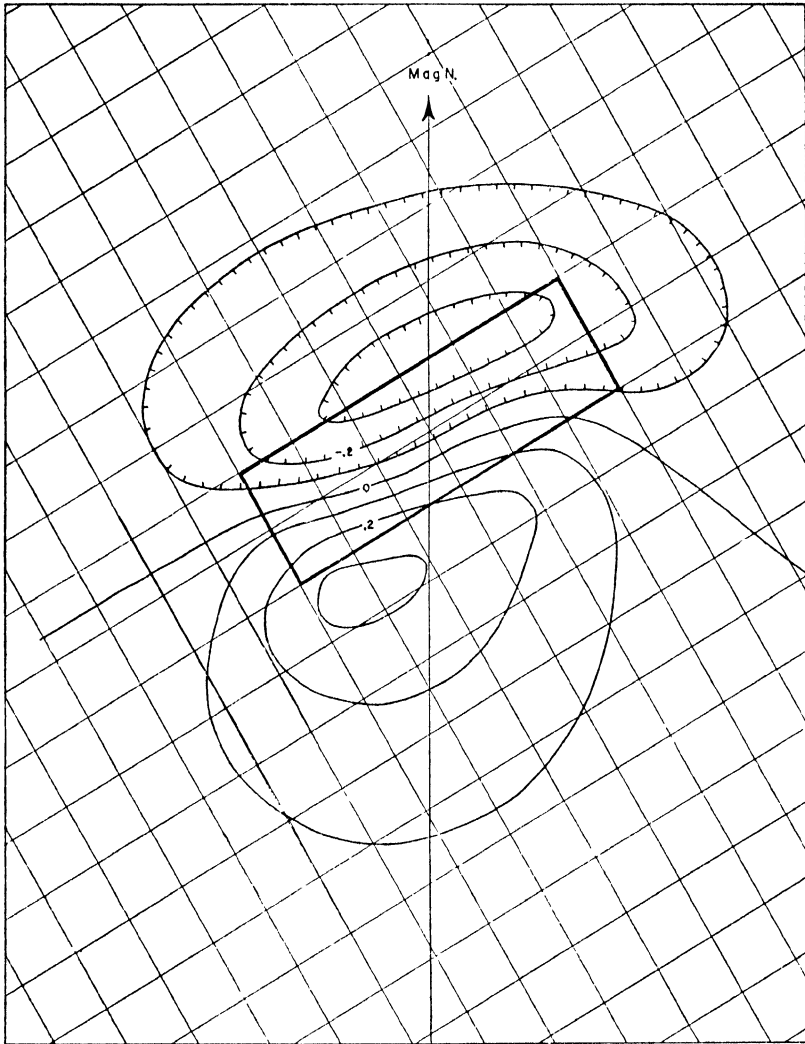
STRIKE = N 60° E or W (Mag)

FIGURE A37



$\text{CURVATURE, } \frac{\partial^2 \Delta T}{\partial Z^2} / 41$
 INCLINATION 30° GRID INTERVAL • DEPTH OF BURIAL
 STRIKE = N 60° E or W (Mag)

FIGURE A38



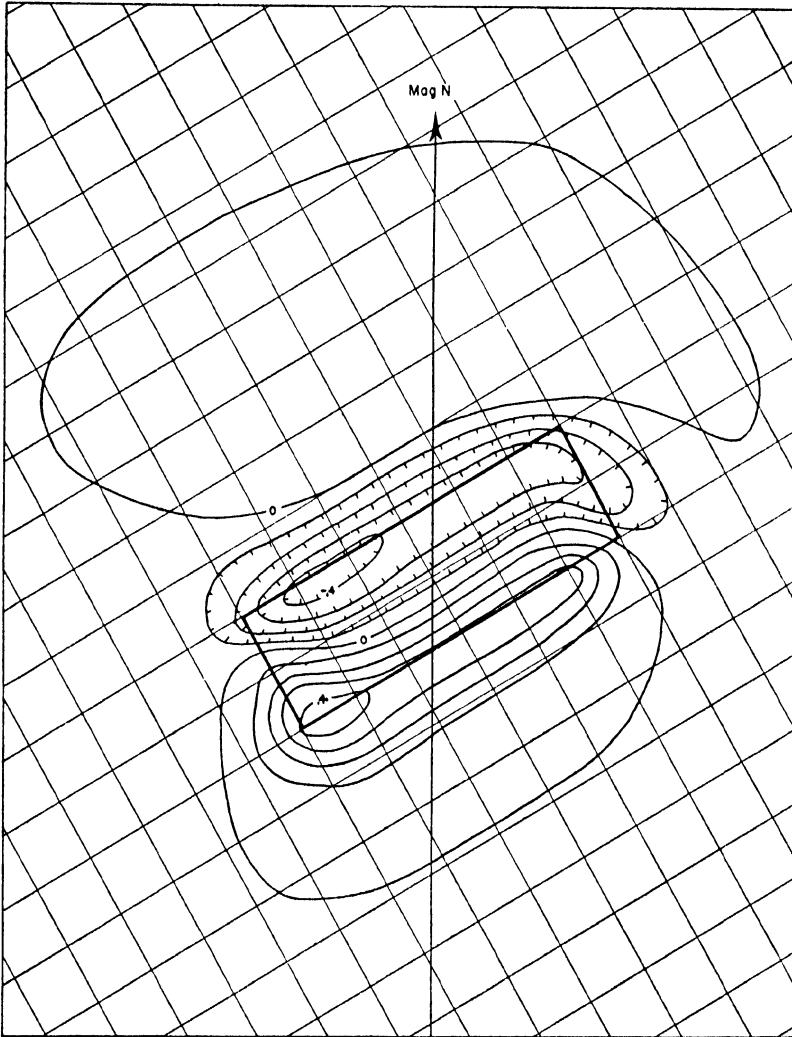
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

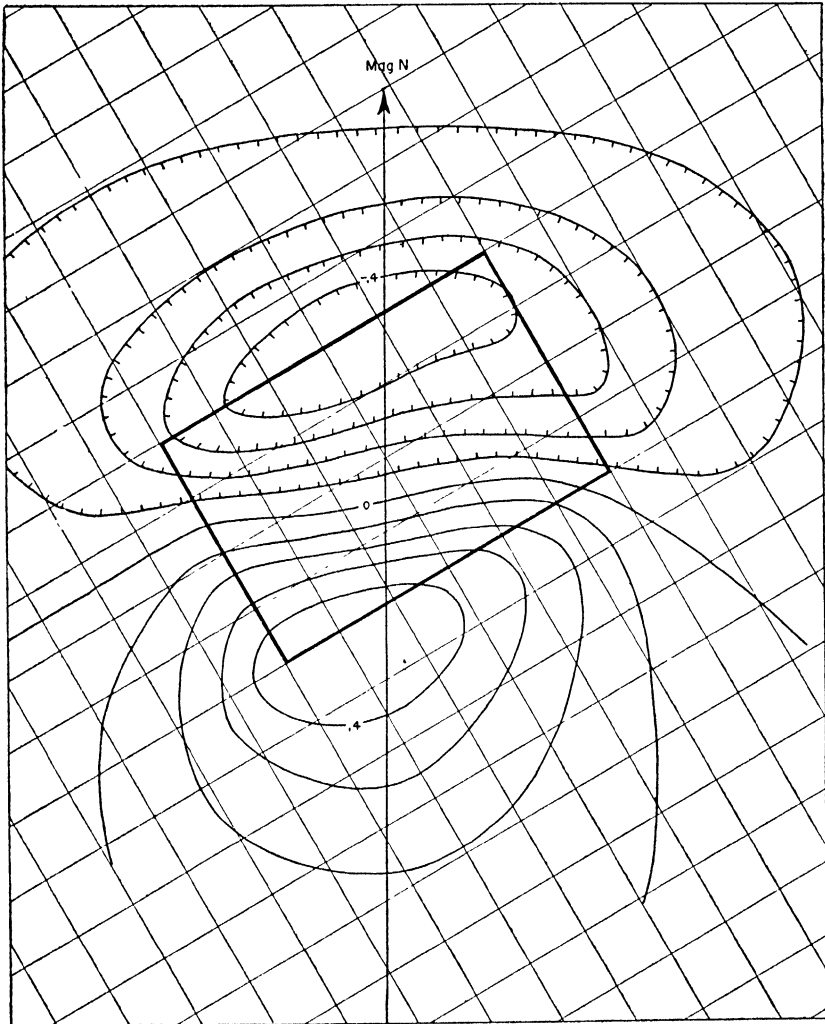
STRIKE = N 60° E or W (Mag)

FIGURE A39



$\text{CURVATURE} = \frac{\partial^2 I}{\partial x^2} / 4I$
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL
 STRIKE = N 60° E or W (Mag)

FIGURE A40



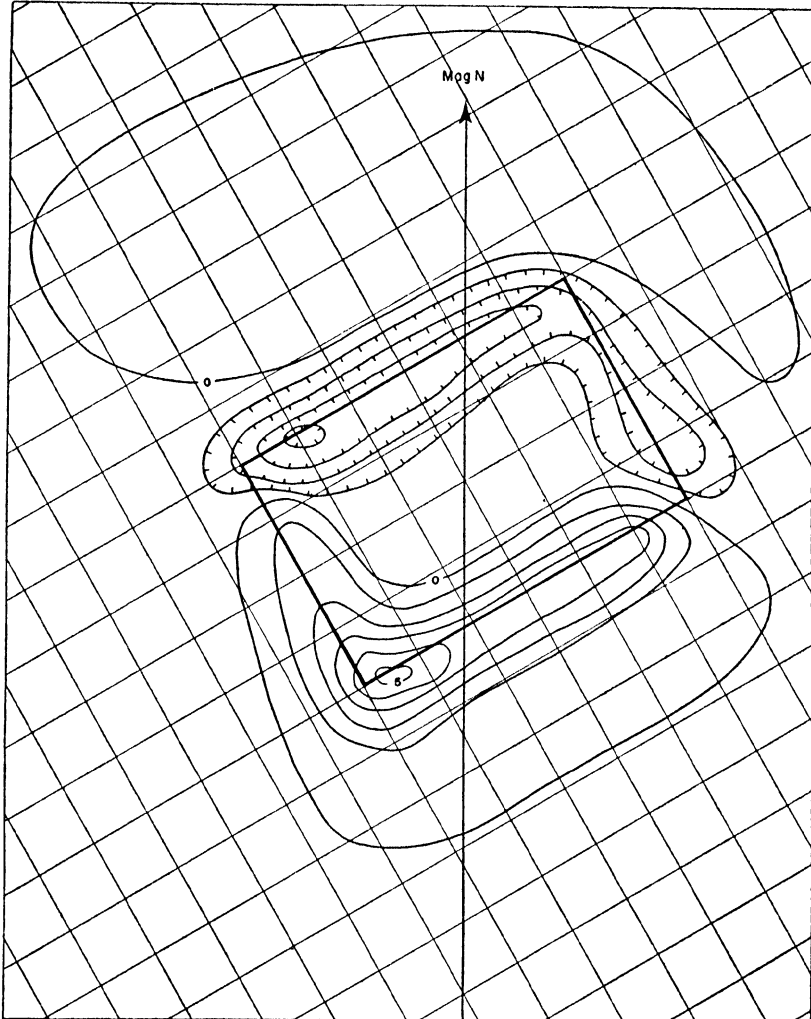
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

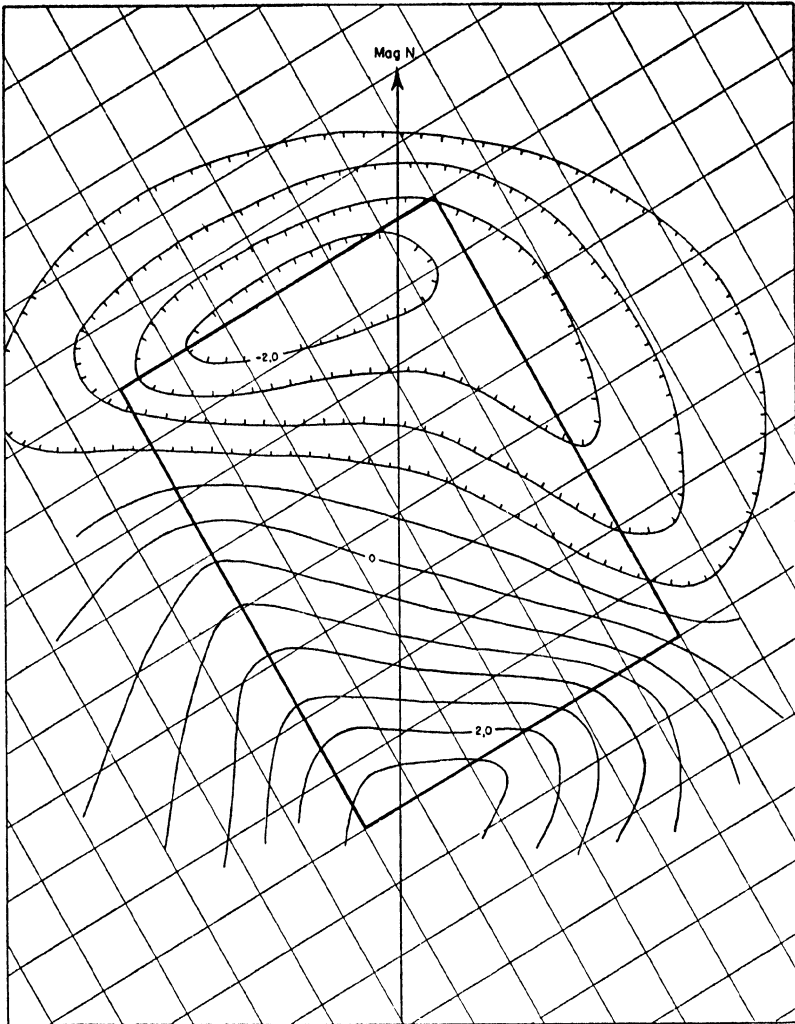
STRIKE = N 60° E or W (Mag)

FIGURE A41



$\text{CURVATURE, } \frac{\partial^2 T}{\partial x^2} / 4I$
 INCLINATION 30° GRID INTERVAL = DEPTH OF BURIAL
 STRIKE = $N 60^\circ E$ or $W (Mag)$

FIGURE A42



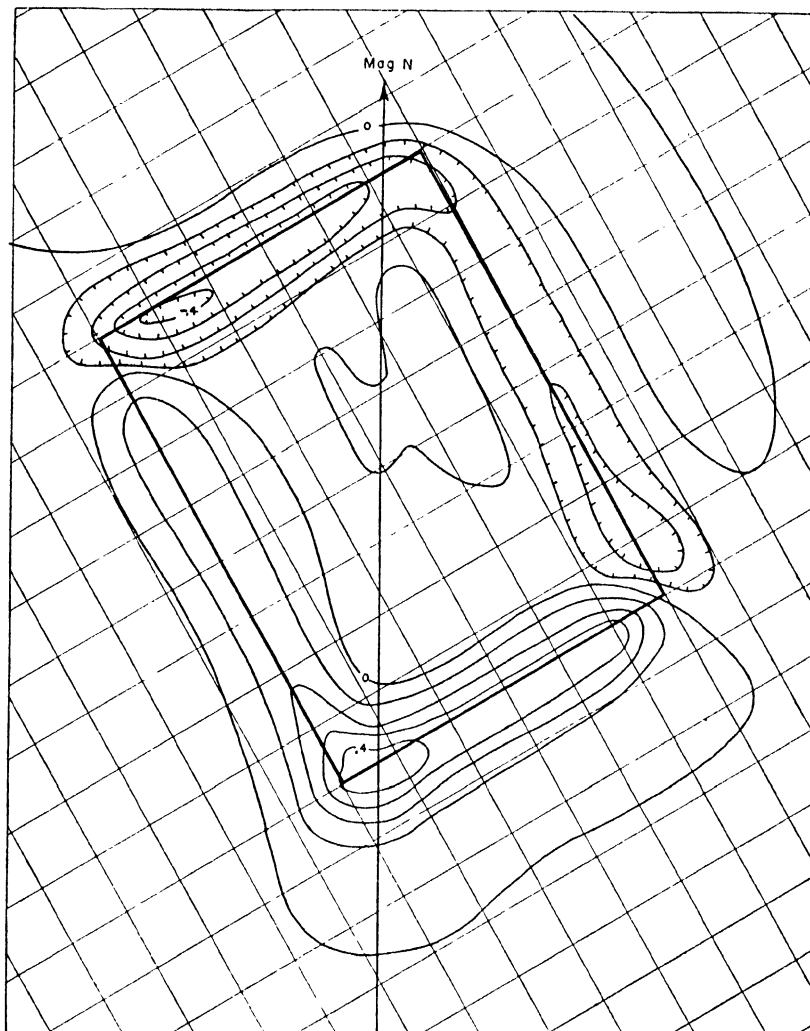
TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

STRIKE = $N 30^\circ E$ or W (Mag)

FIGURE A43



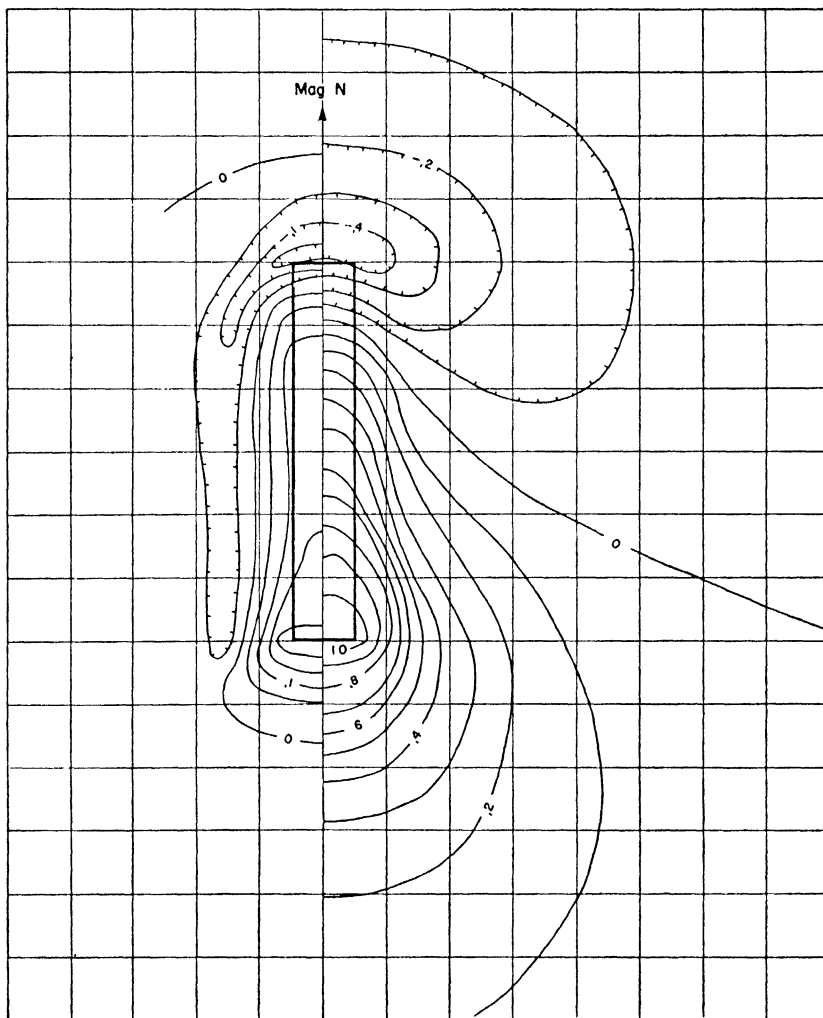
$CURVATURE \frac{\Delta^2 I}{\Delta z^2} / 4I$

INCLINATION 30°

GRID INTERVAL = DEPTH OF BURIAL

STRIKE = N 30° E or W (Mag)

FIGURE A44

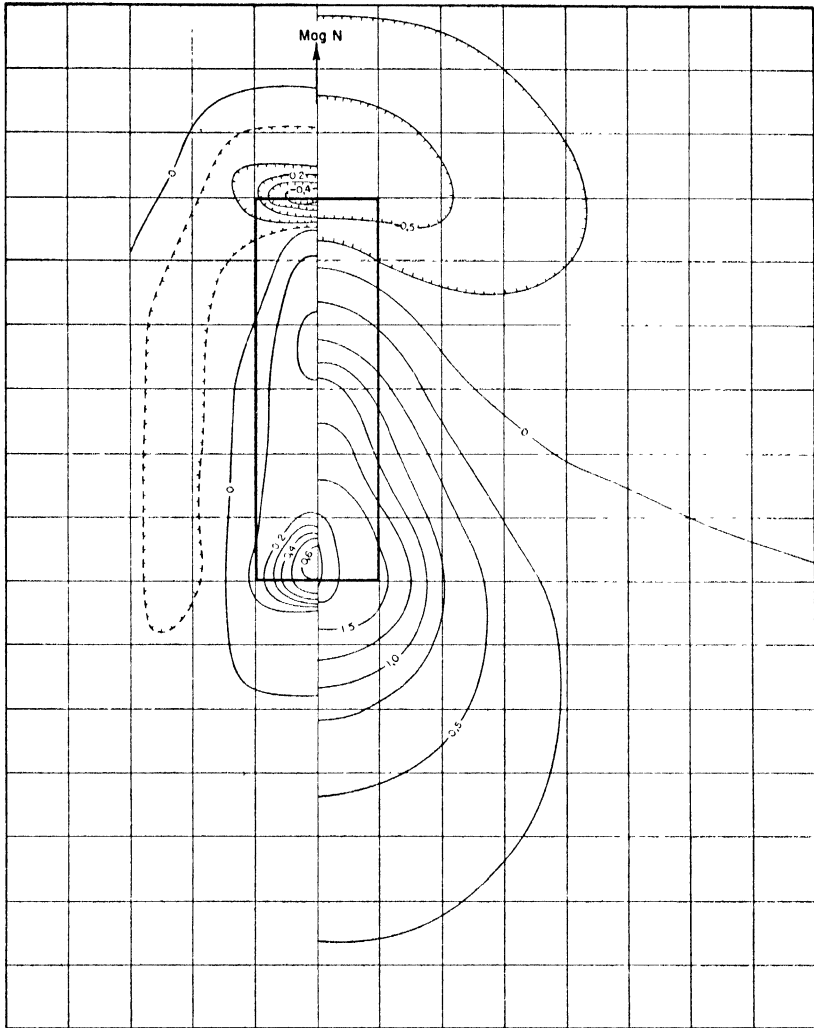


CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \rightarrow$ TOTAL INTENSITY, $4I/I$ (CGS)

INCLINATION 45°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A45

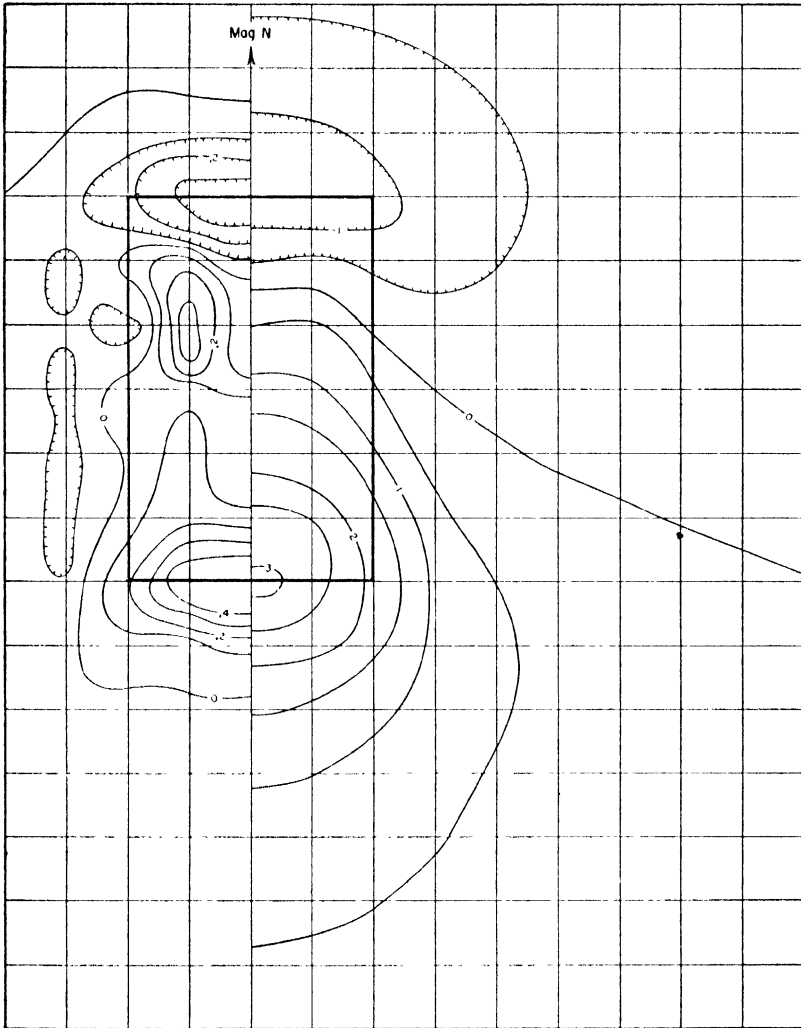


CURVATURE, $\frac{\partial^2 T}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 45°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A46

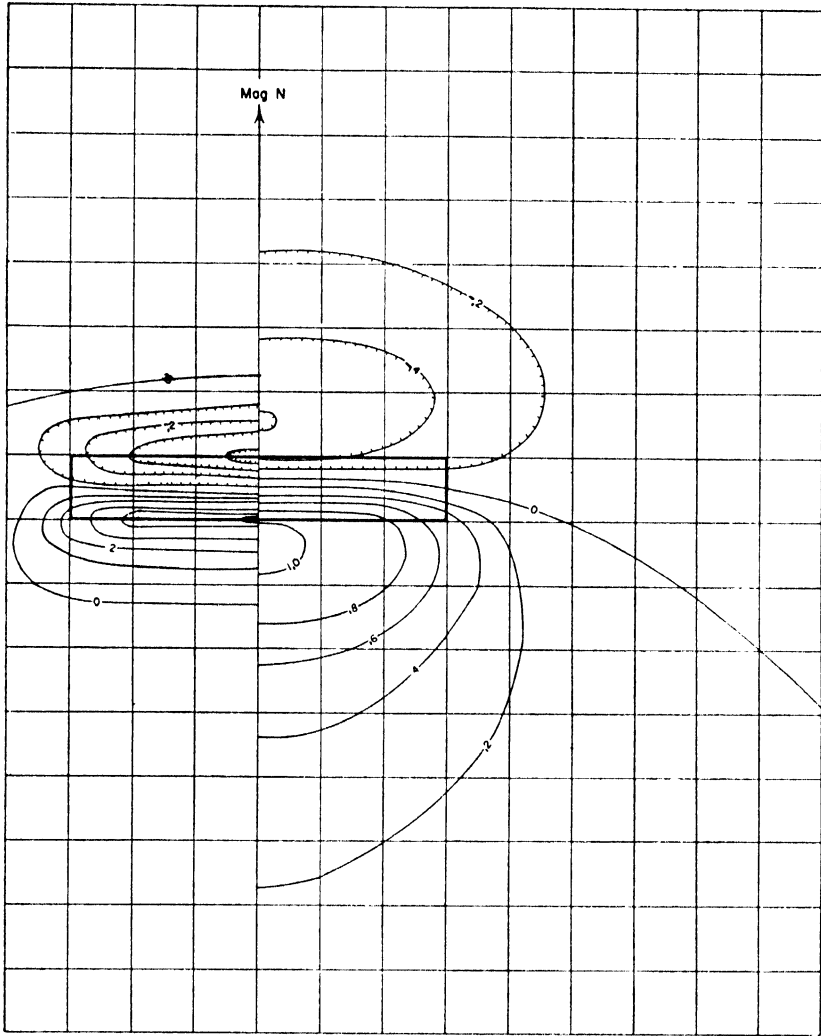


CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \leftrightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 45°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A47

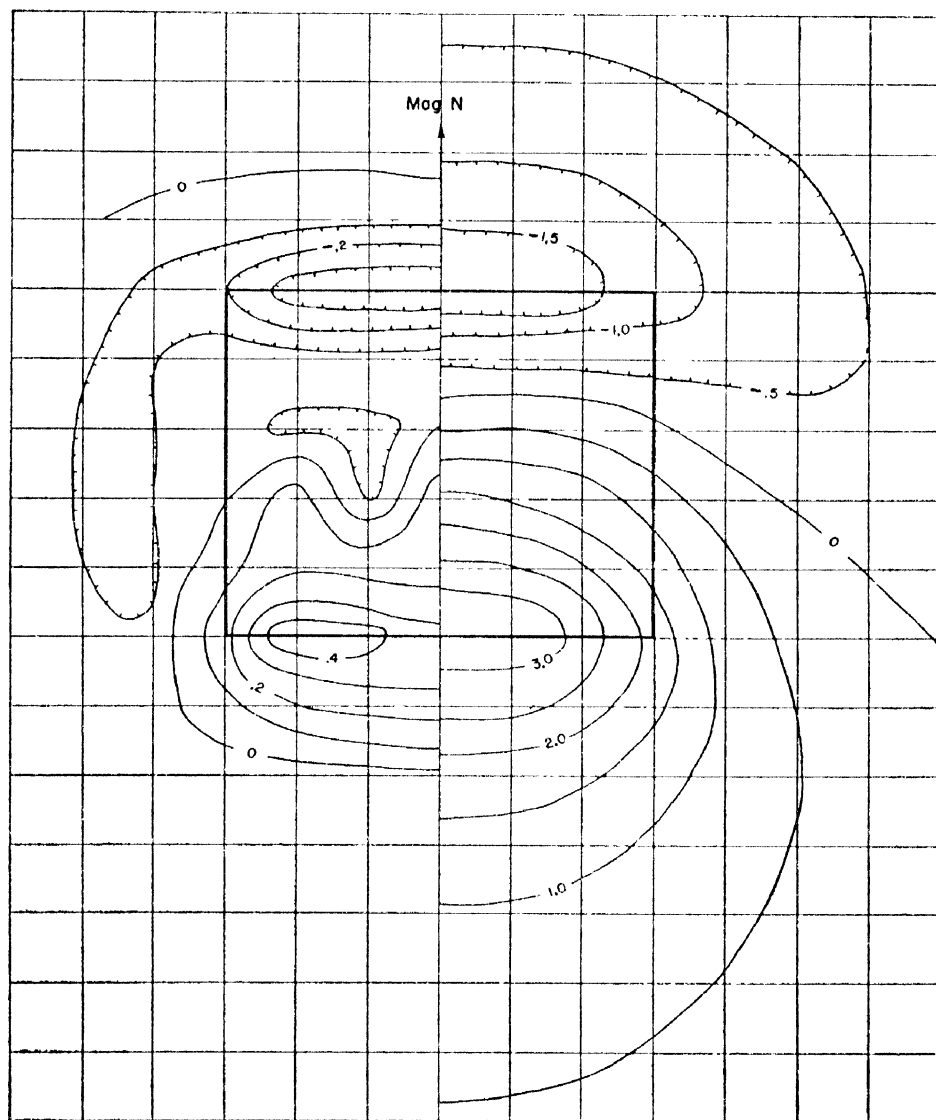


CURVATURE, $\frac{\Delta^2 T}{\Delta t^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (C.G.S.)

INCLINATION 45°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A49

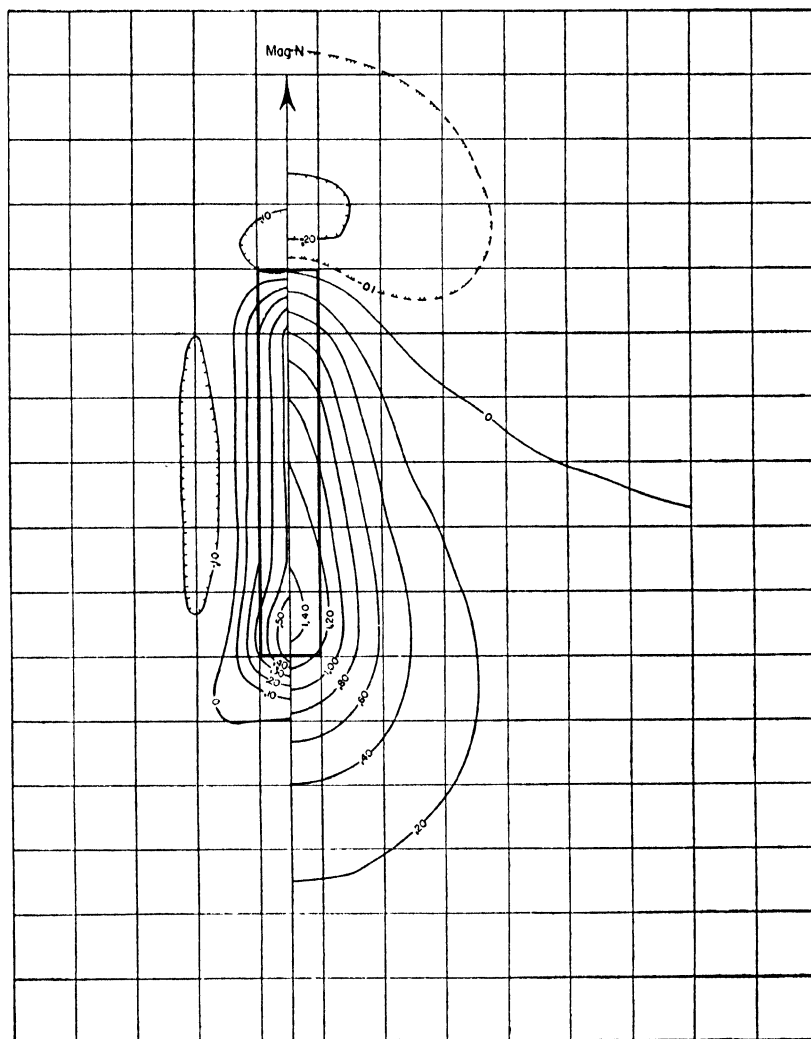


CURVATURE, $\frac{\partial^2 \Delta T}{\partial I^2} / 4I \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 45°

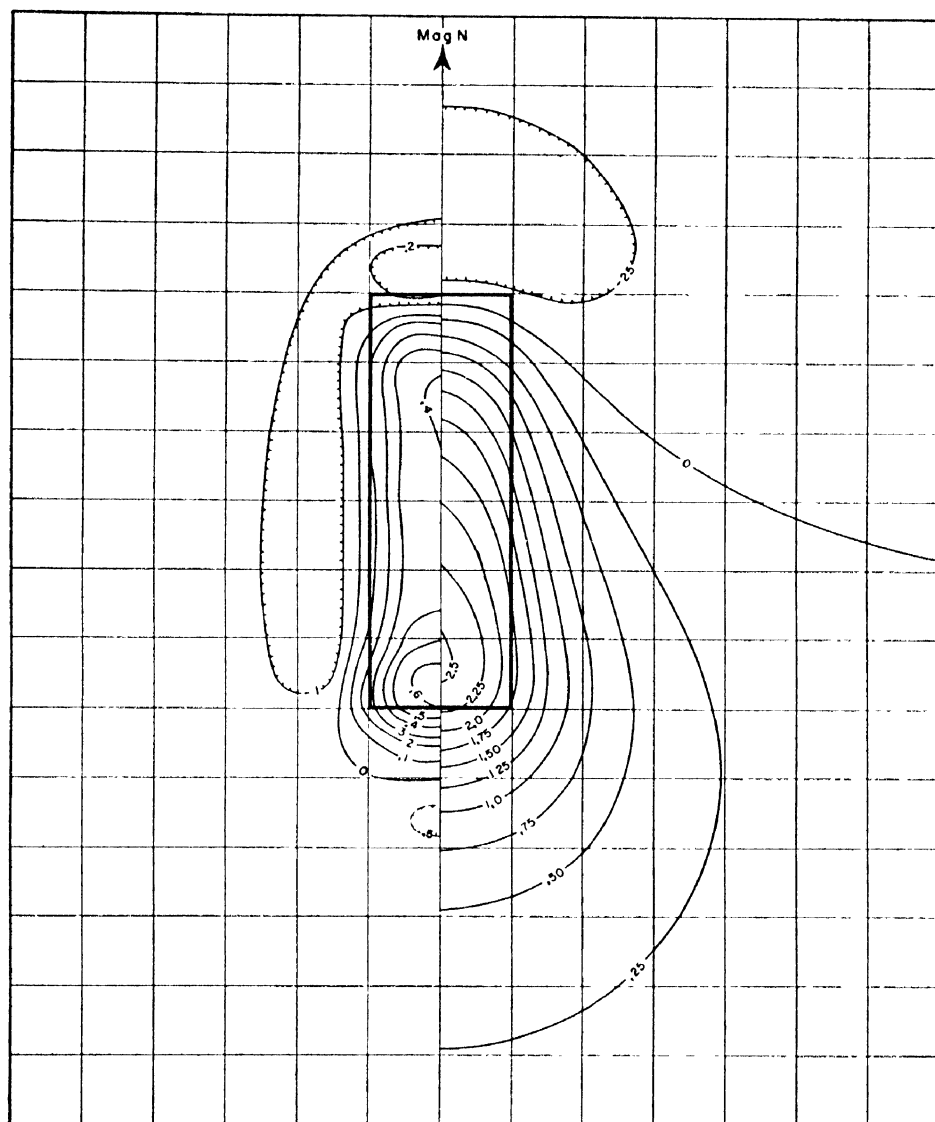
GRID INTERVAL = DEPTH OF BURIAL

FIGURE A50



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (GGS)
 INCLINATION 60° GRID INTERVAL = 0.25TH OF BURIAL

FIGURE A51

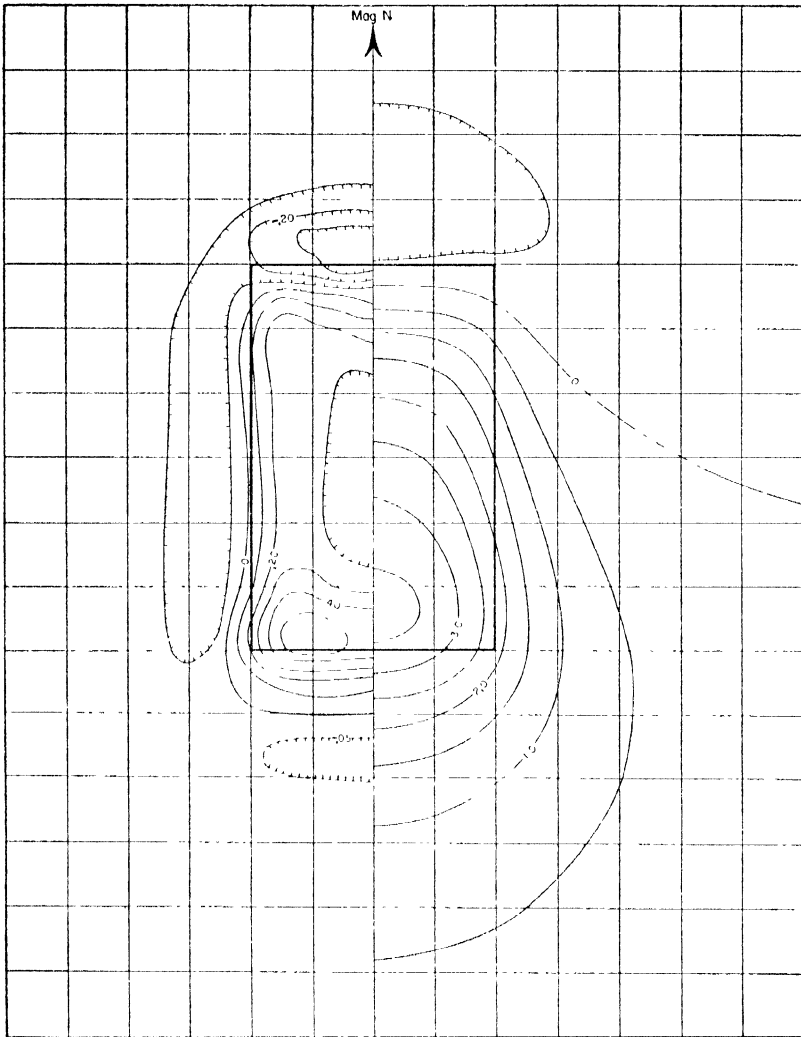


CURVATURE, $\frac{\partial^2 \Delta I}{\partial x^2} \text{ mI} \longleftrightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 60°

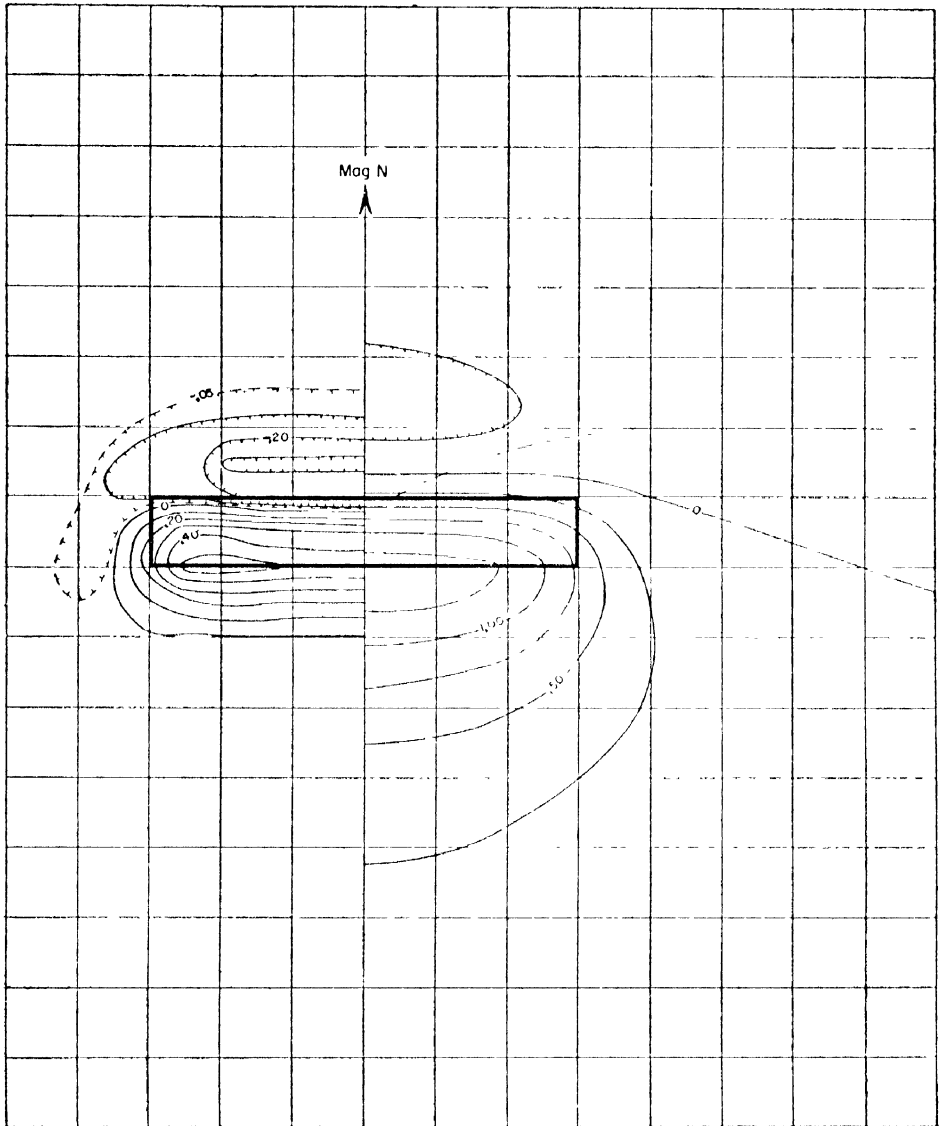
GRID INTERVAL = DEPTH OF BURIAL

FIGURE A52



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)
 (NO. NATIVE G) (Gauss intensity) x DEPTH OF BURIAL

FIGURE A53

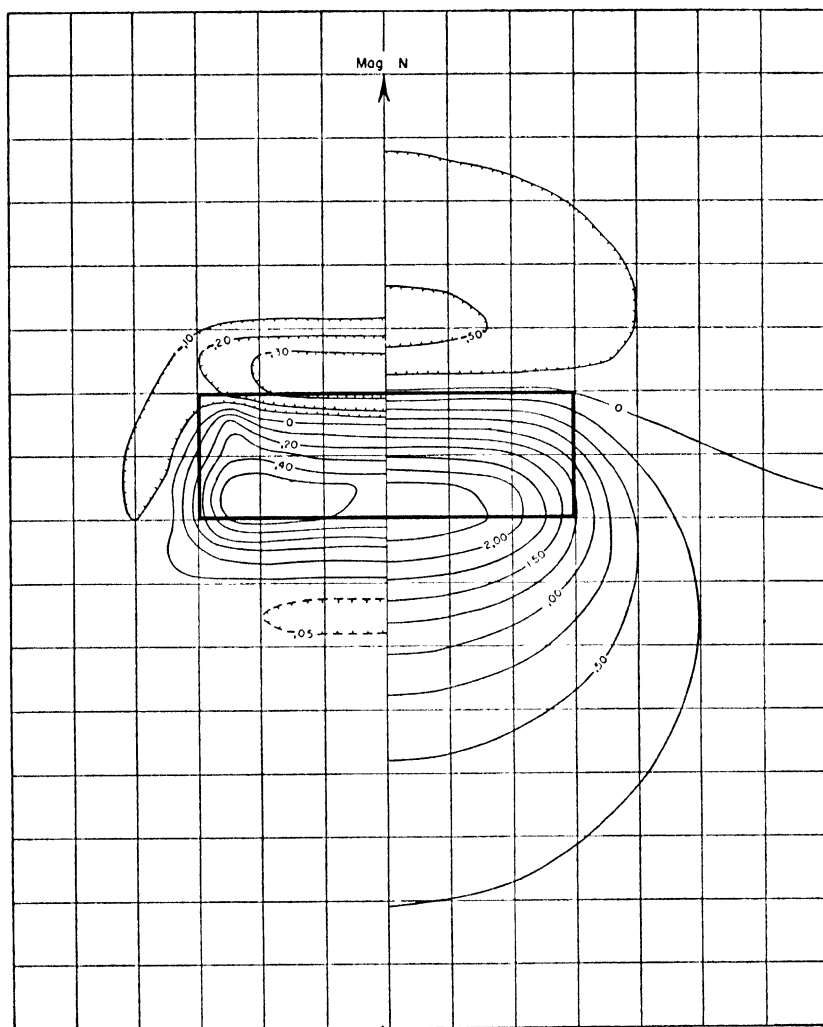


CURVATURE, $\frac{\partial^2 \Delta I}{\partial x^2} / \Delta I \longleftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A54

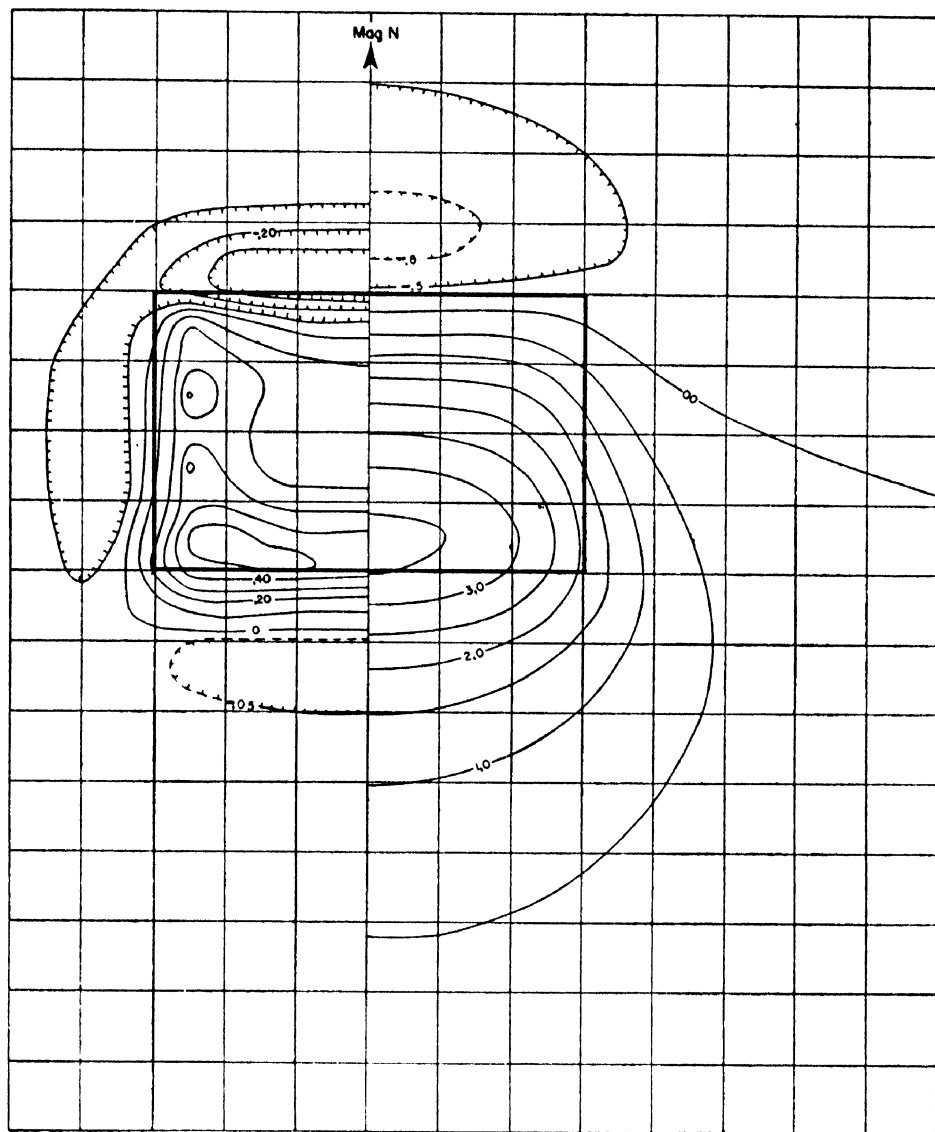


CURVATURE, $\frac{\Delta H}{\Delta I} / 41$ $\longleftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A55

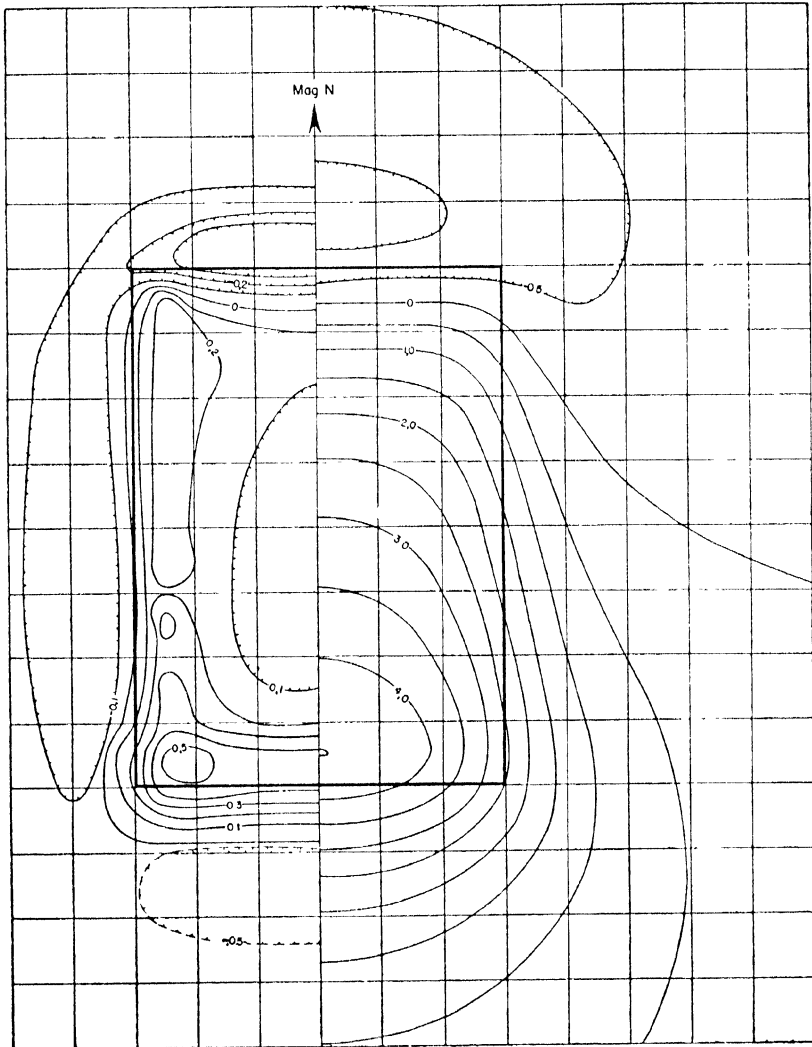


CURVATURE, $\frac{\partial^2 I}{\partial x^2}$ — TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A56

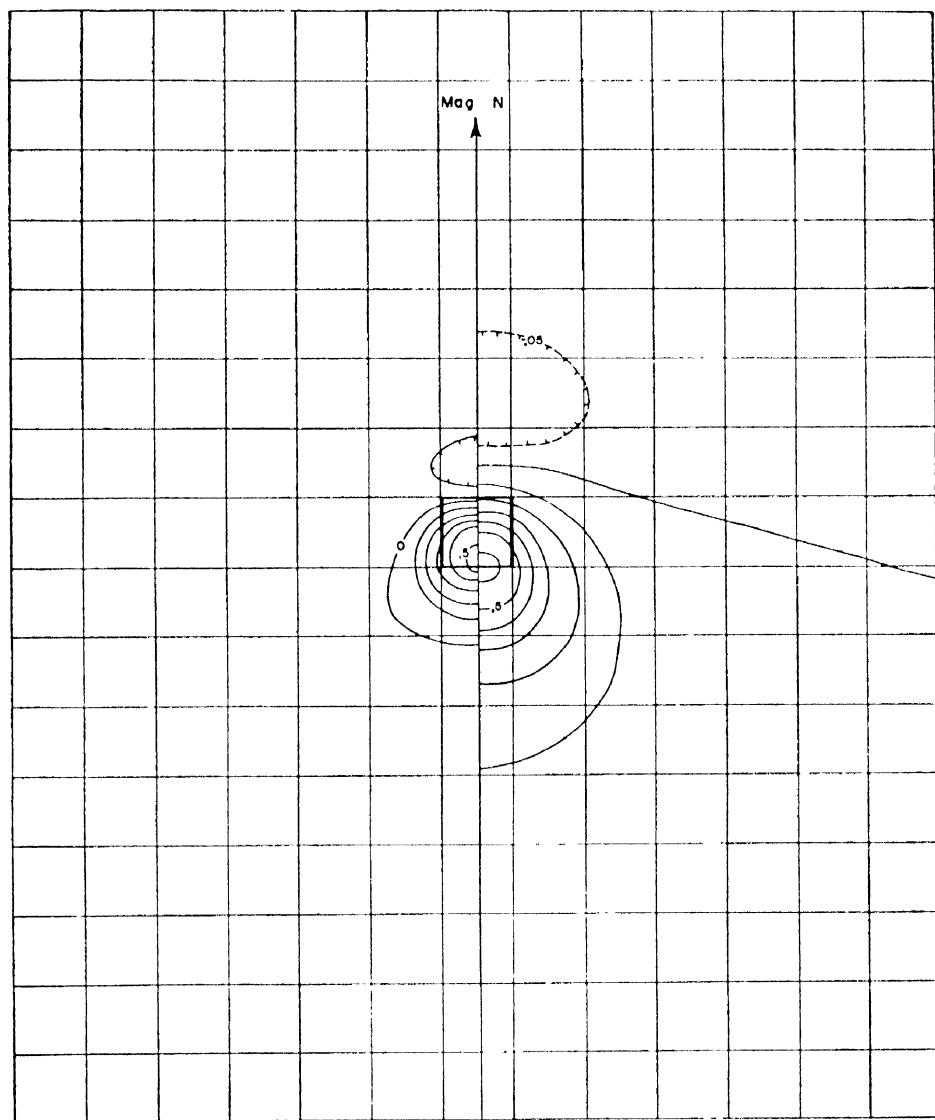


CURVATURE, $\frac{d^2I}{dx^2} / I \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A57



CURVATURE $\frac{\partial^2 T}{\partial x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A58

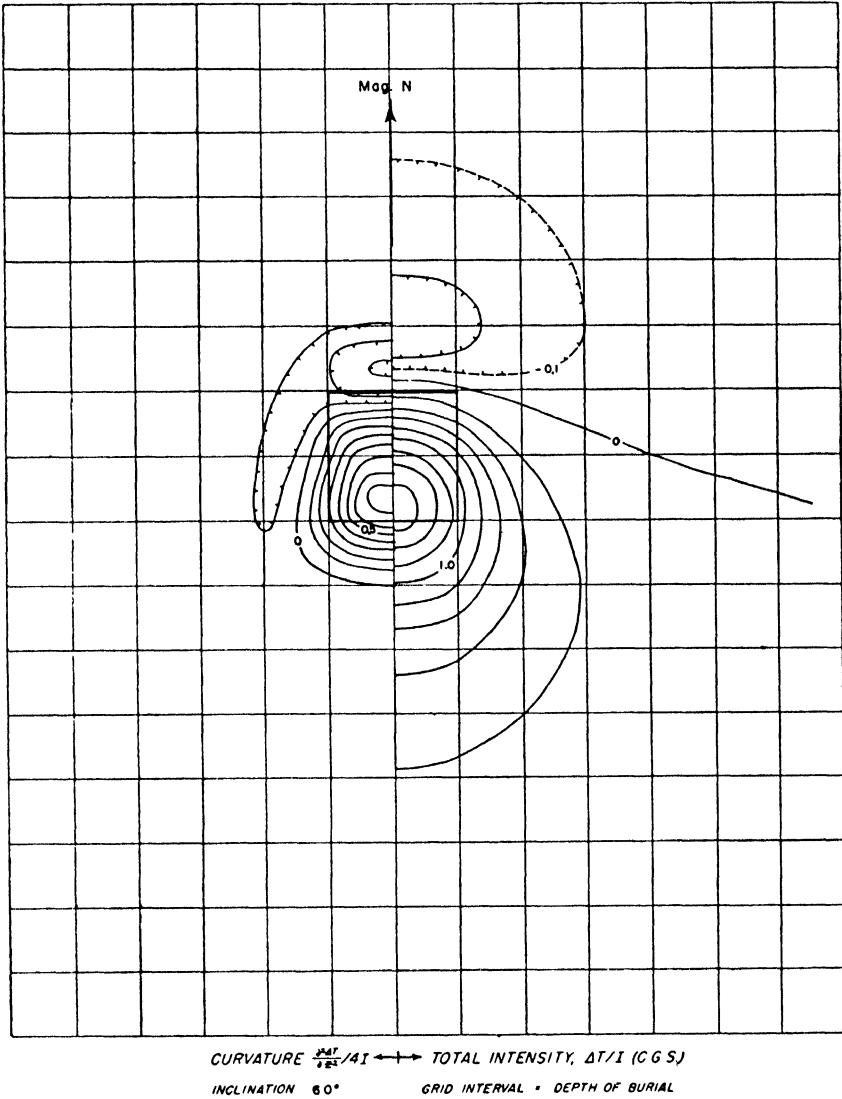
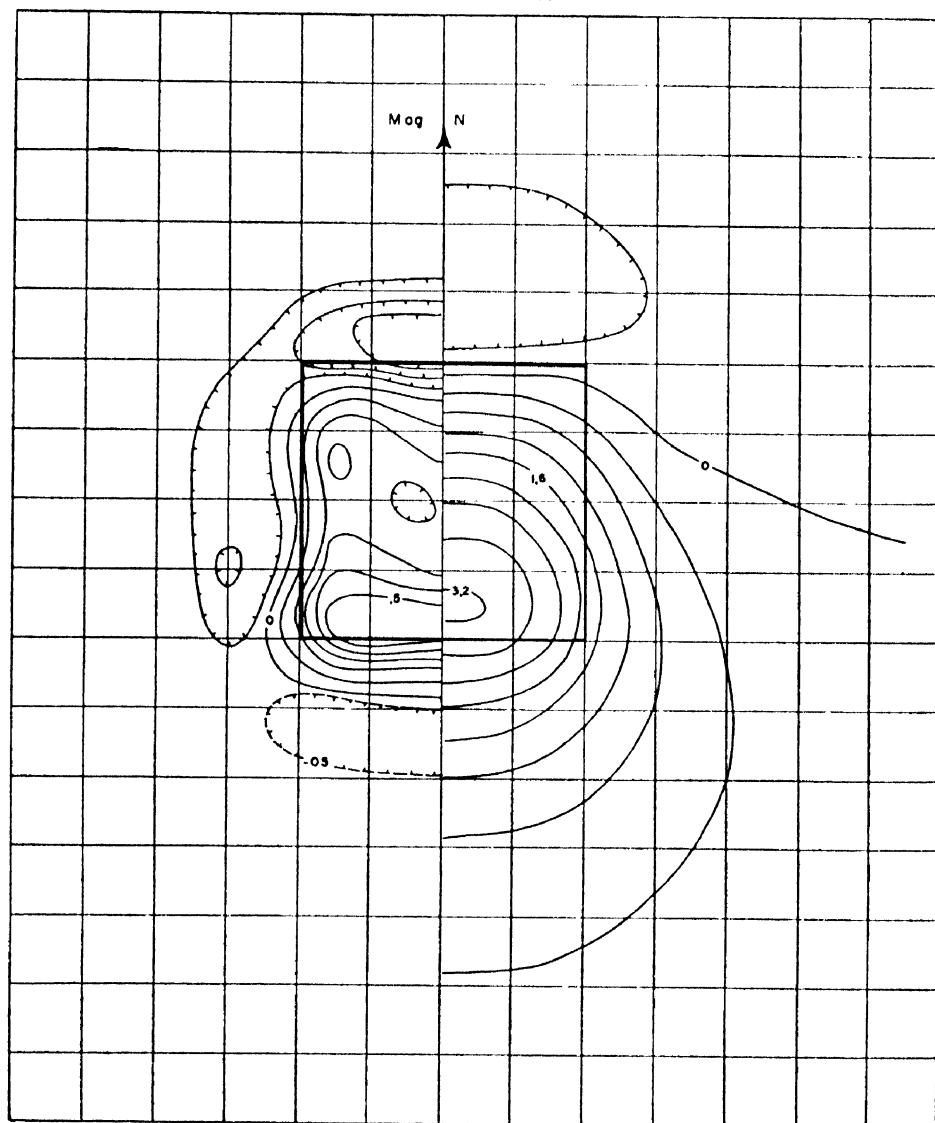


FIGURE A59

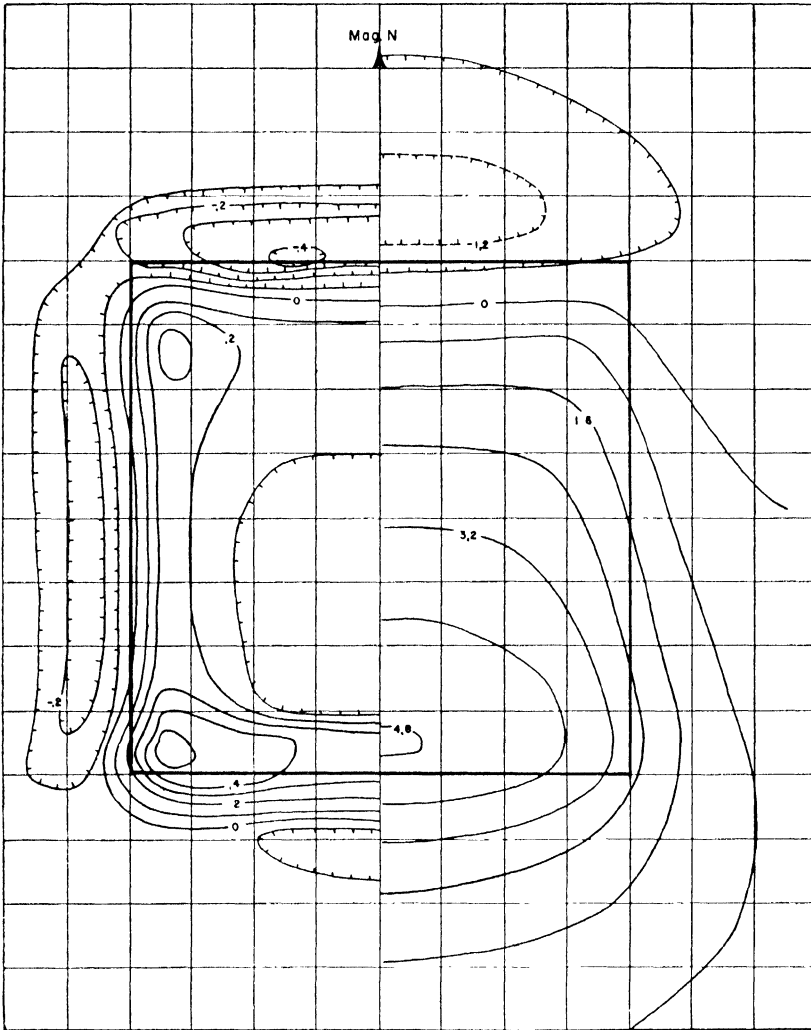


CURVATURE $\frac{\partial^2 \Delta I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A60

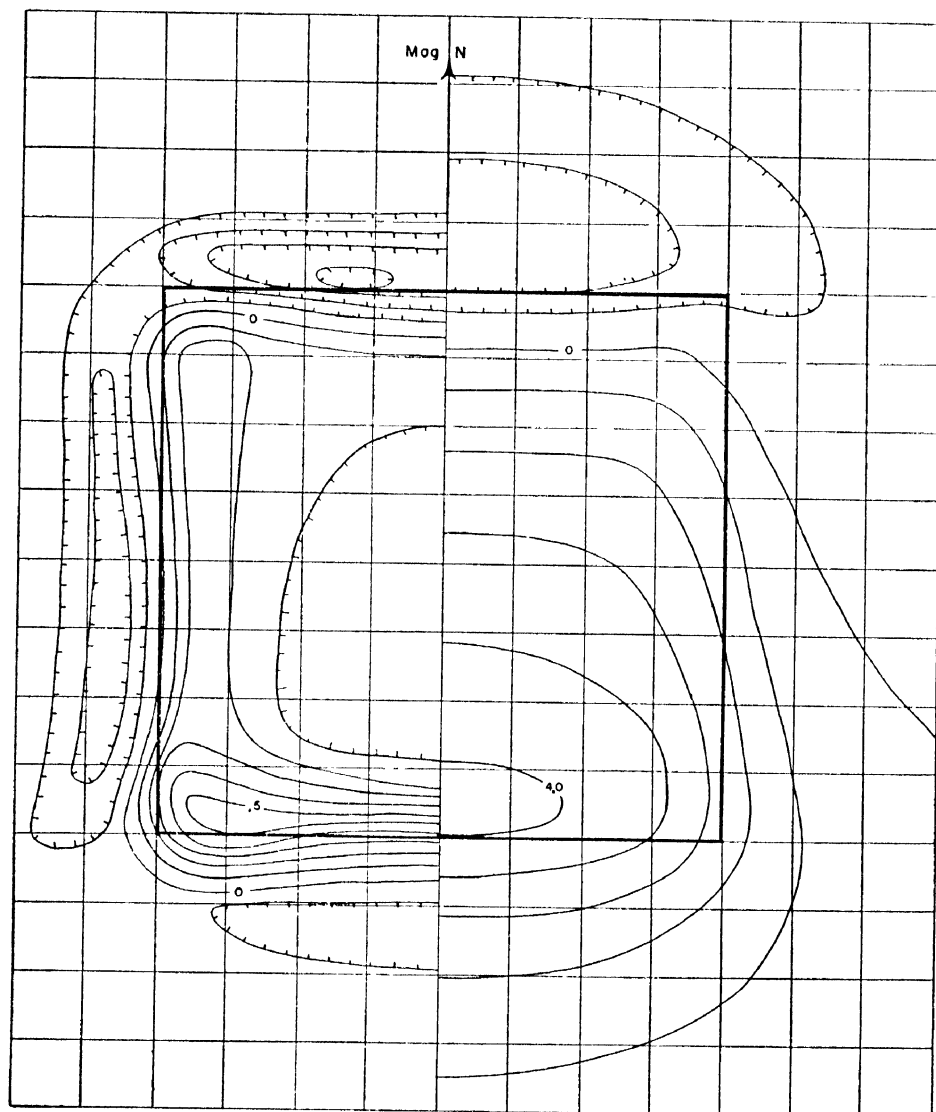


CURVATURE $\frac{\Delta^2 I}{\Delta x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 6.0°

GRID INTERVAL = DEPTH OF BURIAL

FIGURE A61



CURVATURE $\frac{\partial^2 I}{\partial x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

MODEL DIMENSIONS $8 \times 8 \times 7$

FIGURE A62

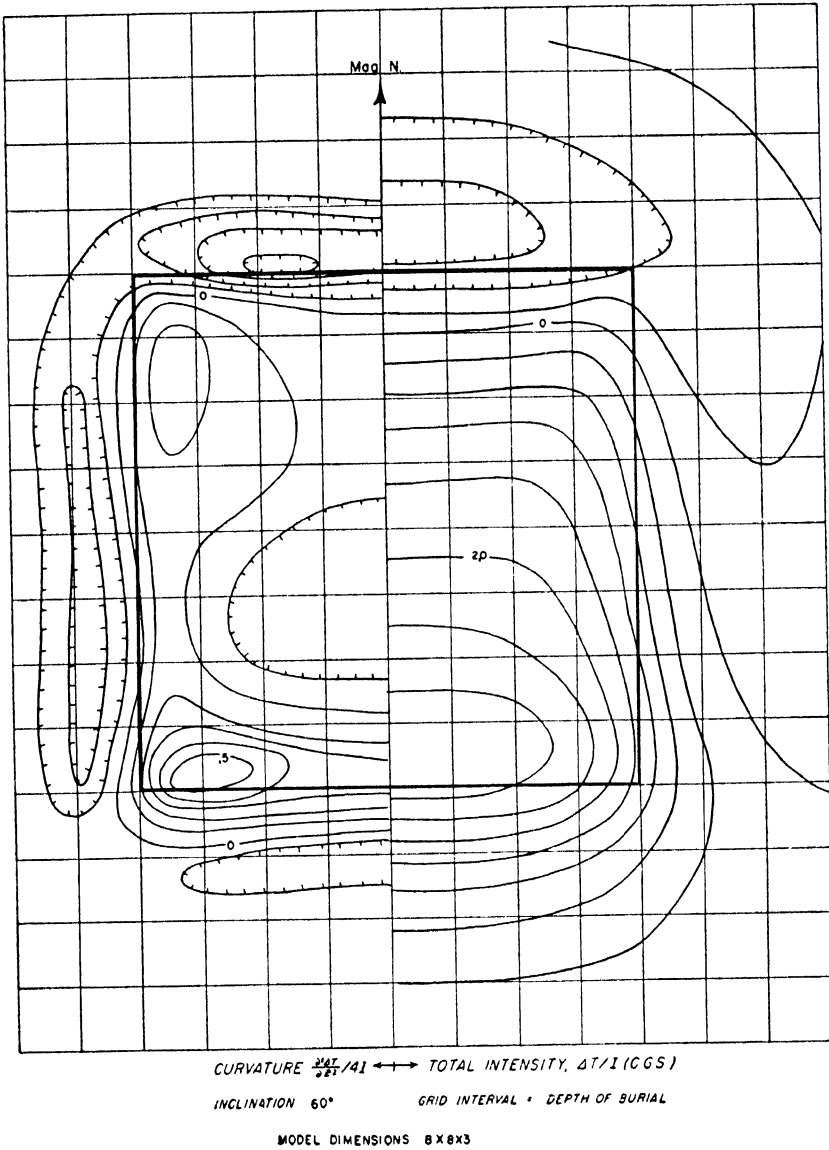
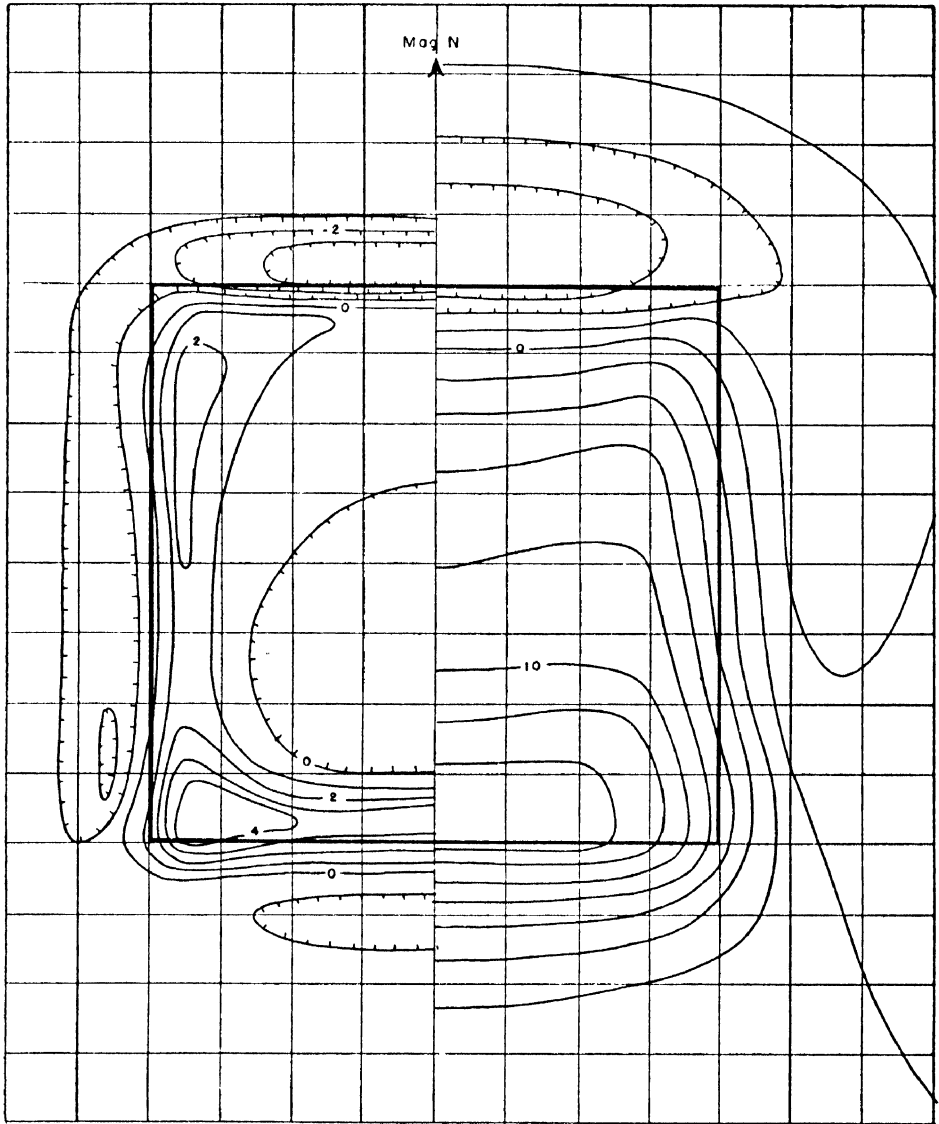


FIGURE A63



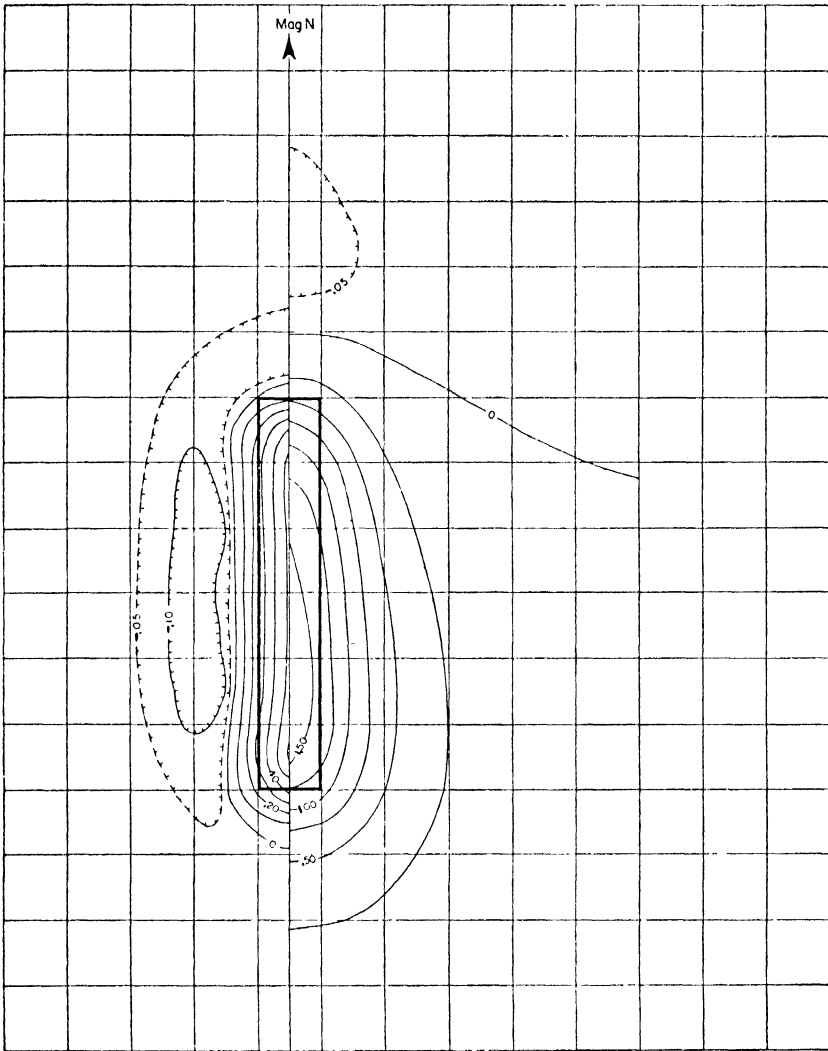
CURVATURE $\frac{\partial^2 I}{\partial x^2} / 4I \leftarrow \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 60°

GRID INTERVAL = DEPTH OF BURIAL

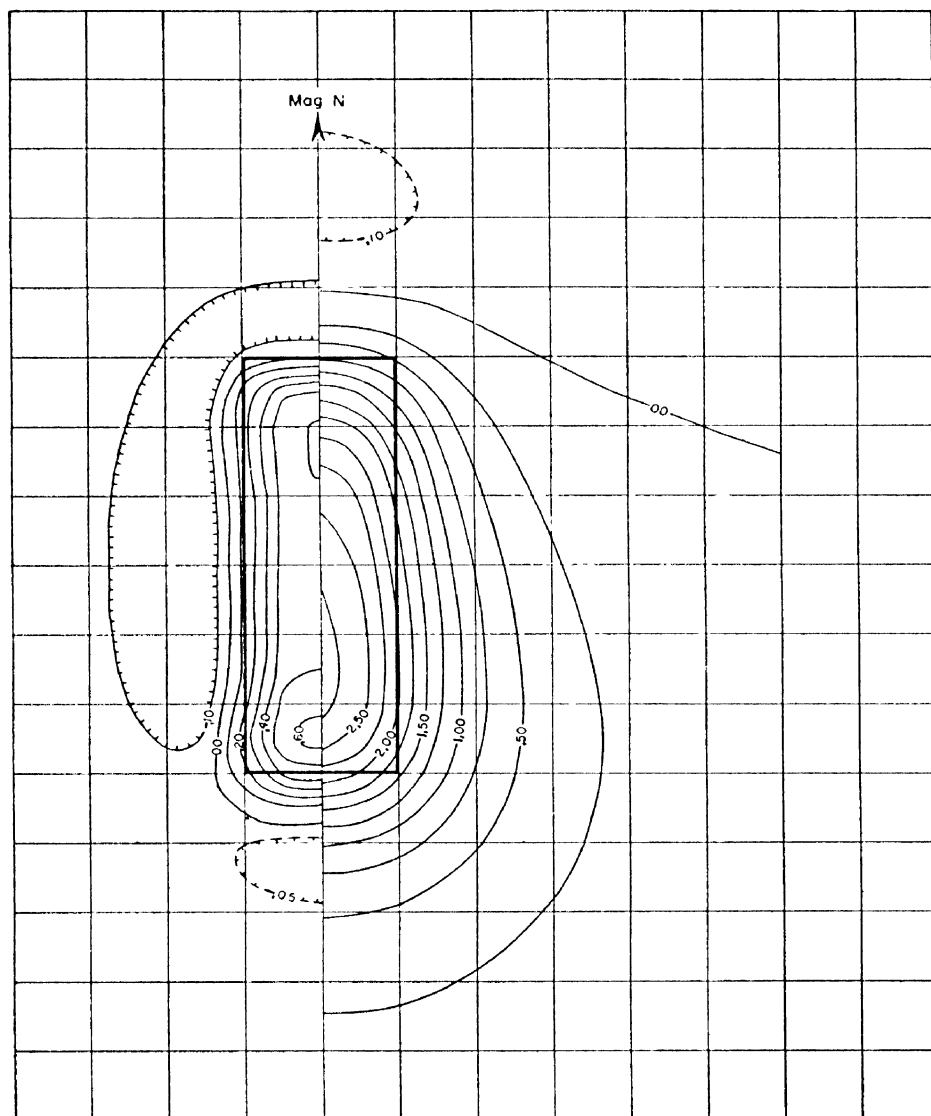
MODEL DIMENSIONS $8 \times 8 \times 1$

FIGURE A64



CURVATURE $\frac{\partial^2 \Delta T}{\partial x^2} / 4I$ $\longleftrightarrow$ TOTAL INTENSITY, $\Delta T/I$ (CGS)
 INCLINATION 75° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A65

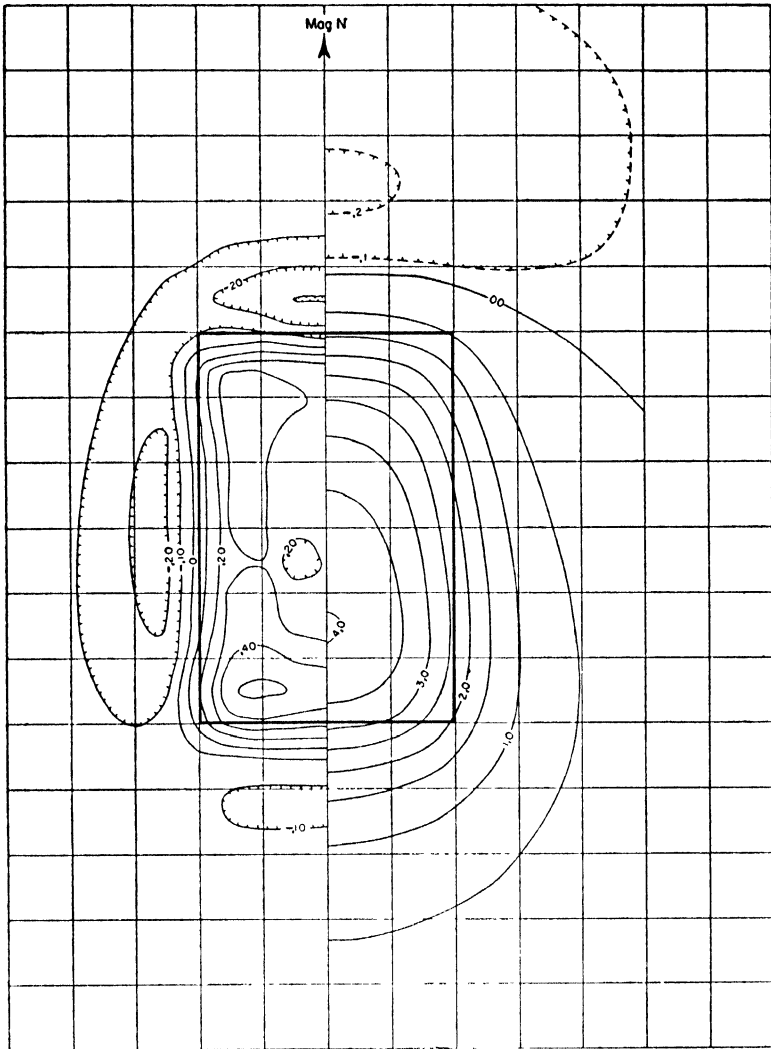


CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 75°

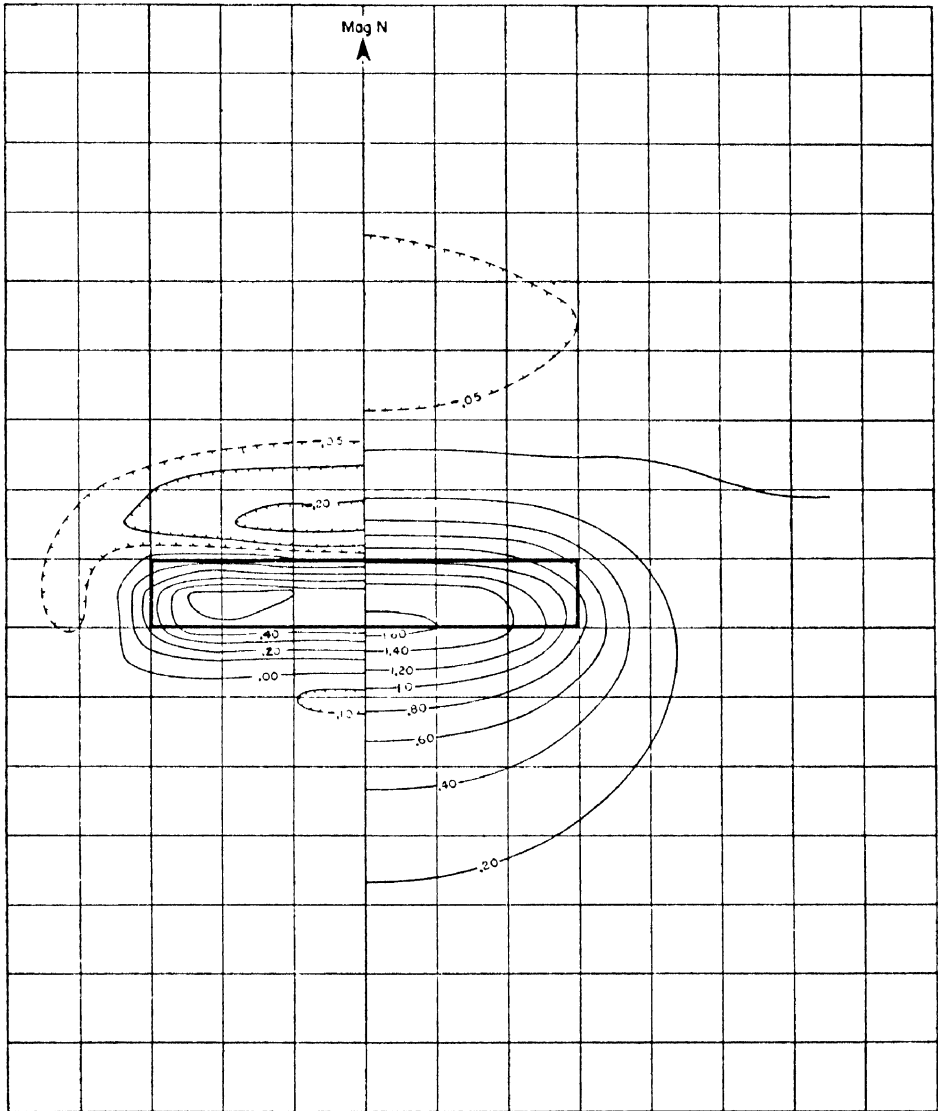
GRID INTERVAL = DEPTH OF BURIAL

FIGURE A66



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)
 INCLINATION 75° GRID INTERVAL - DEPTH OF BURIAL

FIGURE A67



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)
 INCLINATION 75° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A68

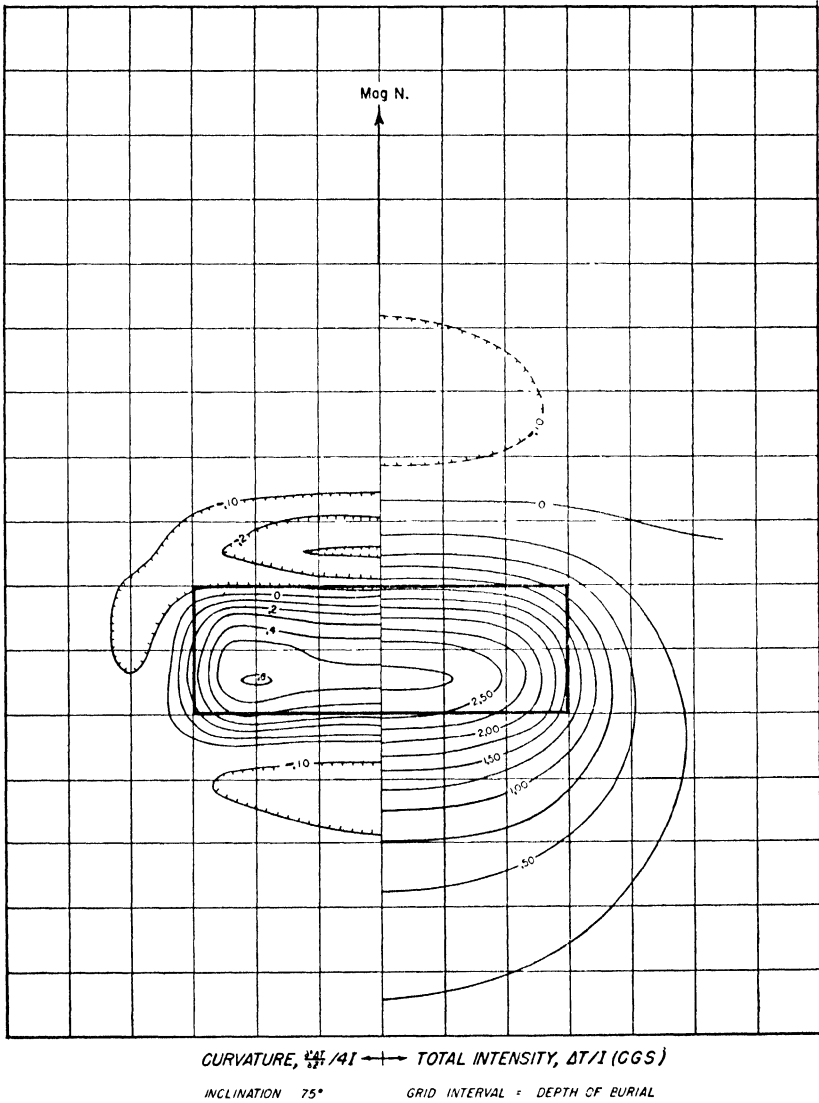
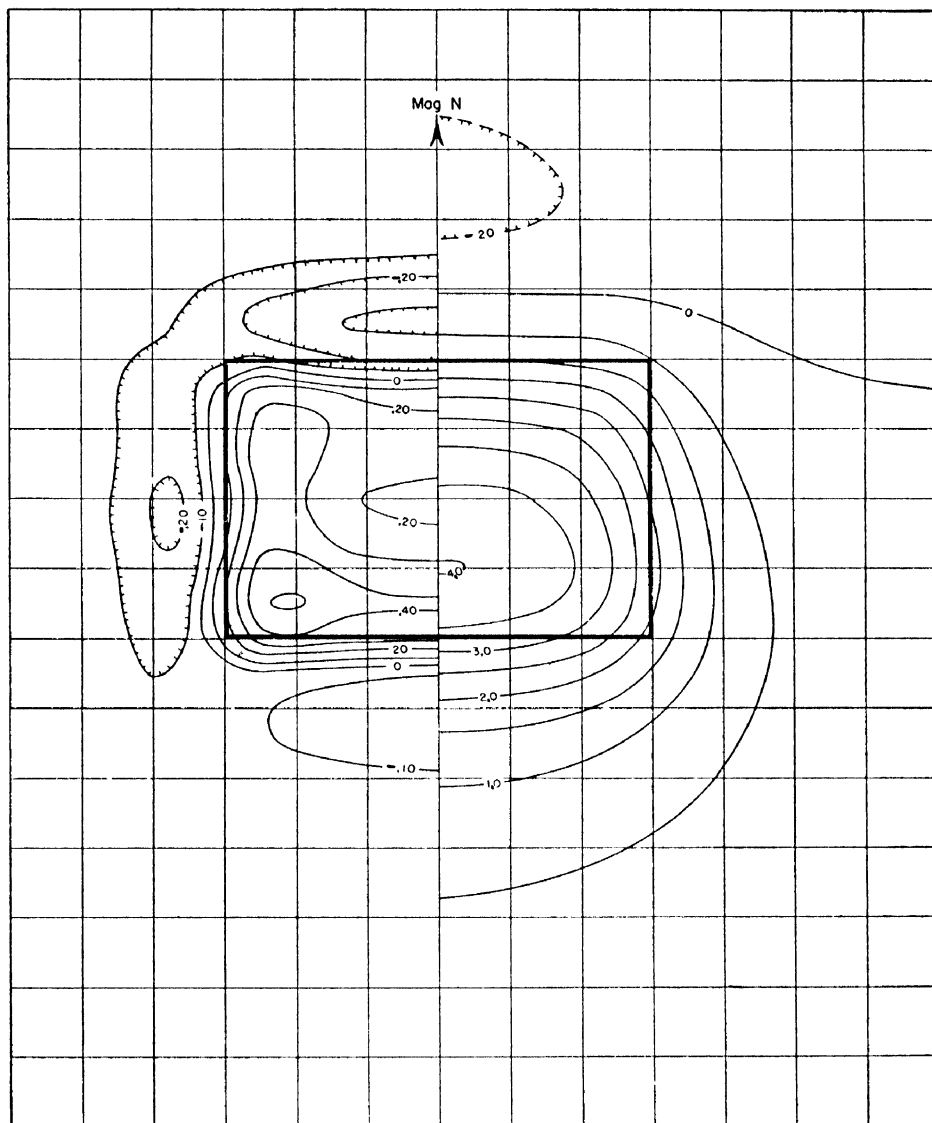


FIGURE A69



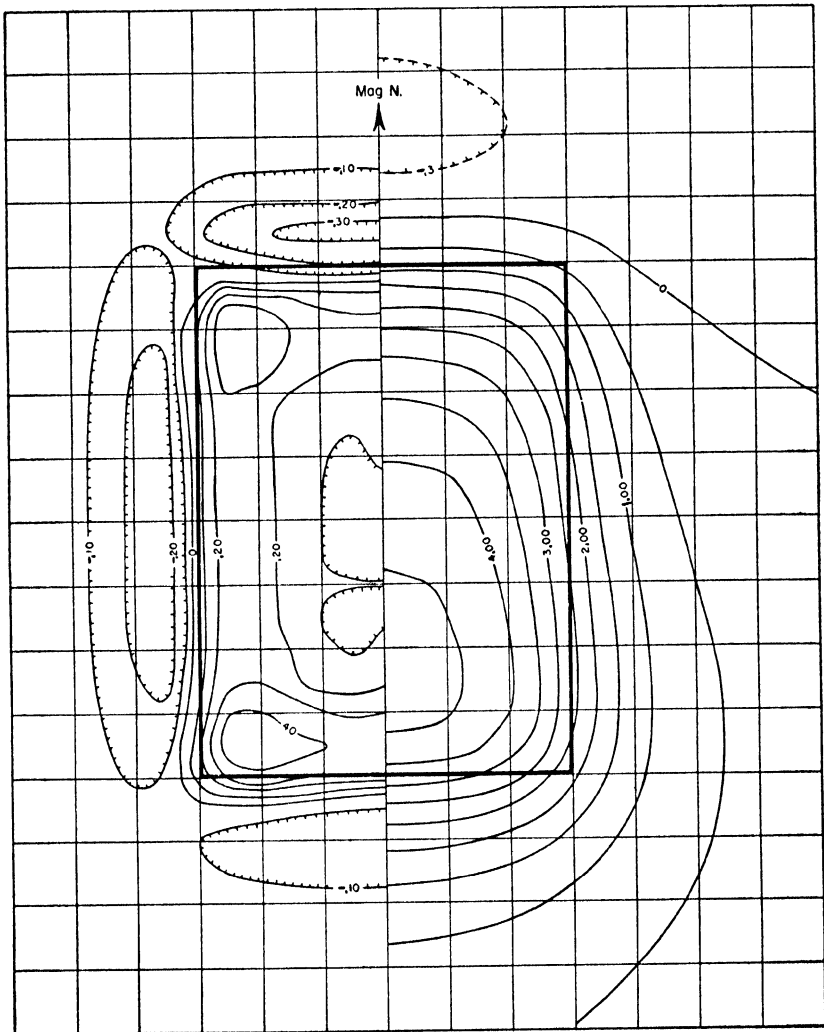
CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \leftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)

INCLINATION 75°

GRID INTERVAL = DEPTH OF BURIAL

123

FIGURE A70

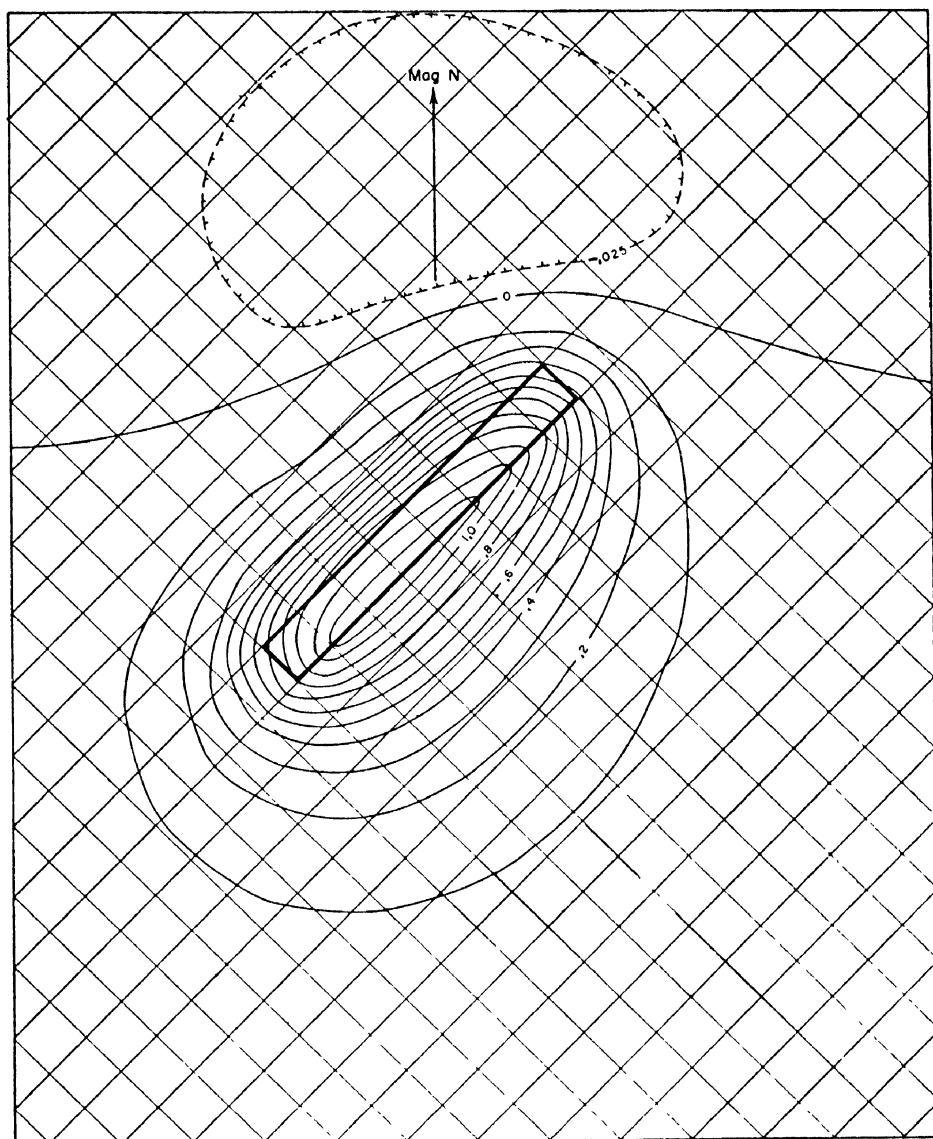


CURVATURE, $\frac{4H}{R}/4I \rightarrow$ TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 75°

GRID INTERVAL = DEPTH OF BURIAL

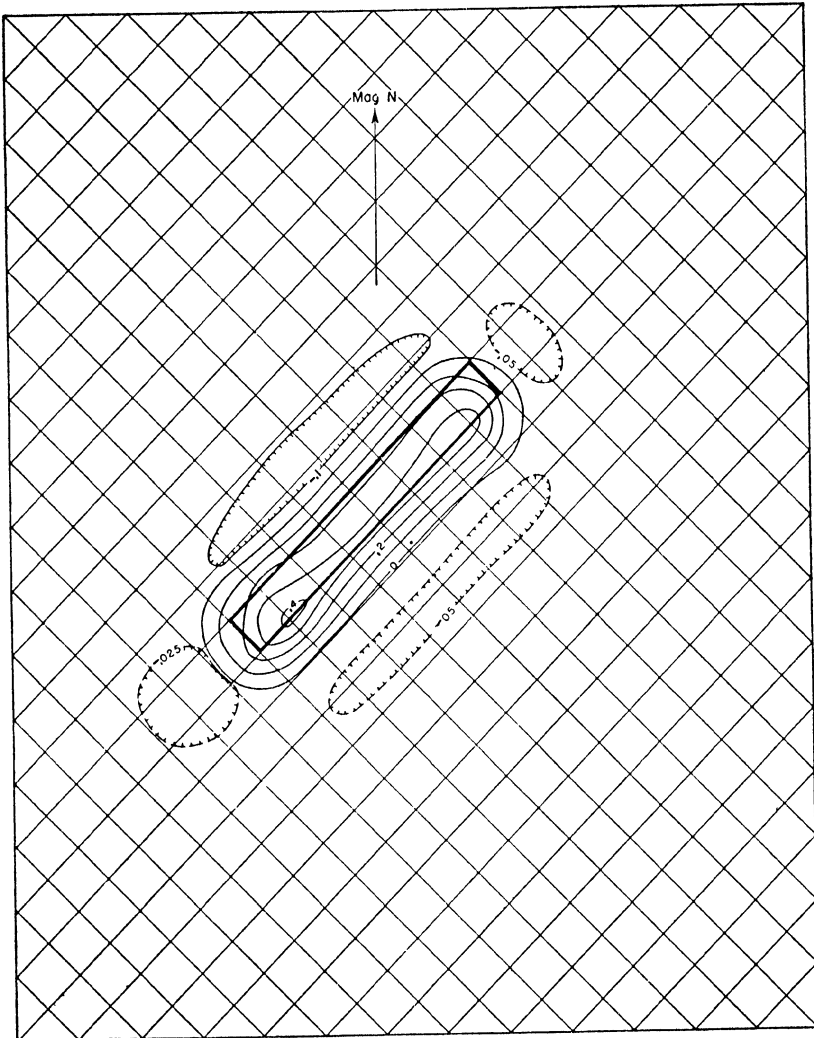
FIGURE A71



TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 75° GRID INTERVAL : 0.7 DEPTH OF BURIAL
STRIKE = $N 45^\circ E$ (MAG)

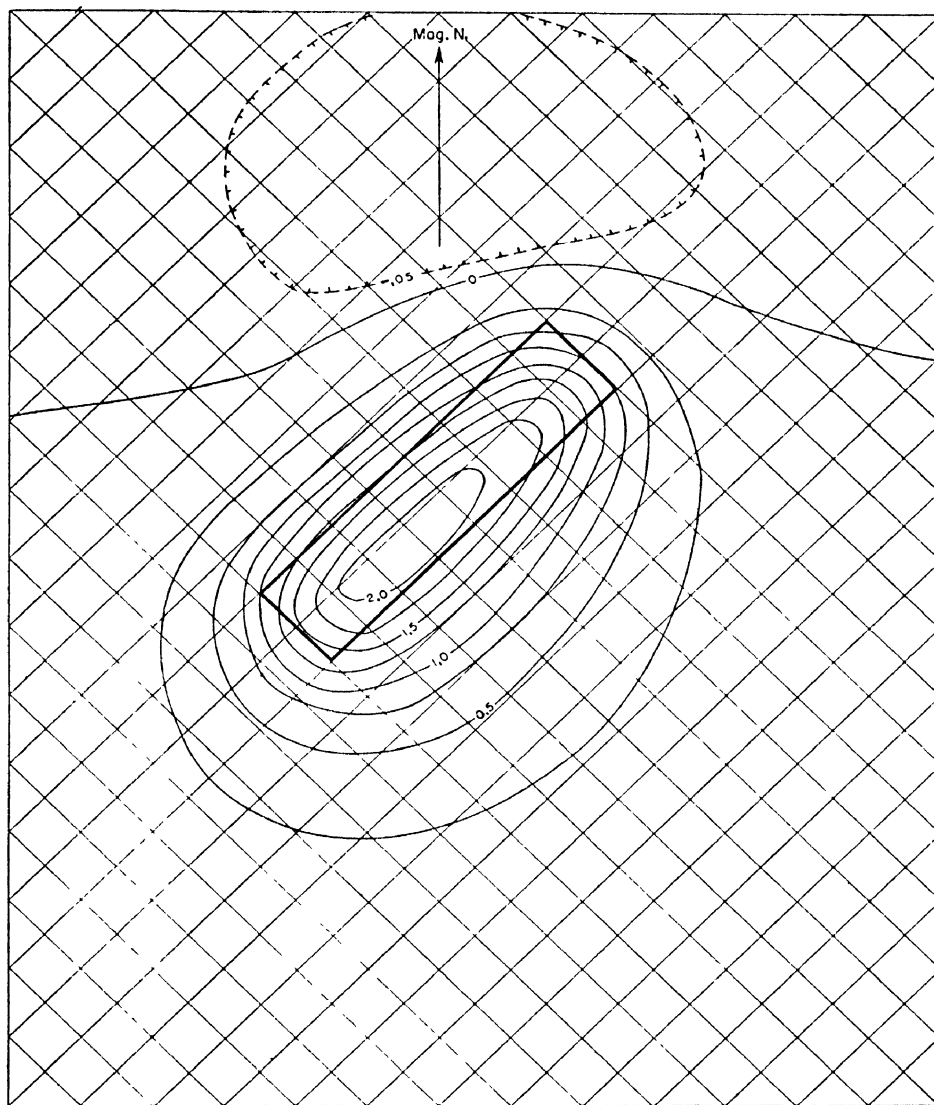
FIGURE A72



CURVATURE, $\frac{d^2H}{dz^2} / 4I$

INCLINATION 75° GRID INTERVAL = 0.7 DEPTH OF BURIAL
STRIKE = N 45° E (MAG)

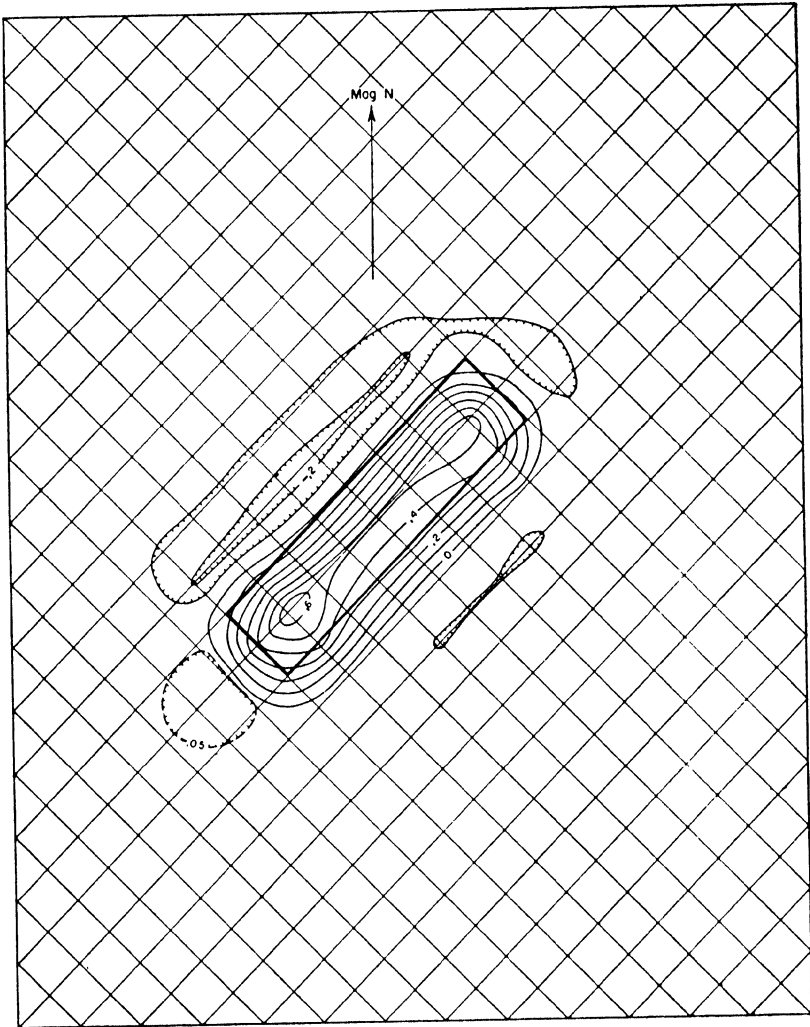
FIGURE A73



TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 75° GRID INTERVAL = 0.7 DEPTH OF BURIAL
STRIKE = N 45° E (MAG)

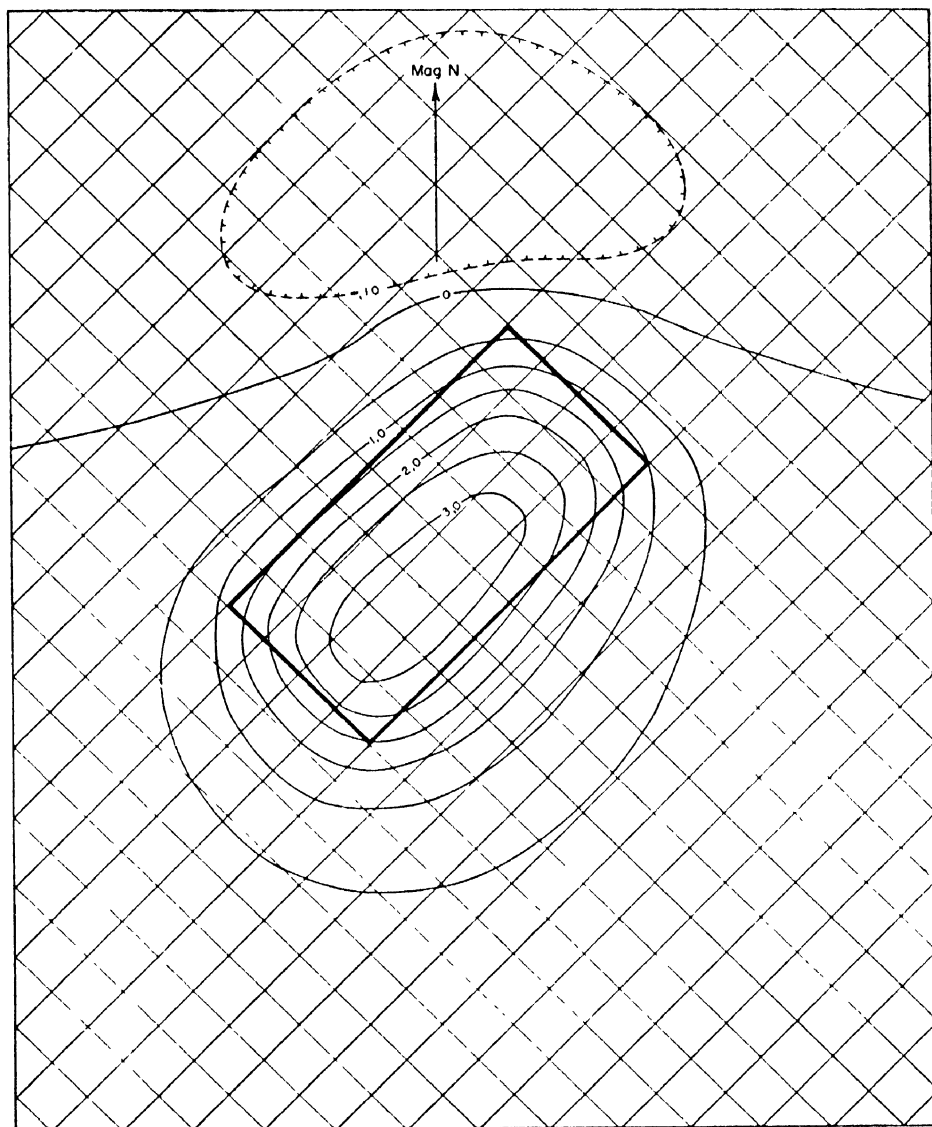
FIGURE A74



CURVATURE, $\frac{\partial^2 \Phi}{\partial x^2} / 4I$

INCLINATION 75° GRID INTERVAL : 0.7 DEPTH OF BURIAL
STRIKE = N 45° E (MAG)

FIGURE A75

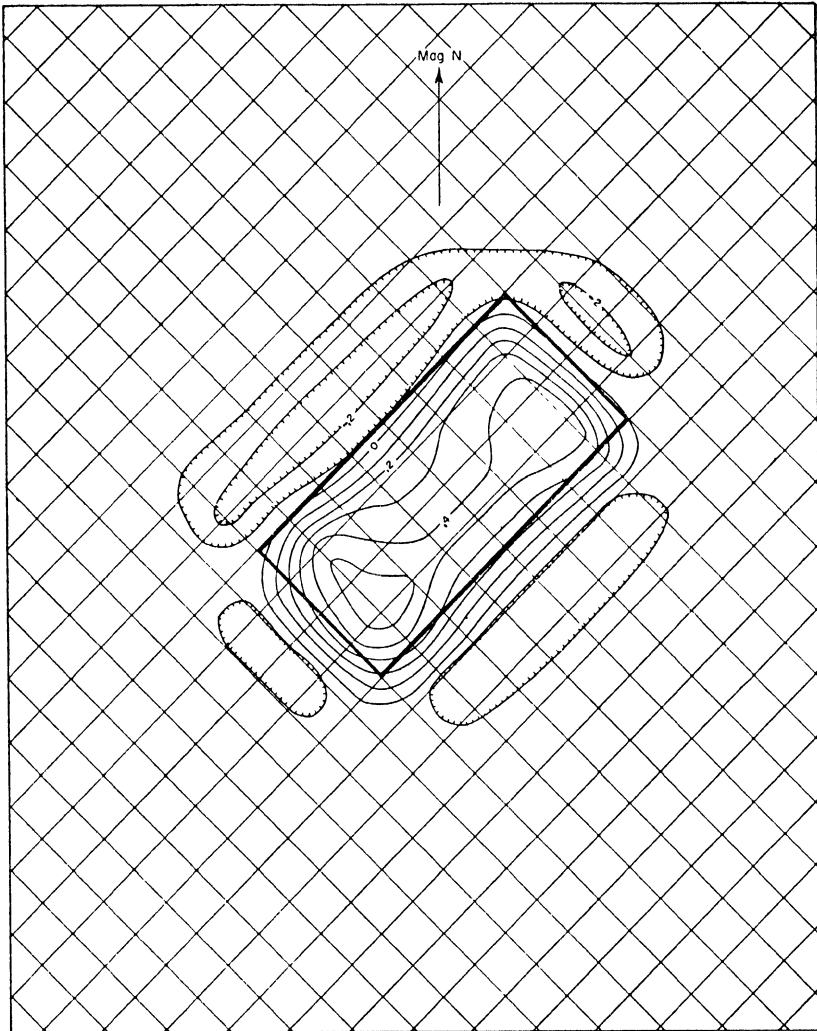


TOTAL INTENSITY, $\Delta T/I$ (CGS)

INCLINATION 75° GRID INTERVAL = 0.7 DEPTH OF BURIAL

STRIKE = N 45° E (MAG)

FIGURE A76



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I$

INCLINATION 75° GRID INTERVAL = 0.7 DEPTH OF BURIAL

STRIKE = N 45° E (MAG)

FIGURE A77

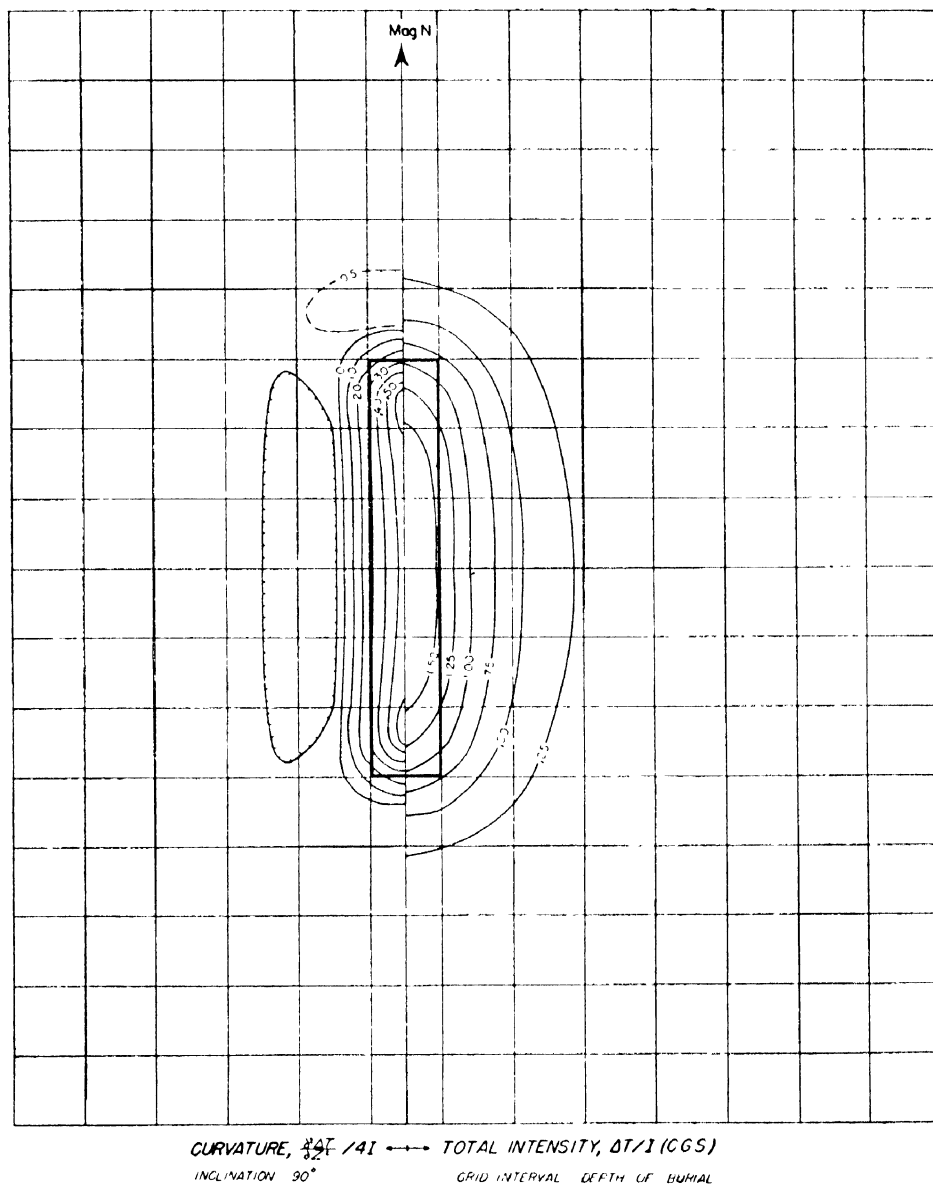
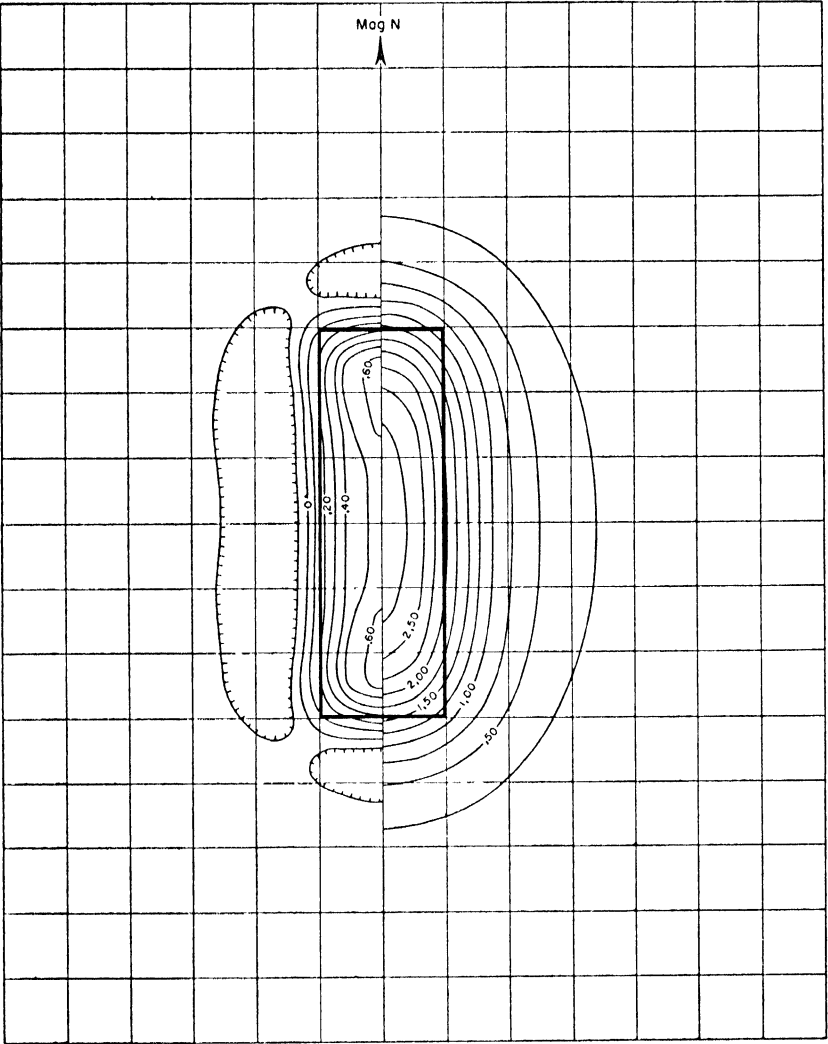
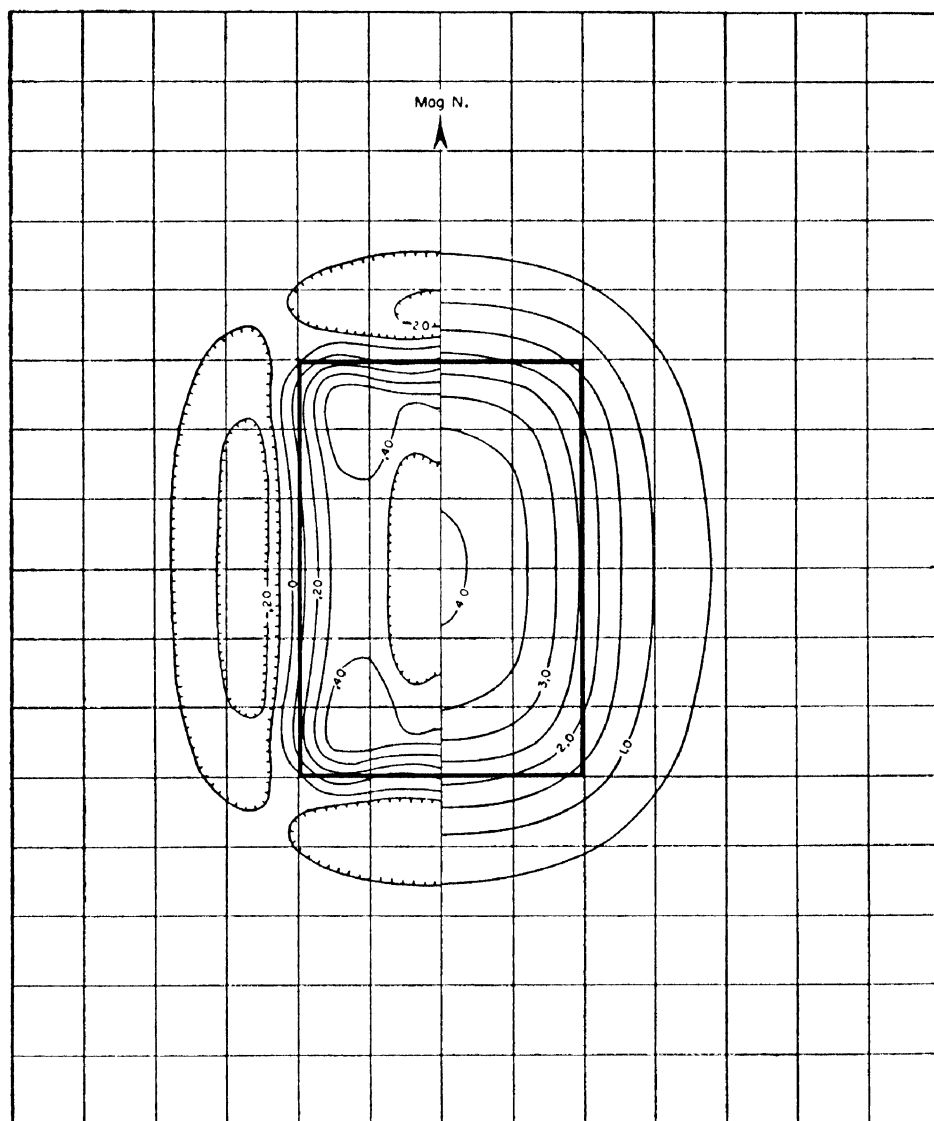


FIGURE A78



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)
INCLINATION 90° GRID INTERVAL = DEPTH OF BURIAL

FIGURE A79

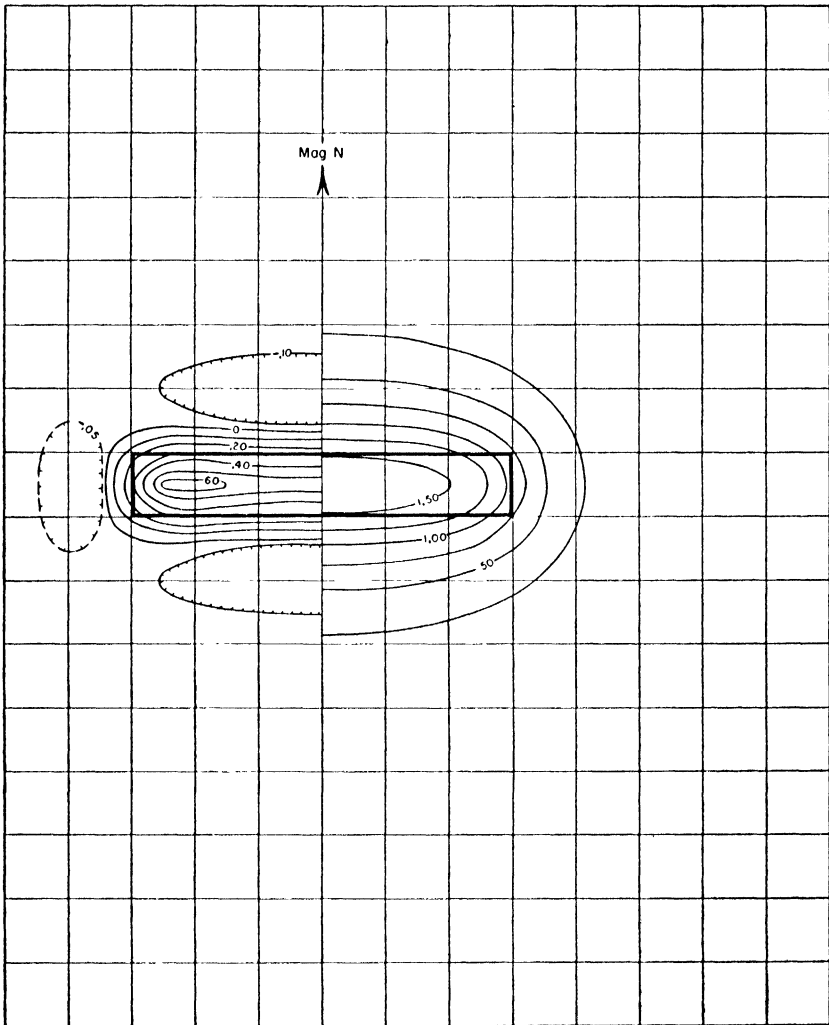


CURVATURE, $\frac{d^2\Delta I}{dx^2} / 4J \rightarrow$ TOTAL INTENSITY, $\Delta I / I$ (CGS)

INCLINATION 90°

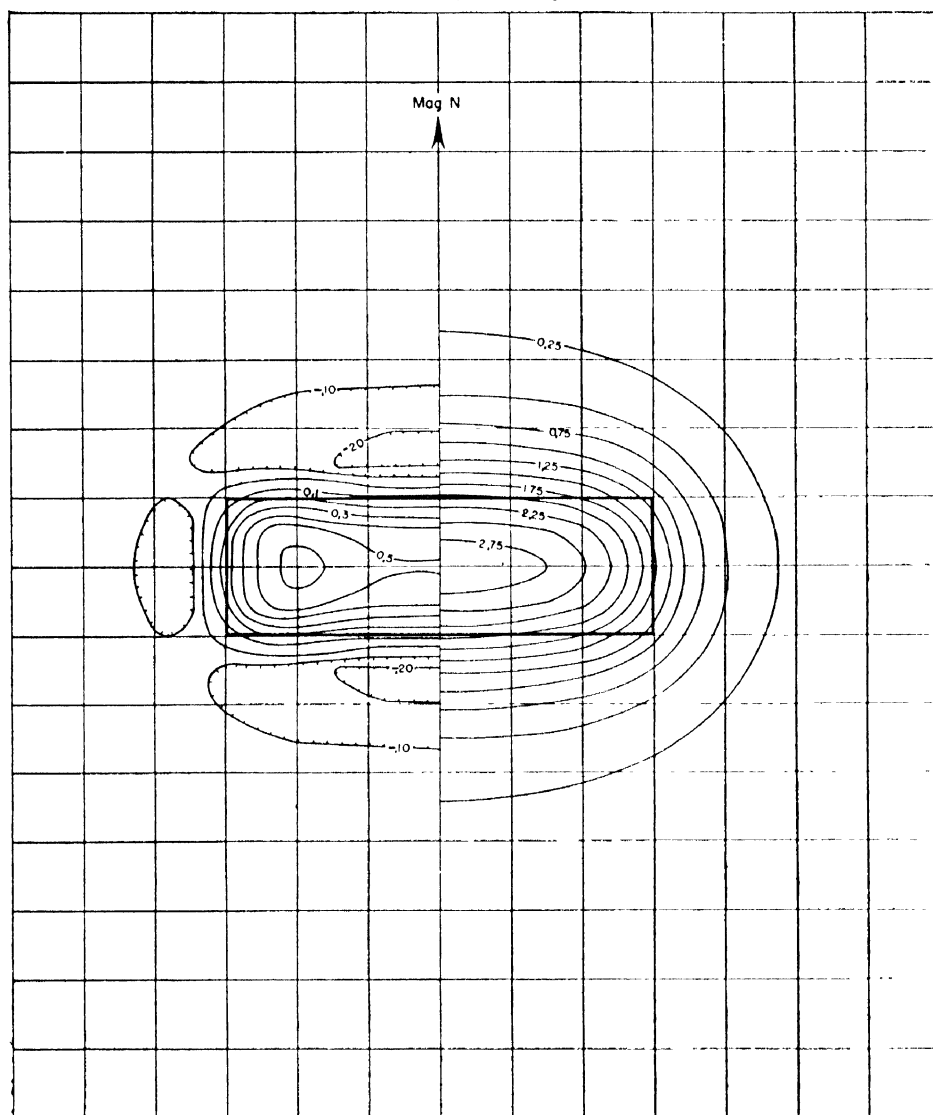
GRID INTERVAL = DEPTH OF BURIAL

FIGURE A80



CURVATURE, $\frac{\partial^2 \Delta T}{\partial x^2} / \Delta T \leftrightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)
 INCLINATION 90° GRID INTERVAL : DEPTH OF BURIAL

FIGURE A81



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \longleftrightarrow$ TOTAL INTENSITY, $\Delta I / 1$ (CGS)

INCLINATION 90°

GRID INTERVAL DEPTH OF BURIAL

FIGURE A82

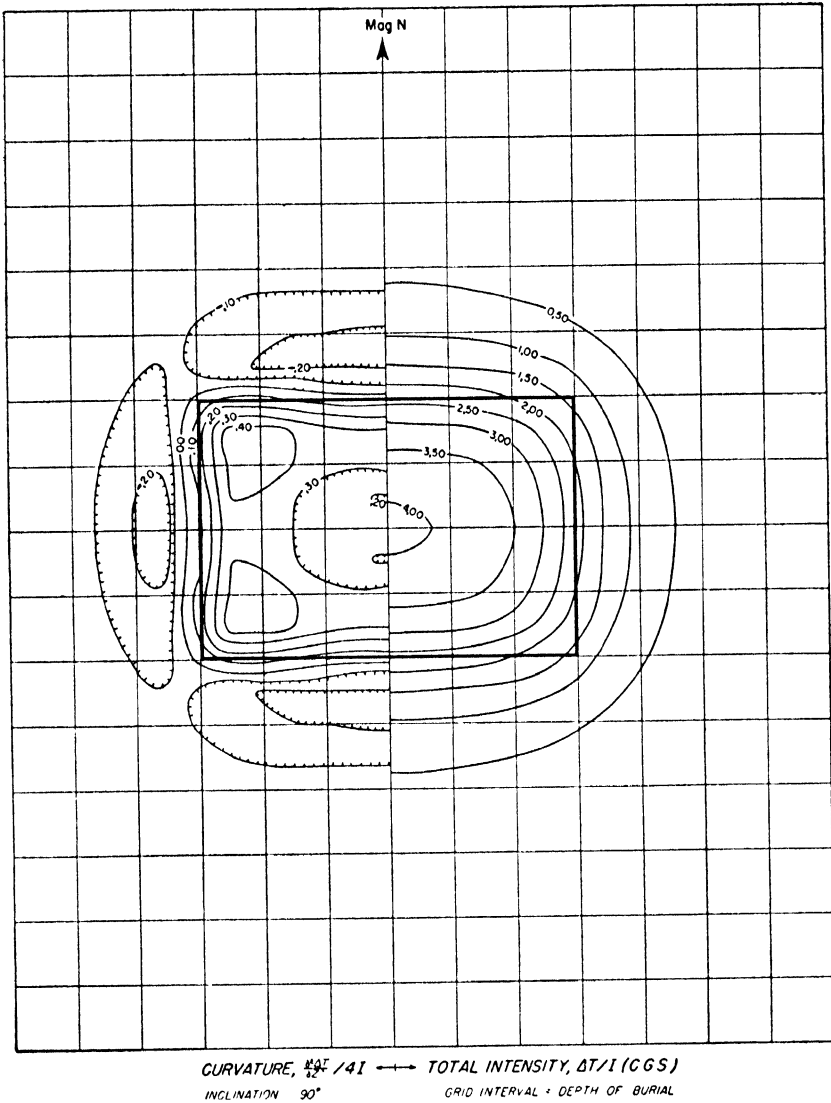
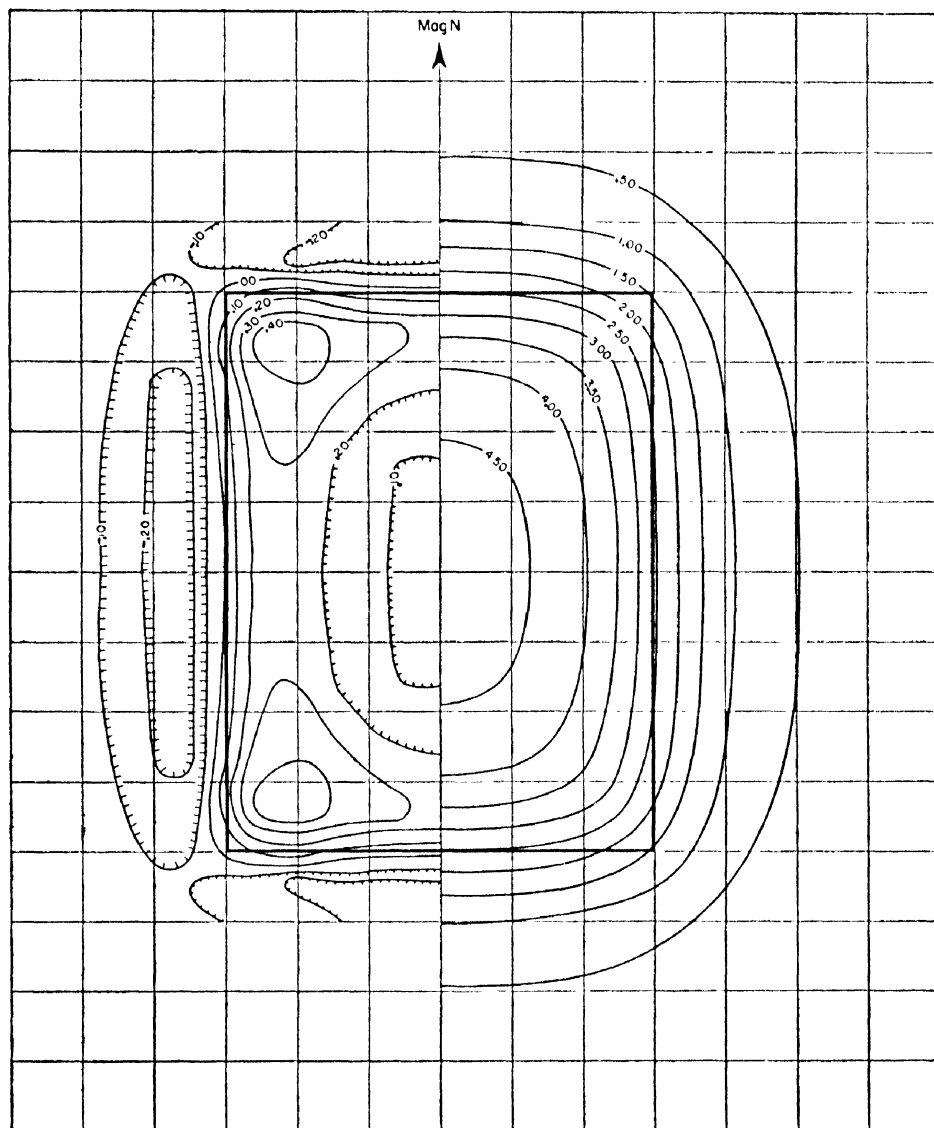


FIGURE A83



CURVATURE, $\frac{\partial^2 I}{\partial x^2} / 4I \rightarrow$ TOTAL INTENSITY, $\Delta T / I$ (CGS)
 INCLINATION 90° GRID INTERVAL = DEPTH OF BURIAL

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