

A COMBINED MAGNETIC AND GRAVITY ANALYSIS
OF THE SAUBLE ANOMALY, LAKE COUNTY, MICHIGAN

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Howard J. Meyer

1963

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ABSTRACT

A COMBINED MAGNETIC AND GRAVITY ANALYSIS OF THE SAUBLE ANOMALY, LAKE COUNTY, MICHIGAN

by Howard J. Meyer

A detailed gravity and magnetic survey was conducted on the Sauble anomaly of Lake County, Michigan. This is a positive circular magnetic and gravity anomaly with a residual maximum amplitude of 1130 gammas and 22 milligals, respectively. Following the reduction of data and the removal of the regional by the cross profile method, the combined analysis method was applied to the isolated gravity and magnetic anomalies. An idealized case was employed to check the accuracy of the combined analysis method. The composition, form, size, and depth of the anomalous body were further studied by depth determinations and by fitting idealized cases to the anomaly profiles. In the geological interpretation of the results it was concluded that the anomalous body is a very basic intrusive stock perhaps of Keweenawan age and bears no relationship to the Sauble oil field. The elevation of the top of the body and the Precambrian in this area is about 8,000 to 9,000 feet below sea level.

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By

Howard J. Meyer

A THESIS

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INTRODUCTION

The regional magnetic and gravity survey of the Southern Peninsula of Michigan, conducted by the Department of Geology, Michigan State University (Hinze, 1962), has led to the discovery of the Sauble anomaly of Lake County. A detailed survey of the Sauble anomaly and the adjacent area was initiated to study this feature, which was found to be one of the outstanding gravity and magnetic highs in the Southern Peninsula.

The purpose of this research is to make a detailed gravity and magnetic study of the Sauble anomaly and to interpret geologically the data, making particular use of the combined gravity and magnetic analysis method. This includes a study of the composition, form, size, depth, and origin of the anomalous body and its relationship to the Sauble oil field, which is located near the center of the anomaly.

The area under study is located in the northwest part of the Southern Peninsula of Michigan in portions of Lake, Mason, and Manistee Counties. This area, shown in Figure 1, lies between $43^{\circ}52'$ and $44^{\circ}15'$ north latitude and $85^{\circ}46'$ and $86^{\circ}14'$ west longitude. Approximately 460 square miles have been covered with 515 magnetic and 339 gravity stations.

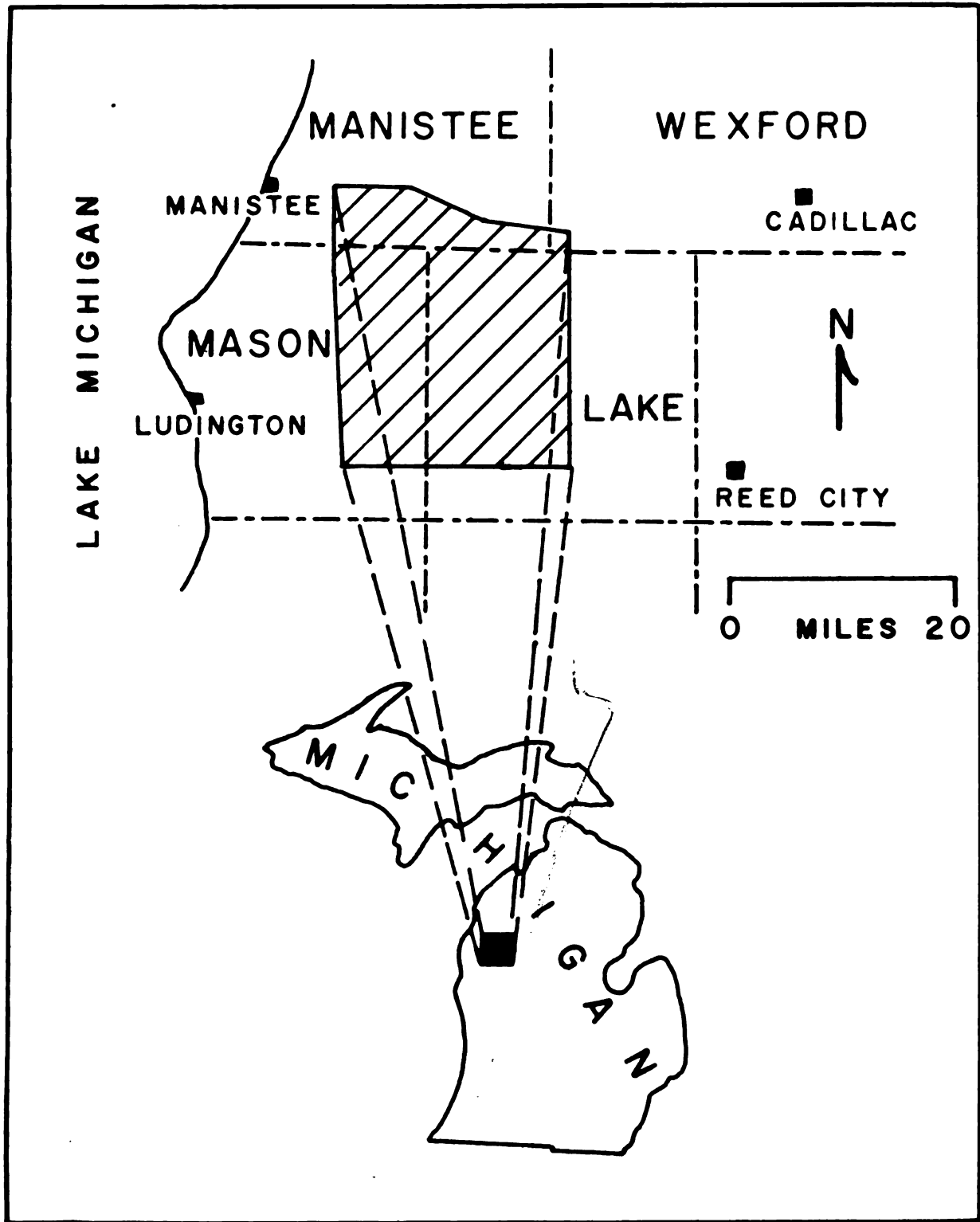


FIGURE 1. LOCATION OF AREA OF INVESTIGATION

GEOGRAPHY AND GEOMORPHOLOGY

The land in this area with the exception of part of Mason County is mostly in state and national forests and contains numerous lakes and swamps within a gentle rolling topography. In general, the elevation varies from about 700 feet above sea level in the west to about 900 feet in the east with hills reaching 1,100 feet in the eastern and southern parts of the region. Drainage is from the east to the west by means of the Little Manistee River, the Big Sable River, and the Pere Marquette River. The road system is very irregular with some areas as large as four square miles being inaccessible by car.

A variety of glacially derived land forms are found in the area (Martin, 1955). Outwash plains, moraines, and till plains cover, respectively, about 75, 20, and 5 per cent of the surface. The thinnest section of glacial drift encountered in 36 drill holes is 280 feet and the average thickness is about 400 feet.

GENERAL GEOLOGY OF THE AREA

The area under investigation is located on the northwest part of the Michigan Basin with the Paleozoic sediments sloping gently to the southeast. From the northwest to the southeast beneath the glacial drift, these sediments are the Coldwater, Napoleon, Marshall, and Michigan formations of the Mississippian system and the Saginaw group of the Pennsylvanian system (Martin, 1957).

In the surveyed region several drill holes have penetrated as deep as the Bass Island formation of the Silurian system and the Sylvania formation of the Devonian system. However, most of the drill holes in the area, especially over the Sauble anomaly, only penetrate the Traverse formation of the Devonian system. The elevation of the top of the Traverse formation with respect to sea level is shown in Plate 1. In the central part of the area the Paleozoic strata take the form of a small syncline superimposed on the edge of the Michigan Basin, like the lip on a pitcher. The generalized stratigraphic column for Michigan is assumed to hold true in this area because of the consistency of the column over the Michigan Basin and the similarity found between the local drill holes and the respective parts of the column.

According to Cohee (1945), the elevation of the top of the Precambrian is about 13,000 feet below sea level in the center of the Michigan Basin and 8,000 feet below sea level in the Sauble anomaly area. Cohee's estimates are based on a very limited number of wells that encounter the Precambrian. The nearest of these wells is more than a hundred miles away, thus limiting the usefulness of the above depth figures.

FIELD INVESTIGATIONS

Gravity Survey

The instrument used in this survey was the World Wide gravimeter #45, which has a scale constant of 0.10093 milligals per scale division and reads a variation of 0.01 milligals. The quantity measured by this instrument is the relative vertical component of the gravity field of the earth.

The gravimeter is sensitive to temperature change, strong wind, atmospheric pressure variation, earth tides, earthquakes, and physical shock. Small variations in the elastic properties of the working parts of the gravimeter also cause changes in the readings over a period of time, known as the instrument or daily drift. The magnitude of the daily drift was found by occupation of base stations of known gravity at various times during the day. The drift can then be plotted on a graph and removed from the individual gravity readings taken between the bases. This survey averaged about one base check per hour, although this was extended to once every two hours on days of mild drift. Figure 2 shows a typical daily drift curve. To keep the time between base check-ins small the gravity and magnetic parts of this survey were conducted separately.

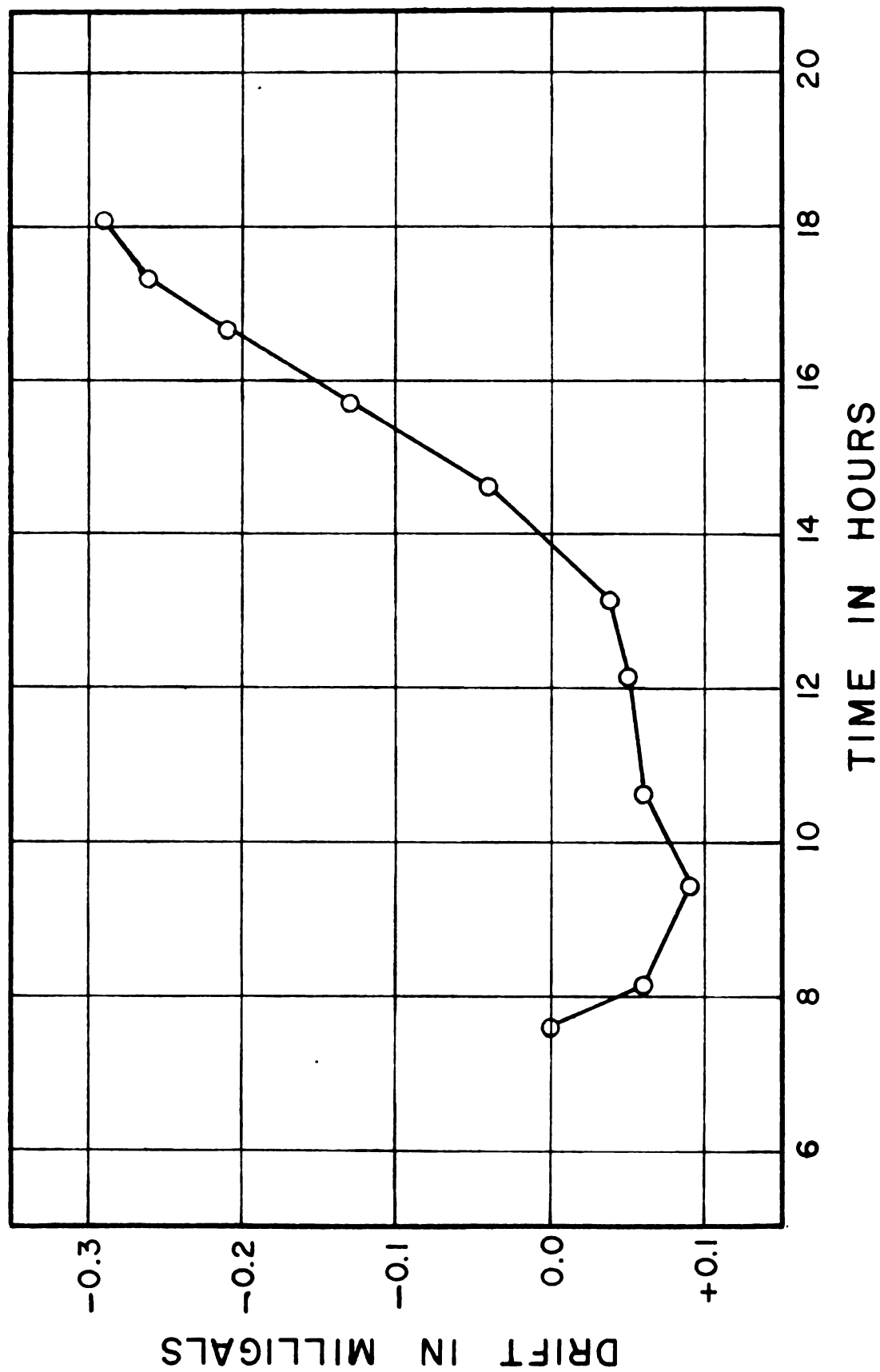


FIGURE 2. TYPICAL GRAVITY DAILY DRIFT CURVE

Terrain corrections must be applied to gravity stations located near sharp changes in relief. To avoid this laborious and sometimes inaccurate correction all stations were established at a sufficient distance from significant topographic features.

Base station looping was conducted at the end of the survey to allow for changes in the preselected base station locations that were made during the actual field work program. The gravity bases were located near accessible roads and away from sources of vibration, such as busy highways and railroads. The tight network of base looping, as shown in Figure 3, consisted of six closed systems, each of which tied about six base stations together and was, in turn, tied to the next system. Base station GB41, included in system (a) at the beginning and in system (f) at the end of base looping, had a total closure error of 0.07 milligals for the entire base looping procedure.

This survey was tied to and corrected to 14 gravity stations of the Michigan State University gravity and magnetic survey of the Southern Peninsula of Michigan, which, in turn, was corrected to the national gravimetric datum.

Wherever possible, a station spacing interval of one mile was used over the surveyed area and an interval of one-half mile was used over the anomaly peak. The very irregular road system and the inaccessibility of some areas limited the proposed station spacing. Gravity stations were located at almost all accessible points that have known elevations and

Explanation:

The number of lines
between stations indicates the
number of direct gravity ties.

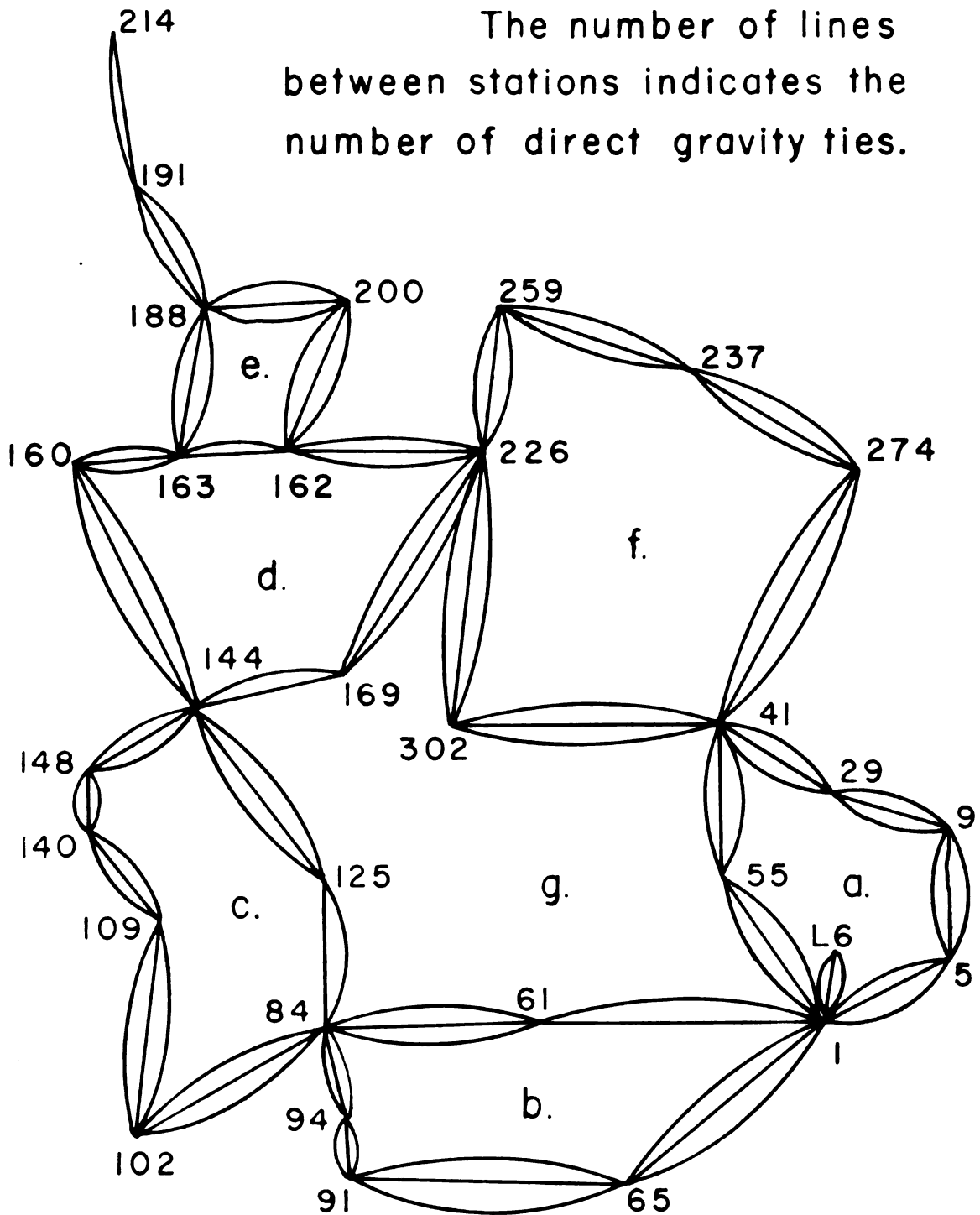


FIGURE 3. NETWORK OF GRAVITY BASE LOOPING

do not require terrain corrections. The objective was to obtain an adequate observed gravity coverage at stations of known elevation without spending the time and money for extensive leveling. To do this, topographic maps of the United States Geological Survey were used and gravity stations were located at bench marks, "UE" markers, and at road junctions, where elevations are given for the center of the intersection. According to the topographic division of the Geological Survey at Rolla, Missouri, elevations at the center of intersections are accurate to one foot on ten foot contour interval maps and to two feet on twenty foot contour interval maps. For the purposes of this survey, elevations of this accuracy are sufficient.

Of the 339 gravity stations observed in this survey five per cent of them were read at stations where elevations were established by barometric altimeter looping. The altimeter controlled stations were located near the center of the area where closer station spacing was desired over the peak of the anomaly.

The author is aware of the great inaccuracies that can be caused by over confidence in the barometric altimeter, when it is used for precise elevation measurements. The following procedures were employed to reduce error: (1) two altimeters were used; (2) each unknown elevation was directly looped to a known elevation (for example, from known elevation to unknown #1 to known elevation back to unknown #1); (3) the distance between the known and unknown elevation

points was never more than two miles to facilitate rapid looping; (4) the difference between the known and unknown elevations was less than 30 feet in all but four of the elevation determinations; (5) the altimeters were read on a very calm night to reduce the effects of atmospheric pressure and temperature changes; (6) the instruments were kept on the car seat with windows open to minimize erratic effects due to handling; and (7) several direct loops between three sets of stations of known elevation were made in the field to determine the constants of the altimeters.

The altimeter constants, measured in feet per scale division, are the average of the three constants determined from loops between three sets of points of known elevation. This constant for each altimeter was used in the calculation of the difference in elevation between the points of known and unknown elevation. In order to evaluate the amount of error possible in the above computations, the altimeters were run between floors of known elevation difference in a high building. The differences in readings between the two points was multiplied by the constant determined from field looping. Subtraction of the known elevation difference from the calculated gave the error obtained in the loop. The two altimeters produced errors of 0.6 feet and 4.0 feet for a 40 feet elevation difference in the building. This is an average error of 2.3 feet. A large difference in elevation between the known and unknown points exaggerates the effect of any error in the altimeter constant and thus the smaller

the elevation difference, the more accurate the results. The difference between the known and unknown elevations was greater than 40 feet in only one of the field elevations determined by the altimeter method. An average of the results of two altimeters reduced errors further.

Stations where elevations were determined by altimeters are marked with a ($\ominus$) on the Bouguer anomaly map (Plate 2).

Magnetic Survey

The instrument used in this survey was an Askania Torsion magnetometer, which measures the vertical component of the earth's magnetic field. The calibration constant of this instrument, as determined by a Helmholtz coil in March, 1962, is 227.6 gammas per scale division, which is consistent with other calibrations in 1960 and 1961. The Askania Torsion magnetometer is sturdy, light in weight, and very easy to read. It does not have to be orientated exactly due north like the Schmidt-type magnetometer and can be left attached to the tripod, while being used in the field.

Base stations were established and tied into regularly to determine and correct for small diurnal changes in the magnetic field of the earth. The average time between base check-ins was about one hour but on days of small diurnal variation this was extended to every two hours. On the whole, diurnal drift was unusually small during the days allotted to the magnetic survey. Figure 4 shows a typical magnetic drift curve.

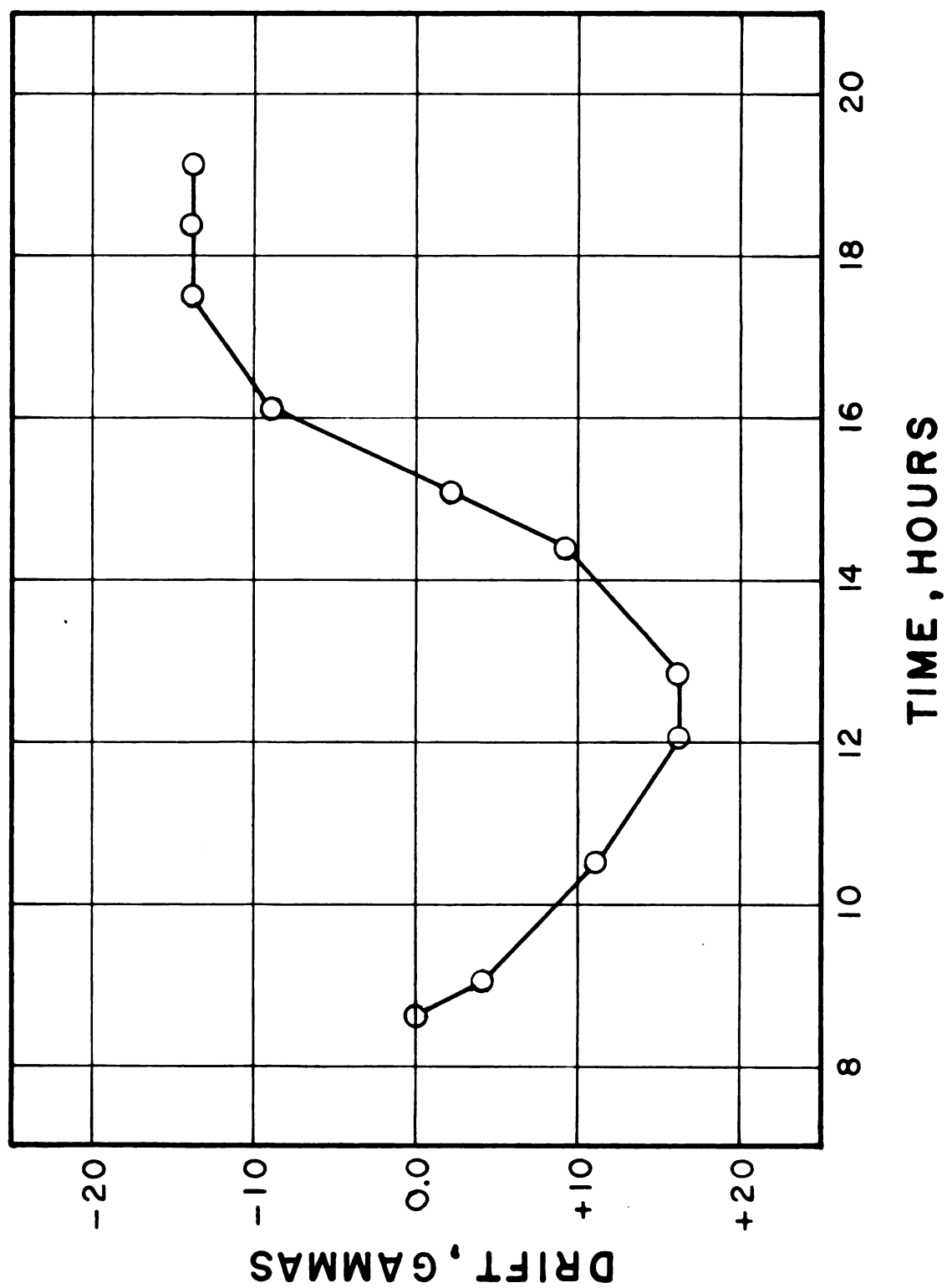


FIGURE 4. TYPICAL DAILY MAGNETIC DRIFT CURVE

The station spacing interval along accessible roads was one mile in the overall area and every one-half or one-quarter of a mile over the center of the area. At every station at least three observation points were read to evaluate the effects of any local surface magnetic material, whether it be of natural occurrence in the glacial drift or buried debris left by man. The three points were 10 paces or 28 feet apart and at the corners of an isosceles right triangle. The 460 square miles covered by this survey contain 515 magnetic stations. The gravity and magnetic surveys were conducted independently with no attempt made to establish gravity and magnetic stations at the same points. The gravity survey has fewer stations, only 339, because of limited elevation control in the area.

As in the gravity survey, the base station looping was conducted last to allow for changes in the preselected base station locations and to reduce the time required for looping. The magnetic bases were established near accessible roads and away from all possible sources of electrical and metallic influence. A tight network of base station looping, shown in Figure 5, was constructed to tie the entire area together. It consisted of five closed looping systems, each of which tied a group of base stations together and was in turn tied to the adjacent systems by common stations.

This survey has been tied into and corrected to 15 magnetic stations of the Michigan State University gravity and magnetic survey of the Southern Peninsula of Michigan.

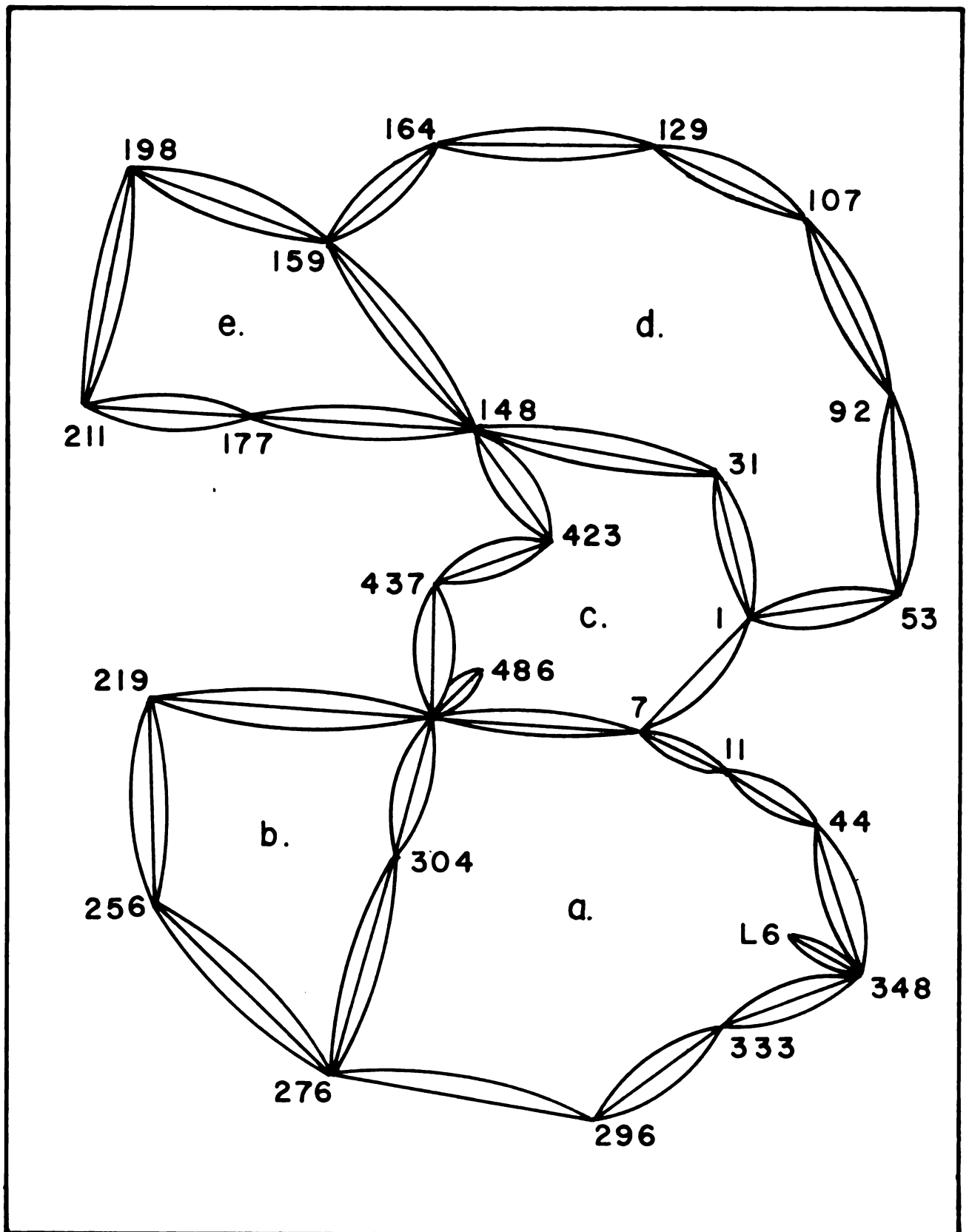


FIGURE 5. NETWORK OF MAGNETIC BASE LOOPING

REDUCTION OF DATA

The reduction of data involves the sequence of corrections that must be applied to the observed readings to eliminate the effect of all factors that are not produced by the anomalous body or bodies which are of interest in the survey.

Gravity

The gravity base stations were first made relative to the secondary base by removal of the gravimeter drift, which occurred during the base looping process. The secondary base is simply the base station read at the beginning of the base looping. These corrected bases were then used to determine the direction and extent of drift on other days of the survey. The drift for each day was plotted on the daily drift curve and the readings on each graph were corrected to the first base station of the day and then adjusted to the secondary base.

The readings were converted from scale division to milligals by multiplying by the instrument constant of 0.10093 milligals per scale division. This survey was next corrected to the Michigan State University survey, which, in turn, was adjusted to the national gravimetric datum. Comparison of the observed gravity of the two surveys for the

14 tie-in stations common to both, resulted in an average difference, which was the correction added to all the readings of the present survey. This made the observed gravity relative to the national gravimetric datum.

The sea level gravity for any latitude is found by using the 1930 International Gravity Formula and serves as a latitude correction.

The free air correction takes into account that the point of observation is not at sea level but at some elevation above it, where the acceleration of gravity is less. The Bouguer or mass correction, which increases with elevation, allows for the downward force exerted by the quantity of material that is between the point of observation and sea level. The free air correction is 0.09406 milligals per foot and the Bouguer correction is 0.01276σ milligals per foot, where σ is the density of the material above sea level. A value of 2.67 grams per cubic centimeter was used for σ since this is the quantity usually assumed in regional gravity surveys. These corrections are always of opposite sign and can be combined into one correction, since they both depend on the elevation above sea level.

The terrain correction was avoided by locating all stations at a considerable distance from any significant changes in relief.

The above corrections were applied to the observed gravity to obtain the Bouguer anomaly in the following well-known equation:

Bouguer anomaly = observed gravity - sea level gravity
+ free air correction - Bouguer correction.

The Bouguer anomaly values were plotted and contoured as shown on Plate 2.

The sea level gravity, the free air, and the Bouguer corrections were applied to the observed gravity through the MISTIC Computer of Michigan State University. The computer program and the original data are available at the Department of Geology, Michigan State University.

Magnetics

The magnetic base station readings were first corrected for diurnal or daily drift and made relative to the secondary base, which was base station MBI as read on May 31, 1962. These corrected base values were then used for diurnal drift control during the other days of the survey. All readings of each day were corrected to the first base station read on that day and each daily series of stations was converted to the secondary base, MBI.

Ordinarily some temperature correction is necessary in a precise magnetic survey, however, the Askania Torsion magnetometer used is so well insulated and temperature compensated that this was not necessary. A temperature calibration in which the instrument was subjected to periods of extreme variation in temperature produced no significant change in readings.

All the corrected readings were next converted from scale division to gammas by multiplying by the instrument

constant of 227.6 gammas per scale division.

The normal variation of the magnetic intensity from place to place on the earth's surface must be corrected for in surveys of this type. The normal correction for each station was taken from magnetic maps published by the United States Coast and Geodetic Survey (1955).

Finally, this survey was corrected to the Michigan State University magnetic survey. Comparison of the magnetic values obtained by this survey and the Michigan State University survey for the 15 tie-in stations common to both, resulted in an average difference in readings, which was the correction to be added to all the readings of the present survey. The vertical magnetic intensity values were plotted and contoured as shown on Plate 3.

ISOLATION OF THE GRAVITY AND MAGNETIC ANOMALIES

The Bouguer gravity and the vertical magnetic intensity anomaly maps (Plates 2 and 3) each show a very pronounced positive anomaly, which predominates over the surrounding regional trends. Nevertheless, these regional trends are significant enough that they must be removed before interpretation.

The Cross Profile Method-- Removal of the Regional

In the cross profile method, as used in this survey, two sets of seven equally-spaced profiles were constructed perpendicular to each other across the surveyed area. The distance between profiles was three miles with one profile across the anomaly center for each direction. Attempts by the interpreter to approximate the regional by drawing smooth lines across one set of profiles must also satisfy the perpendicular set, since points of intersection of two profiles must have the same regional value. Thus, the procedure is to adjust the regional by trial and error until a suitable fit is obtained. For best results, one set of profiles should be drawn parallel to the direction of steepest regional gradient and the other set perpendicular to this.

The survey must include a large marginal area away from the influence of the anomaly so that the lateral profiles can be used as a guide in the construction of the regional in the central profiles. In each set of final profiles the regional should grade gradually across the area from one lateral profile to the other.

The removal of the regional is an interpretive process and does not have a unique solution. The cross profile method can place the regional trend within a certain range but the question still remains, where does the anomaly end and the regional begin. The removal of the regional is a possible source of error that could effect the interpretations that follow. The regionals that were selected for removal from the observed gravity and the vertical magnetic intensity maps have a close similarity to the Gravity Map of Michigan and the Magnetic Map of the Southern Peninsula of Michigan (Hinze, 1962).

The Residual Gravity and Magnetic Anomalies

The residual gravity and magnetic anomalies are shown on Plates 4 and 5. The following observations are made:

- (1) Both the anomalies are positive and of large magnitude, attaining maximums of 22 milligals in the gravity and 1130 gammas in the magnetics.
- (2) The magnetic and gravity anomalies are circular in outline, although a slight elongation in a northwest-southeast direction can be noted in both of them.
- (3) The gravity anomaly is broader and not as sharp

as the magnetic anomaly, as is the case for anomalies from the same source. (See the idealized case shown in Figure 9.)

(4) The positive magnetic anomaly is shifted slightly to the southeast of the gravity anomaly and has an associated negative to the northwest.

The averaged north-south and east-west profiles across the isolated gravity and magnetic anomalies are found in Figures 6 and 7, respectively.

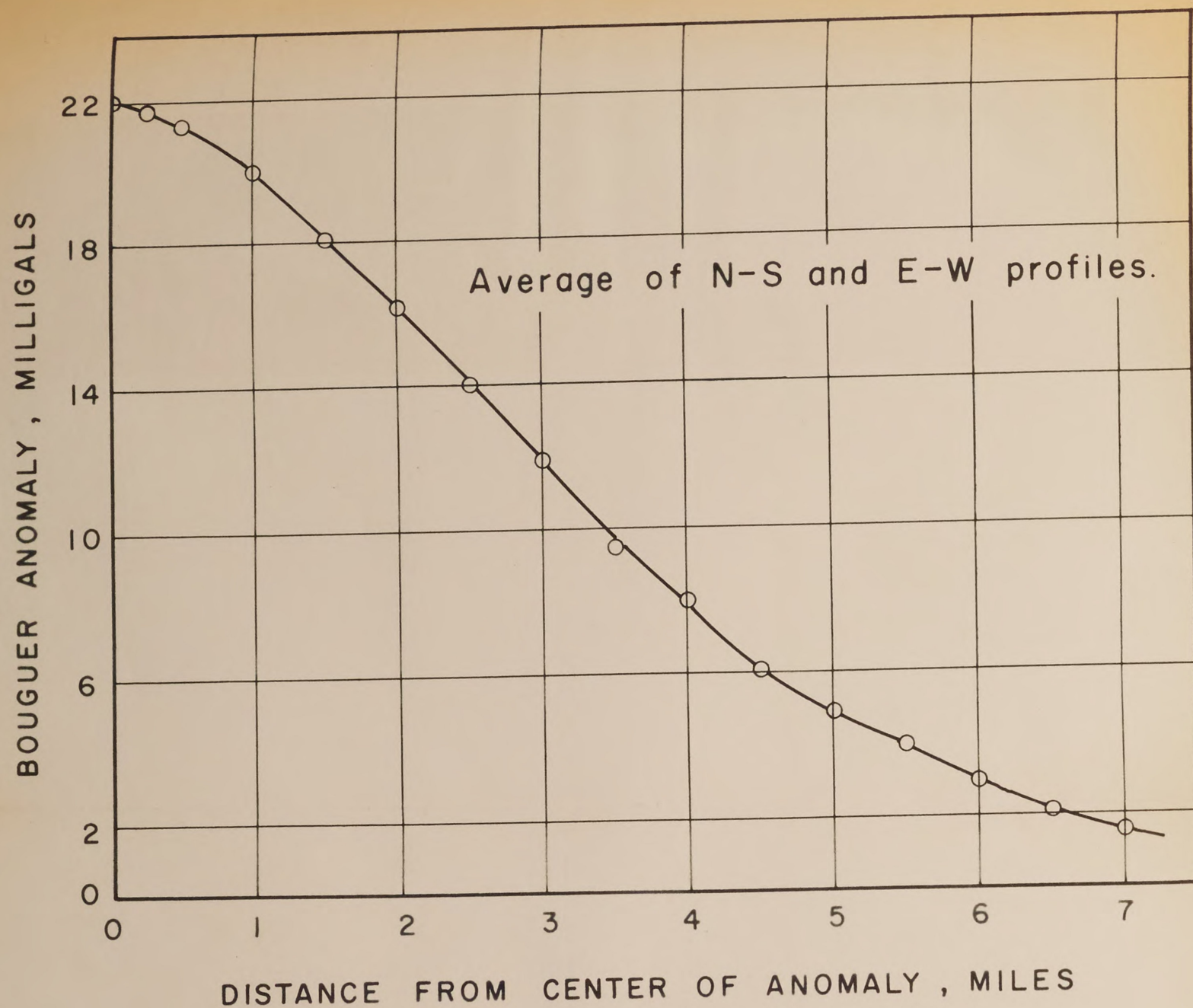


FIGURE 6. RESIDUAL BOUGUER GRAVITY PROFILE

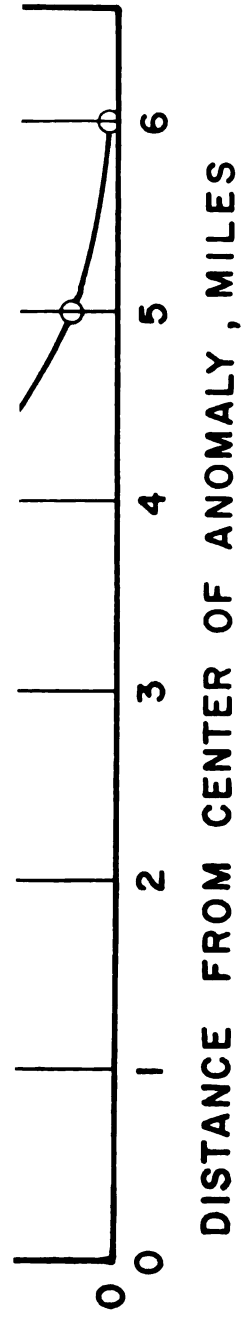
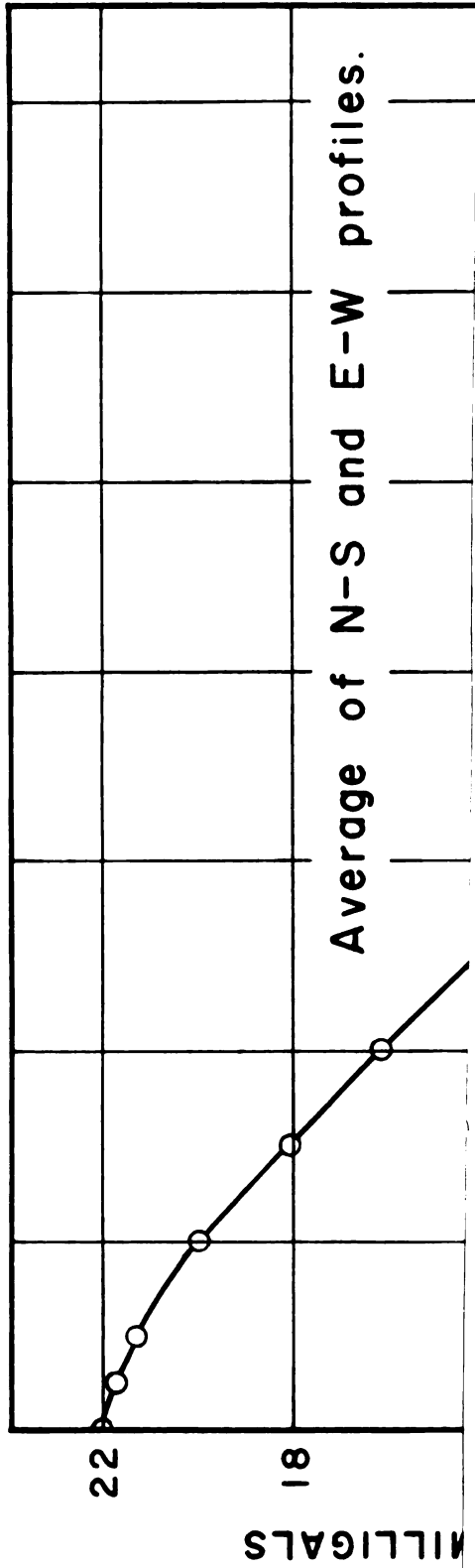


FIGURE 7. RESIDUAL VERTICAL MAGNETIC PROFILE

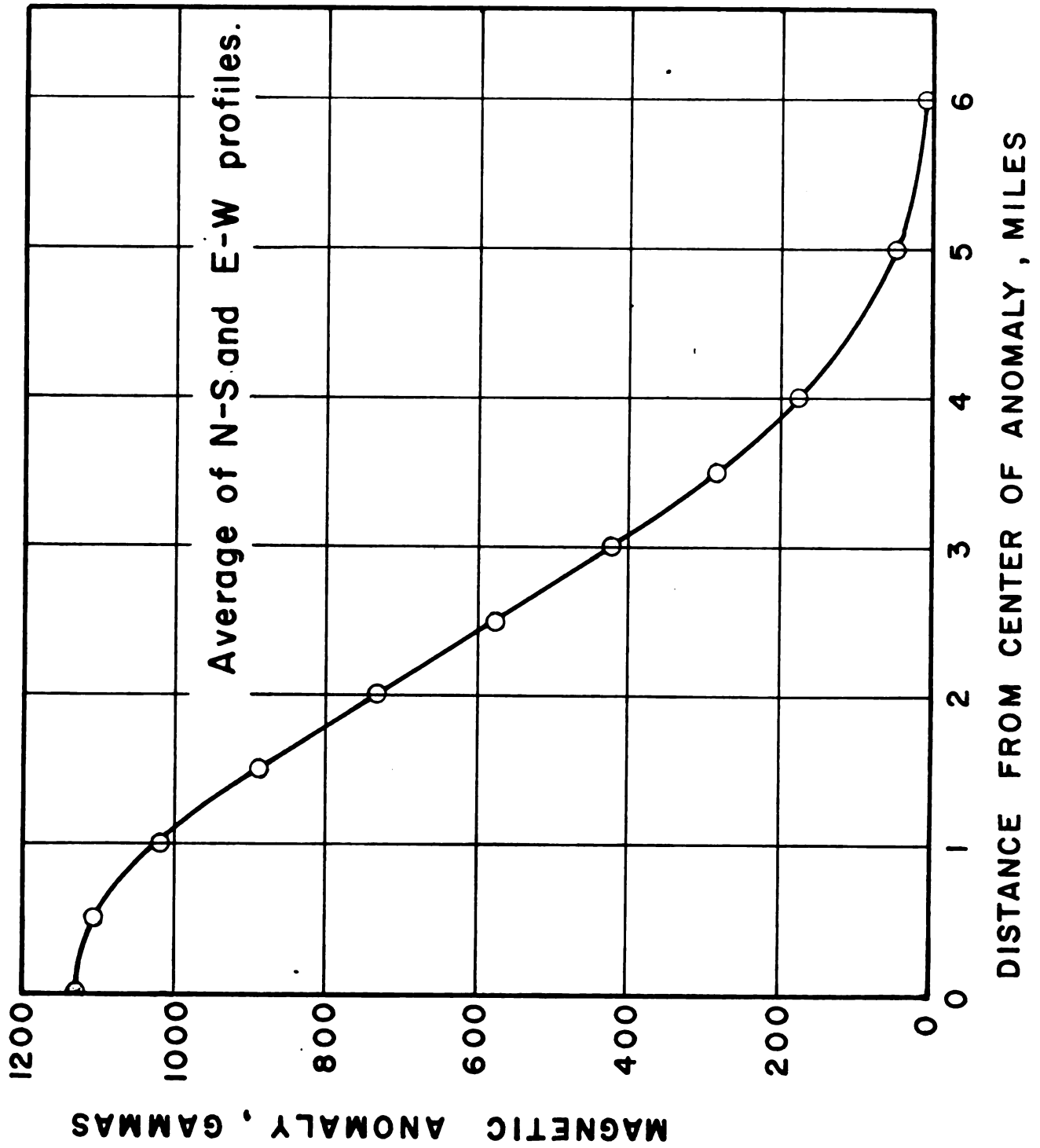


FIGURE 7. RESIDUAL VERTICAL MAGNETIC PROFILE

COMBINED ANALYSIS OF THE GRAVITY
AND MAGNETIC ANOMALIES

Discussion of the Method

The combined analysis of gravity and magnetic anomalies has been described and applied to specific cases in two papers by Garland (1950, 1951). Garland has presented a very comprehensive derivation and discussion of the principles involved in this method, so that only a summary is given below.

When a body produces anomalies in two different force fields, instead of just one, considerably more information about it can be determined. Certain fields of force, including gravity and magnetism, have been shown to be related by a potential factor, which depends on the size and shape of the body and its distance from the point of observation. If the same body produces both gravity and magnetic anomalies, the potential factor can be eliminated and an equation, which is independent of the shape and depth of the unknown structure, can be obtained by relating the two force fields. The relationship as derived by Garland from Poisson's equation is:

$$Z = \frac{I}{G\rho} [g_z \sin d + g_s \cos d] \quad (1)$$

where Z = vertical magnetic intensity anomaly at a point P

I = intensity of magnetization = kF

F = total intensity of the earth's magnetic field

k = magnetic susceptibility differential between the body and the country rock.

G = gravitational constant = 6.670×10^{-8}

ρ = density differential between the body and the country rock

g_z = vertical gradient of the anomalous gravity at a point P .

g_s = horizontal gradient of the anomalous gravity at a point P in the azimuth A .

A = azimuthal angle of the direction of magnetization in the body.

d = angle of inclination of the direction of magnetization in the body.

In order to use the above equation the direction of magnetization must be known or assumed and relatively uniform throughout the body. The gravity and magnetic anomalies must, of course, originate from the same structure. Garland states that this

equation allows us to calculate the magnetic anomaly field, i.e., to within a constant factor I/ρ , directly from the observed gravity field, for any assumed direction of magnetization of the anomaly-producing structure. Comparison of the general form of this calculated field with the observed magnetic anomalies will indicate the justification of the assumptions regarding the direction of magnetization and the uniformity of properties.

Determination of the Vertical and Horizontal Gradients of Gravity

The vertical gradient of gravity can be approximated quite accurately from the residual gravity anomaly map

by using a graticule and a related equation proposed by Baranov (1953). The graticule is composed of nine circles of given radii, on each of which lie a number of points. It is centered on the place where the vertical gradient is required and the observed gravity values for the points on each circle are recorded. The average of the observed gravity values for each circle is multiplied by a constant given in the equation. A typical grid, reduced in scale, is shown in Figure 8. The equation given below has been devised by Baranov (1953, p. 181):

$$\begin{aligned}
 g_z \approx & \frac{10^{-8}}{S} \left\{ 2.30518 g_p - 1.70975 \frac{\sum_1^4 g_i (S)}{4} - 0.05284 \frac{\sum_1^4 g_i (S\sqrt{2})}{4} \right. \\
 & - 0.17401 \frac{\sum_1^8 g_i (S\sqrt{5})}{8} - 0.09577 \frac{\sum_1^8 g_i (S\sqrt{10})}{8} - 0.05249 \frac{\sum_1^{12} g_i (S\sqrt{17})}{12} \\
 & - 0.04174 \frac{\sum_1^{12} g_i (S\sqrt{25})}{12} - 0.04038 \frac{\sum_1^{16} g_i (S\sqrt{40})}{16} + 0.20340 \frac{\sum_1^{16} g_i (S\sqrt{68})}{16} \\
 & \left. - 0.34160 \frac{\sum_1^{20} g_i (S\sqrt{100})}{20} \right\} \quad (2)
 \end{aligned}$$

where g_z = the vertical gradient of gravity at a point P

S = the radius of the innermost circle of the graticule

g_p = the observed gravity at a point P

g_i = the observed gravity at a point on one of the circles

(S) , $(S\sqrt{2})$, $(S\sqrt{5})$, etc. = the radii of the circles on which the sets of points fall.

$\frac{\sum_1^4 g_i (S)}{4}$ = the average observed gravity value for four points on the circle of radius S kilometers.

The coefficients used are those found by Baranov to give the best results in the approximation of the vertical gradient of

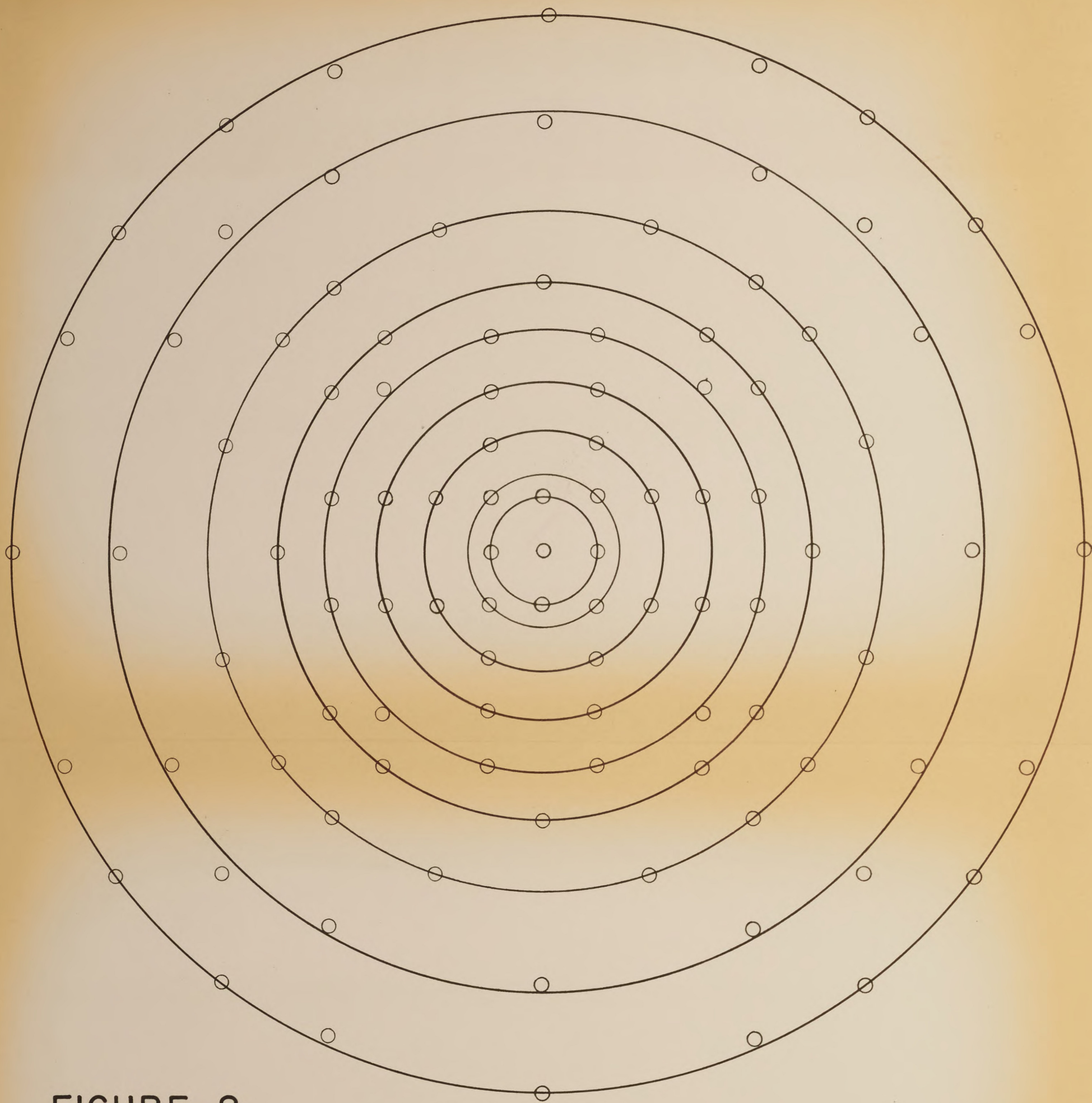


FIGURE 8.

VERTICAL GRADIENT GRATICULE

gravity and the 10^{-8} corrects the results to the proper final dimensions, that is from milligals per kilometer to gals per centimeter.

The horizontal gradient of gravity at a point P can be found by determining the slope at P on the anomaly profile which is orientated in the azimuth of magnetization of the anomalous body. The slope for the point is obtained by selecting points on either side of P and dividing the difference in gravity of these points by the difference in the horizontal distance between them and then converting the dimensions to gals per centimeter.

The vertical and horizontal gradients of gravity can now be used in the combined analysis equation by multiplying them by the sine and the cosine, respectively, of the angle of inclination of the direction of magnetization in the anomalous body. This direction of magnetization is either known or assumed; however, it is often advantageous to try several directions and compare the results.

Application to an Idealized Case

The combined analysis method employing equation (2) for the vertical gradient was used on an idealized case, prior to its application to the Sauble anomaly to determine the accuracy of the method. The magnetic and gravity anomalies were calculated over a spherical body of given radius, depth, density contrast, and intensity of magnetization. A vertical direction of magnetization was used to simplify the case. The characteristics and dimensions of the idealized anomalous body and

the equations for the determination of the magnetic and gravity anomalies are given below (Nettleton, 1942, p. 296).

$$g = 8.52 \frac{\sigma R^3}{z^2} \left[1 + \frac{x^2}{z^2} \right]^{-3/2} \quad (3)$$

$$Z = 8.38 \times 10^5 \frac{R^3 I}{z^3} \frac{\left[1 - \frac{x^2}{2z^2} \right]}{\left[1 + \frac{x^2}{z^2} \right]^{-5/2}} \quad (4)$$

<u>Notation</u>	<u>Given Dimensions</u>
g = gravity in milligals	
Z = vertical magnetic intensity in gammas	
σ = density contrast	0.3 gm per cm ³
I = intensity of magnetization	0.00236(in cgs units)
R = radius of the body	10 kilofeet
z = depth to center of body	20 kilofeet
X = the horizontal distance from a point above the center of the body to the point where the effect is calculated.	

Profiles of the magnetic and gravity anomalies are shown in Figure 9.

The next step is to calculate the magnetic anomaly from the gravity anomaly for several points on the profile by using equation (1). The values for I and ρ are known and can be applied to the equation. The factor $g_s \cos d$, which is dependent on the horizontal gradient and the inclination of the direction of magnetization, will be zero in this case because the inclination is vertical and the cosine of 90° is zero. The vertical gradient at selected points on the gravity anomaly map is calculated by using equation (2) and a

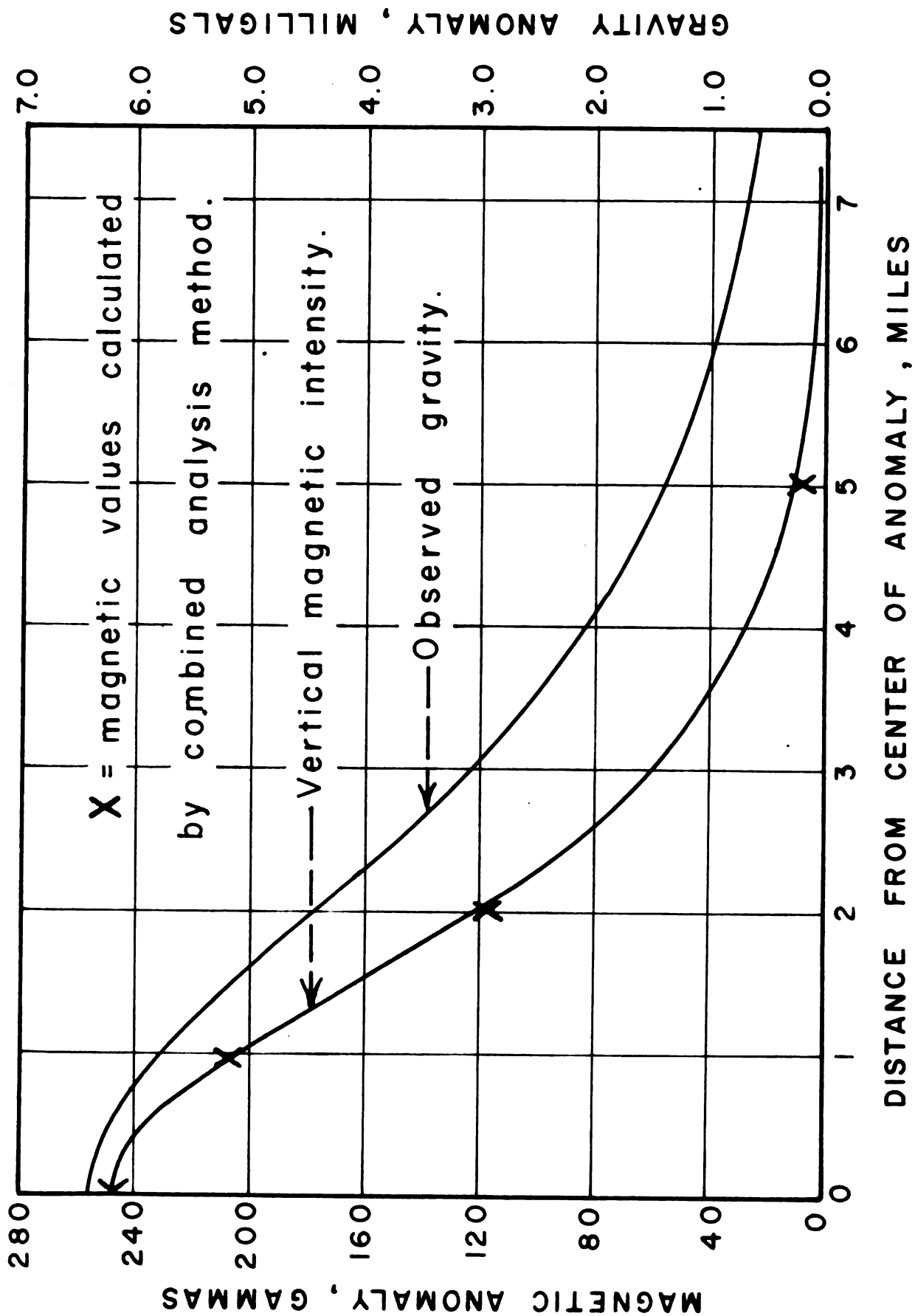


FIGURE 9. IDEALIZED CASE

gradicule with an inner radius of one mile (1.609 kilometers). The calculated magnetic anomaly is determined by equation (1), which for this special case has been reduced to $Z = I/G\rho$

$[g_z \sin d]$. A comparison of the actual magnetic anomaly over this idealized body and the calculated magnetic anomaly is shown in Figure 9. The closeness of fit of the two curves indicates that both Garland's combined analysis equation and Baranov's vertical gradient equation are extremely accurate. The theory of the combined analysis method is quite sound, as shown above, but in an actual field case it is still dependent on a number of assumptions.

Application to the Sauble Anomaly

The purpose of the combined analysis method is to determine the ratio of the anomalous susceptibility (k) to the anomalous density (ρ) of the body causing the Sauble anomaly. Independent values of the susceptibility and the density can not be determined by this method.

Necessary assumptions that must be made in the combined analysis method are that (1) the sources of the magnetic and gravity anomalies are from the same body, (2) the properties of density, susceptibility, and direction of magnetization are uniform throughout the body, and (3) the direction of magnetization is in the present magnetic field of the earth or some other known direction.

The close proximity of the maxima and similarity in the shape and form of the anomalies support the first assumption.

The second is more difficult to evaluate from surface readings alone because the body is probably at considerable depth and only large variations in its properties would cause changes in the otherwise smooth gravity and magnetic anomalies.

Some idea of the direction of magnetization in the body can be obtained by comparison of the residual gravity and magnetic anomaly maps. Under the discussion of these maps it was noted that the positive magnetic high is shifted slightly to the southeast of the gravity high and that there is also a small magnetic negative to the northwest. Both of these conditions tend to indicate that the direction of magnetization in the anomalous body is not vertical but inclined at an angle of probably 70 to 80 degrees to the northwest (Nettleton, 1940, p. 214). The magnetic negative found to the northwest might also extend to the north of the positive anomaly but has been concealed there by the regional.

In Lake County, the magnetic field of the earth has an azimuth or declination of $N1^{\circ} W$ and an angle of inclination of 75° north. The similarity of this to the interpreted direction of magnetization in the anomalous body leads to the conclusion that the magnetization is due to induction by the present field of the earth. In the following calculations an angle of inclination of 75° due north was assumed for the direction of magnetization in the body. To evaluate this assumption further an azimuth of $N 45^{\circ} W$ and angles of inclination of 50° and 90° for the direction of magnetization were

also calculated and will be discussed later in this section.

As shown earlier, the intensity of magnetization (I) given in equation (1) is equal to kF where k is the magnetic susceptibility of the body and F is the total intensity of the magnetizing field, which is assumed to be the field of the earth in this case. Now we can determine k/ρ for various points across the anomalies by using Garland's combined analysis equation (1) in the form:

$$\frac{k}{\rho} = \frac{Z G}{F(g_z \sin d + g_s \cos d)} = \frac{6.67 \times 10^{-8}}{0.59} \times \frac{Z}{(g_z \sin d + g_s \cos d)}.$$

The value of k/ρ was calculated at eleven points on both a north-south profile and an east-west profile over the anomalies. The average of the k/ρ values for the seven points nearest the center of the anomalies was determined for each profile. The stations on the periphery were omitted from the average because the values for the gravity and magnetic anomalies are smaller there and any small deviation or discrepancy in readings has a much larger effect on the ratio determination.

The magnetic anomaly calculated from the gravity anomaly was determined by substituting the average value of k/ρ for each profile into equation (1) and solving for Z . The actual magnetic anomaly and the calculated magnetic anomaly were graphed and compared. The closeness of fit indicates the degree of validity of the assumptions made in the beginning of this section. Figure 10 is a graph of the

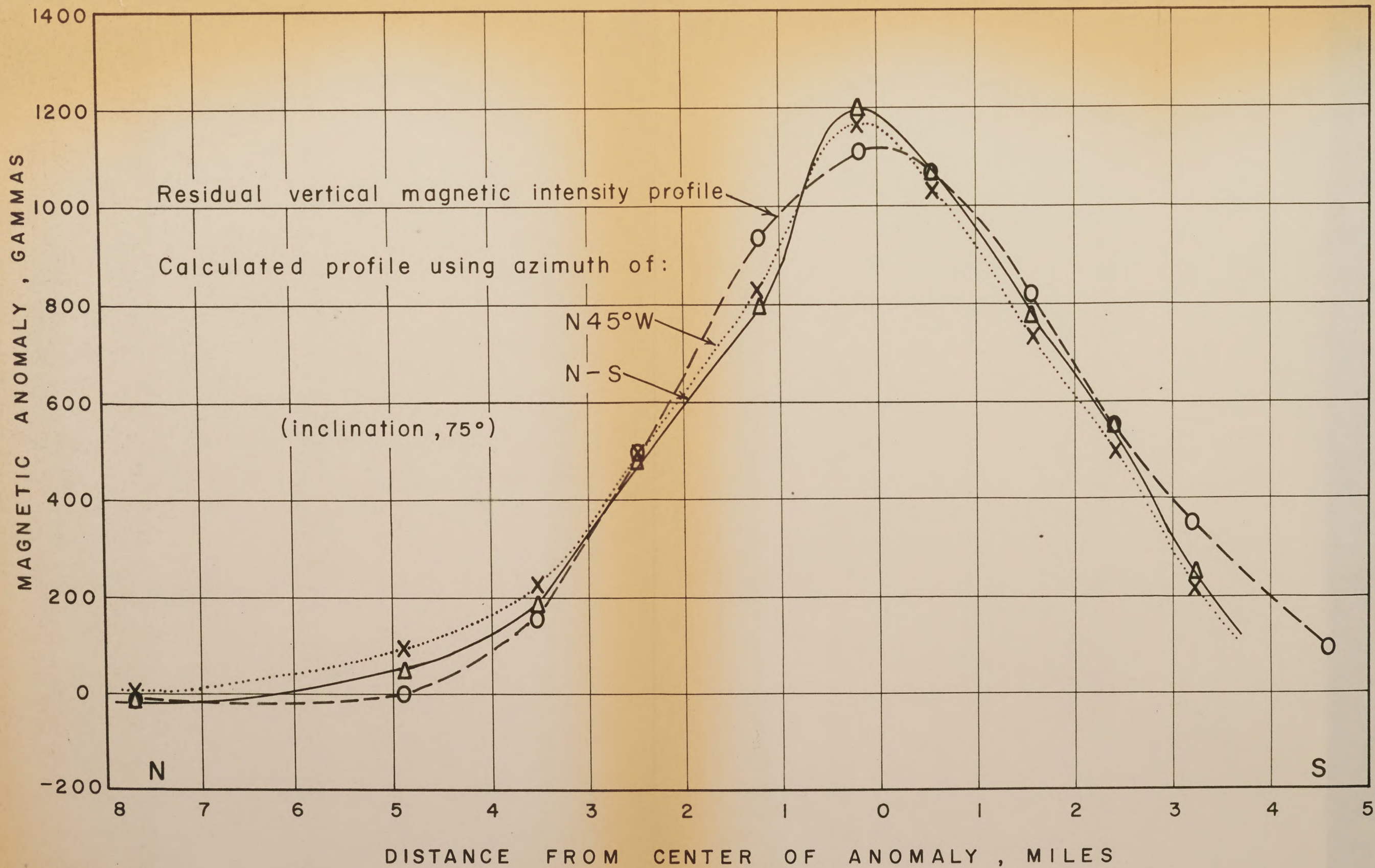


FIGURE 10.

MAGNETIC PROFILE CALCULATED BY COMBINED ANALYSIS METHOD, N-S PROFILE

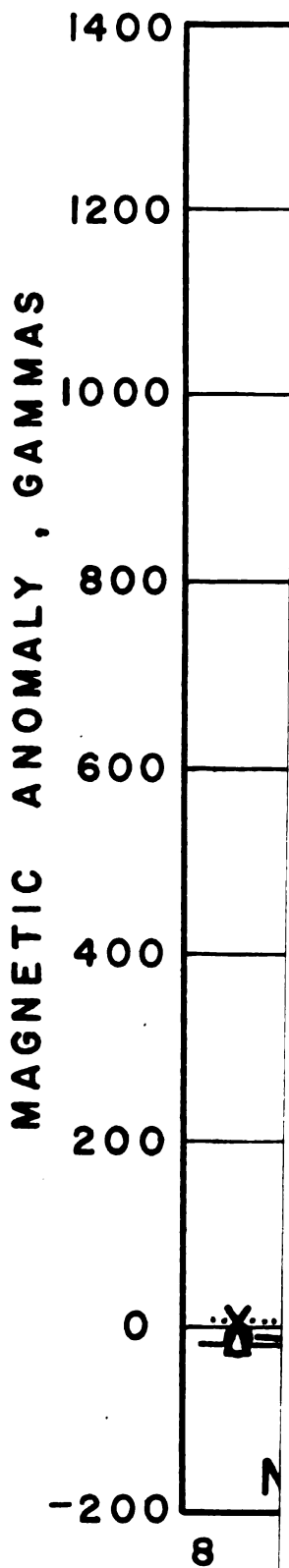


FIGURE 10
MAGNETIC

calculated magnetic anomaly along the north-south profile, using a two mile grid for the vertical gradient determination, an angle of 75° for the dip of the direction of magnetization and both a due north and a $N 45^\circ W$ azimuth for the direction of magnetization. Figure 11 is a graph of the east-west profile using the same conditions.

Graticules with an inner radius of one mile and two miles were used in the vertical gradient determination in order to note any differences in the results. The curves are quite similar indicating that the selection of the graticule will not effect the results substantially. The assumed direction of magnetization with respect to azimuth and dip was also varied to determine the effect on the results. A small variation between the cases where azimuths of due north and $N 45^\circ W$ were used was found. However, a change in the angle of inclination of the direction of magnetization causes a very significant difference in the calculated magnetic anomaly profiles. The curves obtained using 50° , 75° , and 90° for the angles of inclination are compared in Figure 12. The variations found in the curves using the 50° and the 90° directions of magnetization are opposite in their deviation from the observed magnetic profile, indicating that some angle between 50° and 90° would give the best fit.

The results obtained for the north-south and the east-west profiles are very similar. Using a two mile graticule

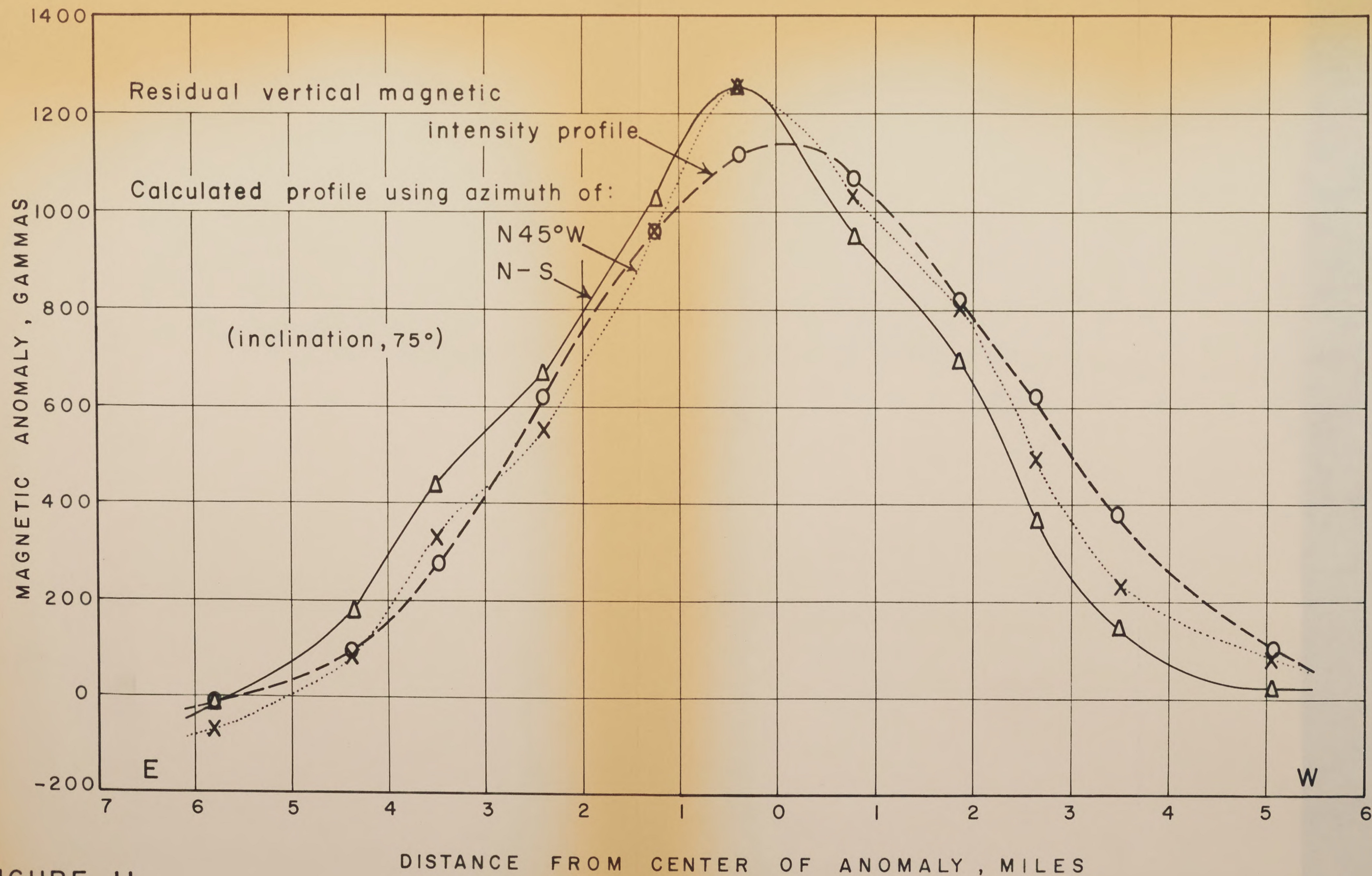


FIGURE II.

MAGNETIC PROFILE CALCULATED BY COMBINED ANALYSIS METHOD, E-W PROFILE

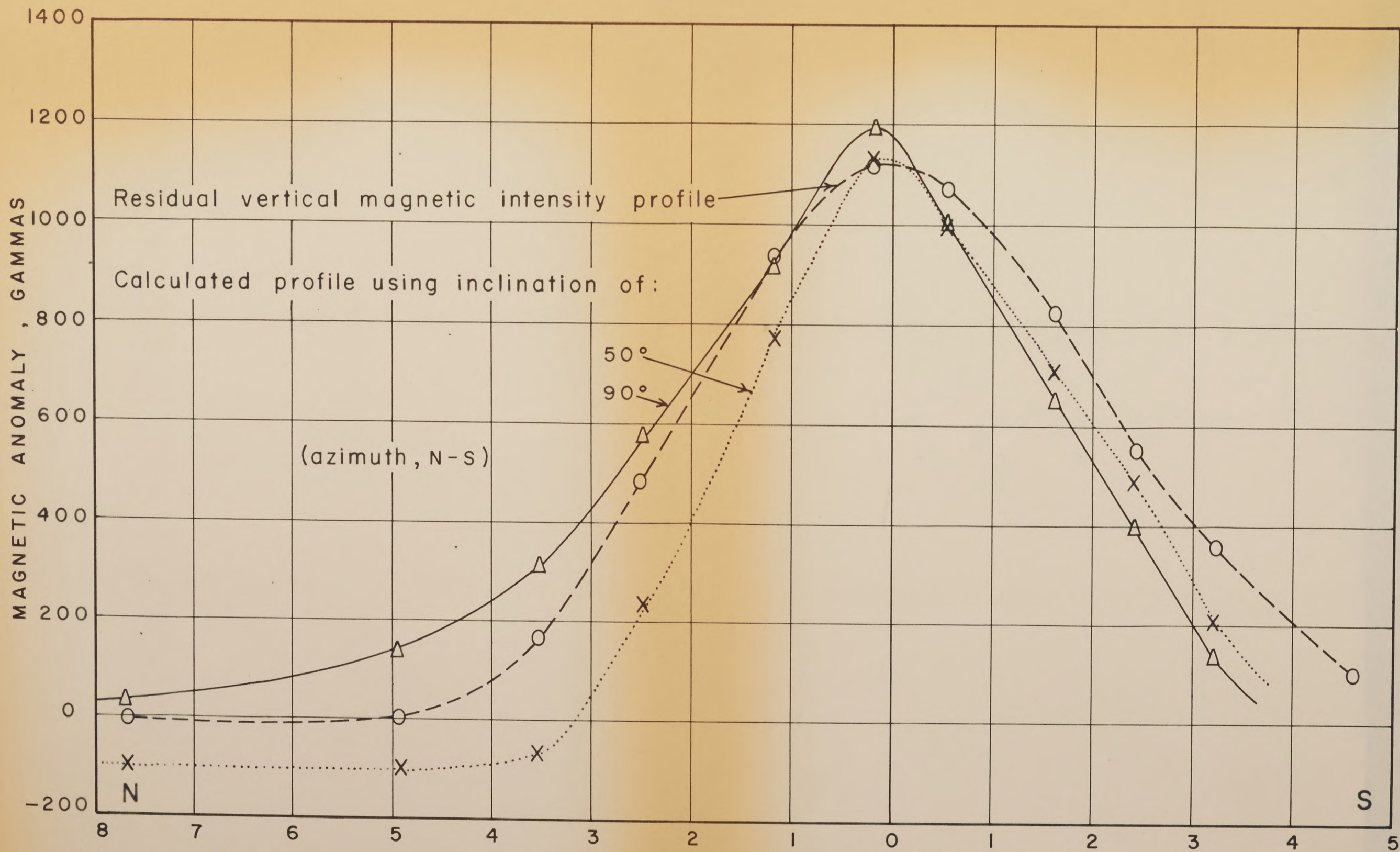


FIGURE 12. DISTANCE FROM CENTER OF ANOMALY , MILES

MAGNETIC PROFILE CALCULATED BY COMBINED ANALYSIS METHOD , N-S PROFILE

(Using 50° and 90° for the inclination of the direction of magnetization)

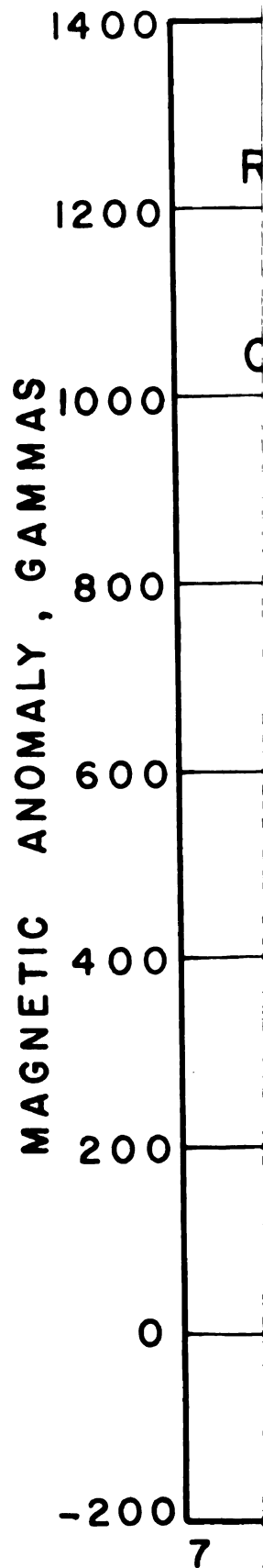
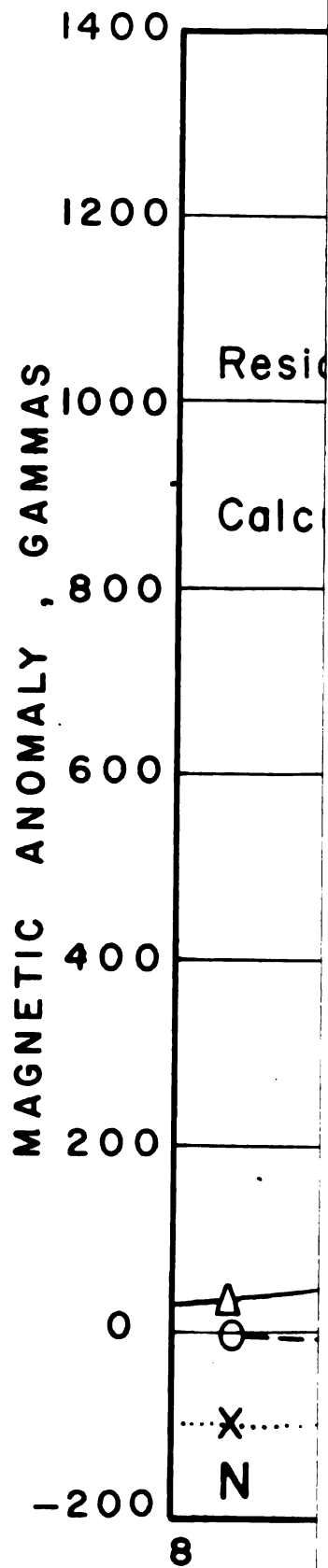


FIGURE II

MAGNETIC



FIGURE

MAGNETIC

and a direction of magnetization inclined at 75° due north, the average of the k/ρ values determined from the north-south and the east-west profiles is 0.022 (in cgs units). The small sample standard deviation for the 14 values of k/ρ was ± 0.0052 .

DEPTH DETERMINATIONS

The approximate elevation of the top of the Precambrian in the Sauble anomaly area is 8,000 feet below sea level, according to Cohee (1945). The surface elevation is about 750 feet above sea level so that the total depth to the Precambrian in this area is about 8,750 feet. The lack of wells that actually penetrate the Precambrian was noted earlier as a limitation of Cohee's determinations.

A depth estimation to the anomalous body was made by applying the half width method to the average of the four limbs of the north-south and the east-west gravity anomaly profiles, shown in Figure 6. This determination is limited by the assumption that the mass of the body is concentrated along a vertical line element in the center of the body instead of throughout the entire body. The equation, $Z = 0.58 X_{1/2}$ was used where Z is the depth to the top of the body and $X_{1/2}$ is the half width of the anomaly at half of its total magnitude. The depth to the top of the body was 9,575 feet as calculated from the half width value of 16,509 feet taken from the graph.

Although the above determinations are both estimates, they give some idea of the depth to the top of the anomalous body.

COMPARISON OF THE MAGNETIC AND GRAVITY PROFILES TO IDEALIZED CASES

Introduction

The curves over idealized bodies of variable dimensions and depth were calculated and compared to the magnetic and gravity profiles which were obtained by averaging the four limbs of the north-south and east-west profiles. The geometric form that most closely fits the Sauble anomaly is the vertical cylinder. Numerous attempts to fit the anomalies to the profiles calculated over spherical idealized bodies produced unrealistic results.

Calculation of Gravity and Magnetic Profiles of Various Cylinders

The gravity profiles over many idealized vertical cylinders were calculated using a template similar to the terrain correction chart designed by Hammer (1939, p. 184). The compartments in the template devised for this determination were more equal in size than in the terrain correction chart, but the principles are the same in both methods.

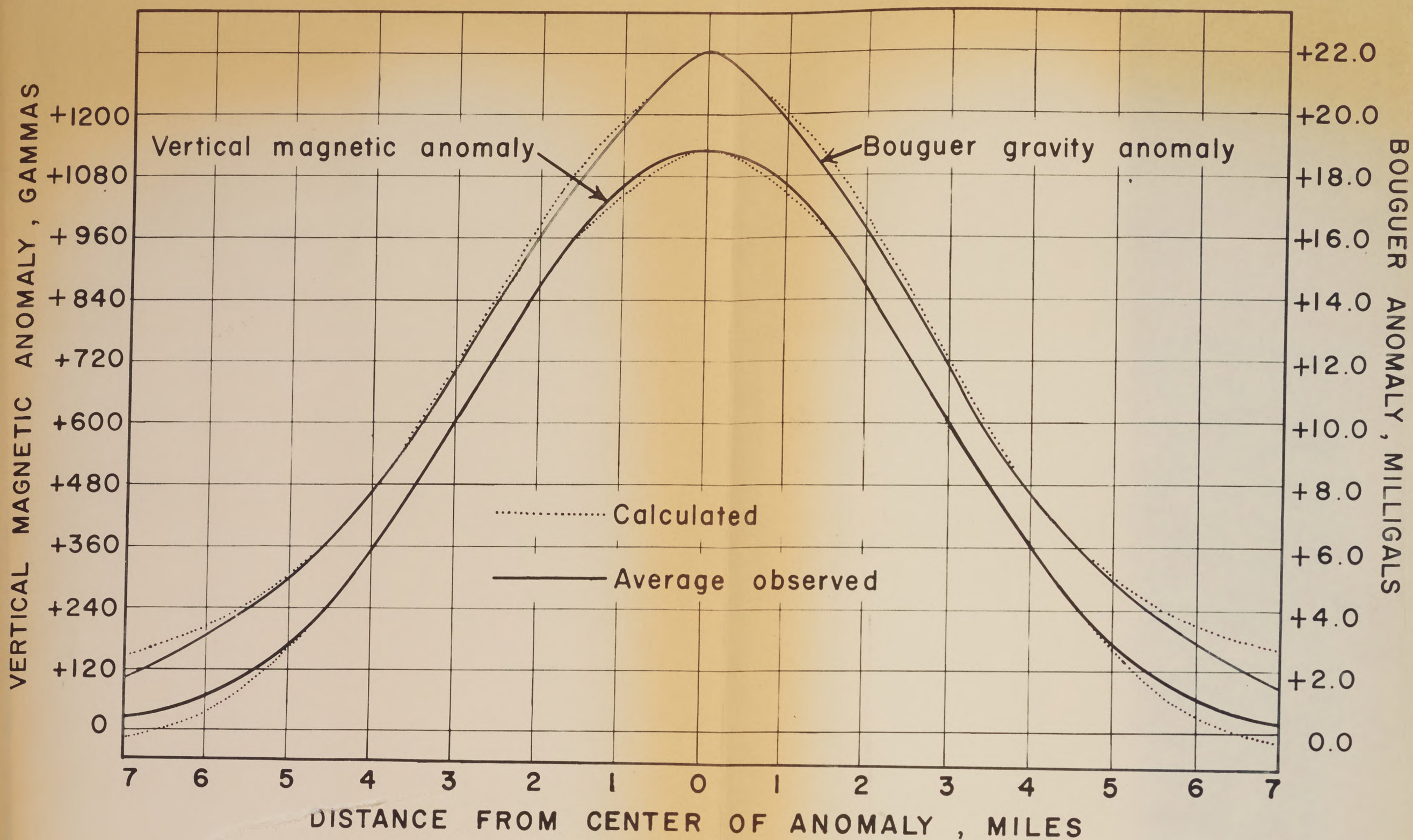
The gravity profiles over cylinders of various depths to top, depths to bottom, and radii of the body were graphed and the effect of each variable was determined by holding the other properties constant for several calculations. The

point over the center of each idealized cylinder was made equal to the actual gravity curve by adjustment of the density differential. The nearness of fit of the rest of the curve is an evaluation of the approximation of the subsurface form. This trial and error method was used until a reasonable fit was obtained between the actual gravity profile and a calculated profile. The comparison of the calculated and the actual curves is shown in Figure 13.

The magnetic profiles over numerous idealized vertical cylinders were determined using the equation and solid angle chart of Nettleton (1942, p. 304). As in the gravity approximation, the profiles over cylinders of various depths to top, depths to bottom, and radii of the body were graphed, letting the point directly over the cylinder equal the actual anomaly value by varying the magnetic susceptibility. The process of trial and error was used until a good fit was obtained between a calculated profile and the actual anomaly profile. The best-fitting calculated profile is compared to the actual profile in Figure 13.

Nettleton's equation for the calculation of the magnetic profile over a vertical cylinder assumes that the direction of polarization is vertical. This is not true in this case, however, Nettleton (1942, p. 294) has stated that the equations

. . . . approximate actual conditions closely enough to be useful in indicating the approximate magnitude and general shape of expected effects as ordinarily measured with the vertical magnetometer and are very much simpler to use than the complete expression . . .



GROUND SURFACE

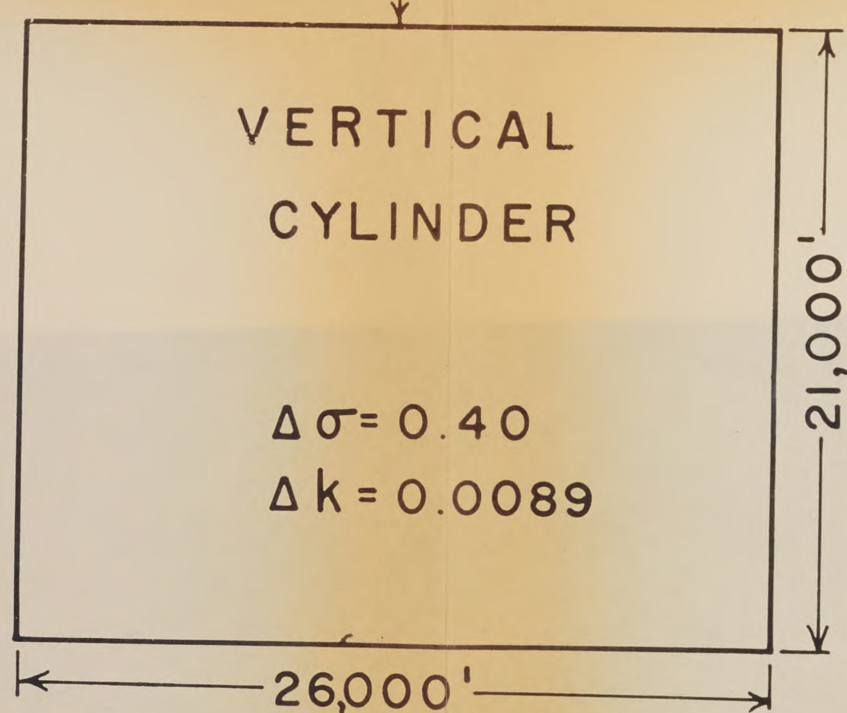


FIGURE 13. RESIDUAL GRAVITY AND VERTICAL MAGNETIC PROFILES
COMPARED TO THE BEST FITTING IDEALIZED CASE

Also the actual profile of the anomaly used in the above comparisons was an average of the north-south and the east-west profiles and thus reduced the effects of a slightly dipping direction of magnetization in the body.

Discussion of Results

Nettleton (1940, p. 101) has shown that the determination of the origin of an anomaly, using only the magnetic method or the gravity method, is not unique. Any anomaly from just one of these force fields could be caused by numerous structures. The solution becomes more definite when additional information is known about the anomalous body from drill holes or a second geophysical method. In the determination of the size, depth, and properties of a body producing both gravity and magnetic anomalies, certain conditions must be satisfied in the selection of the best-fitting idealized case. First, the dimensions of depth and size of the idealized body, which produce the calculated curves that best approximate the actual profiles, must be the same in the gravity and magnetic calculations. Second, the ratio of the magnetic susceptibility differential to the density differential determined from these best-fitting cases, must equal the k/ρ ratio computed by the combined analysis method.

The results of the best-fitting calculated profiles for gravity and magnetics over a vertical cylinder are given below.

Gravity

$Z_1 = 8$ to 9 kft. (both fit observed case well)

$Z_2 = 30$ kft.

$R = 13$ kft.

$\rho = 0.36$ to 0.40 gm/cc

Magnetics

$Z_1 = 9$ to 10 kft. (both fit observed case well)

$Z_2 = 30$ kft.

$R = 13$ kft.

$k = 0.0089$ to 0.0103 (in cgs units)

where Z_1 = depth to top of the cylinder

Z_2 = depth to bottom of the cylinder

R = radius of the cylinder

ρ = density differential between cylinder and surrounding material

k = magnetic susceptibility differential between cylinder and surrounding material.

The depth to the bottom of the cylinder, Z_2 , could vary as much as five kilofeet without changing the results substantially. Z_1 and R have a much stronger effect on the calculated curves. The final dimensions for the buried idealized vertical cylinder, which fit the actual results closest are:

$Z_1 = 9$ kilofeet

$Z_2 = 30$ kilofeet

$R = 13$ kilofeet

$\rho = 0.40$ gm/cc

$k = 0.0089$ (in cgs units)

$\frac{k}{\rho} = \frac{0.0089}{0.40} = 0.022$ (in cgs units)

Using the combined analysis method discussed earlier and assuming a direction of magnetization in the present earth's

field, the average value of the k/ρ determinations for the north-south and the east-west profiles is 0.022.

GEOLOGICAL INTERPRETATION OF THE RESULTS

Origin of the Anomalous Body

The dimensions, depth, and properties of the anomalous body discussed in the previous section significantly reduce the possibility of a sedimentary origin of the body. A sedimentary origin would also present problems concerning the source, means of transportation, and method of deposition of material into a circular deposit.

Two possibilities are noted for the most probable igneous origin of the anomalous body. Either the body was intrusive into the Paleozoic sediments during the Paleozoic era or later, or the body originated in Precambrian time and has been covered by Paleozoic sedimentation. The first possibility might be accompanied by evidence of disruption of the Paleozoic sediments and of dikes and emanating solutions originating from the intruding mass. This is not substantiated from drill hole data in this area and from information on the Michigan Basin as a whole. The limited drill hole information available in the Michigan Basin indicates that some folding and faulting have occurred, but evidence of igneous intrusion is lacking. Pirtle (1932, p. 151) has described the Michigan Basin as " . . . a zone of comparative quiescence relative to the diastrophic movements

that occurred around its rim." In addition to this the previous calculations have established that the depth to the top of the anomalous body is quite similar to the depth to the Precambrian surface determined by Cohee. Thus, igneous intrusion into the Paleozoic sediments is not supported by any positive evidence.

This leaves the hypothesis that the anomalous body is of Precambrian age and was exposed during erosion of the Precambrian rocks prior to Paleozoic sedimentation. This proposal will be discussed further after a description of the composition of the anomalous body.

Composition of the Anomalous Body

A magnetic susceptibility contrast of 0.0089 (in cgs units) and a density contrast of 0.40 gm/cc were obtained between the anomalous body and the adjacent country rock, through the use of the combined analysis method and the application of idealized cases. The susceptibility and density of the body were approximated by assuming granite or a similar material to be the adjacent country rock. Granite was assumed because it has been encountered in the majority of the wells drilled into the Precambrian in the Michigan Basin, even though these wells are a considerable distance from the Sauble anomaly (Cohee, 1945, Figure 7). If a density of 2.67 gm/cc is assumed for the granitic country rock, the density of the anomalous body is approximately 3.07 gm/cc. Tables of the density range of various igneous rocks are

given in Jakosky (1960, p. 264) and Heiland (1940, p. 80). The 3.07 value falls into the range of gabbro composition. The density of the ultrabasic rocks, peridotite and pyroxenite, is generally higher than 3.07 but is sometimes in this lower range. If the country rock is denser than 2.67 gm/cc, this would raise the density of the intrusive body and suggest an even more ultrabasic rock. Thus, from the density data a very basic composition for the intrusive anomalous body is suggested.

The determination of the susceptibility of the body is limited by the large variation in susceptibility of the igneous rock types. For instance, the susceptibility of granite, the assumed country rock, can vary from 0.000020 to 0.002900 (in cgs units). Using the tables of susceptibility given in Jakosky (1960, p. 165), Heiland (1940, p. 312), and Mooney and Bleifuss (1953, p. 389-392), calculations were made to determine the most likely composition of the anomalous body. The susceptibility contrast between the body and the country rock was computed as 0.0089 (in cgs units). When this value was added to the limits of the susceptibility range for granitic rocks given above, the range of the susceptibility of the anomalous body was obtained as 0.0089 to 0.0118 (in cgs units). Using an average value of 0.00047 for the susceptibility of granite, the susceptibility of the body was calculated as 0.0094 (in cgs units). The above figures are too high for the range of susceptibility generally given for rocks of gabbro composition and a little

low for ultrabasic rocks. This indicates that the composition of the anomalous body is intermediate between basic and ultrabasic rock. However, Mooney and Bleifuss (1953, p. 389) have given several examples of Minnesota basalts that have susceptibilities as large as 0.0088 and 0.0096 (in cgs units). The per cent magnetite of the anomalous body was calculated as 3 per cent by using the equation, % magnetic = susceptibility of the rock / susceptibility of magnetite (0.3).

The conclusion from the above density and susceptibility determinations is that the anomalous body has a very basic composition, probably intermediate between gabbro and peridotite.

An Igneous Intrusive of Precambrian Age

The proposal that the anomalous body is an igneous intrusive of Precambrian age was presented earlier in this section. The basic composition, the circular outline, and the fitting of idealized cases to the anomaly profiles indicate that the anomalous body is a basic to ultrabasic stock of about five miles in diameter. During Keweenawan time basaltic intrusion and lava flows were common in northern Michigan, Wisconsin, and Minnesota. The susceptibility of some of the Minnesota basalts (Mooney and Bleifuss, 1953, pp. 383-393) was found to be similar to the calculated values of the anomalous body. This intrusive body is probably not an isolated feature but rather is related to similar masses in Wisconsin and the Northern Peninsula of Michigan. In a

discussion of gravity measurements in the Northern Peninsula Bacon (1957, p. 58) has stated that, " . . . There is a definite possibility that it is a continuation of these lavas [along the north and east shores of Lake Superior in Ontario] which produces the anomaly running down through the Lower Peninsula of Michigan." Whether the intrusive mass and its counterparts in other areas initiated extensive basaltic lava flows over what is now the Michigan Basin, is uncertain. If this was the case, erosion and partial peneplanation of the Precambrian rocks prior to Paleozoic sedimentation has probably removed these flows and eroded down into the basic rock. The basic intrusive could have remained as a positive element and an influence to early Paleozoic sedimentation, however, this is difficult to evaluate because the type of erosion and the environmental history of the Precambrian surface are uncertain.

Geological Relationship of the Anomalous Body to the Sauble Oil Field

The above conclusions on the source of the anomalous mass also imply that probably no relationship exists between the intrusive body and the structural or stratigraphic entrapment of oil in the Sauble oil field. The structural contour map of the top of the Traverse formation (the Sauble oil field pay zone) in Plate 1 shows a northwest-southeast trending syncline superimposed on the edge of the Michigan Basin. This is parallel to other folds in the central and southeast parts of the basin (Pirtle, 1932, Fig. 1, and

Newcombe, 1933, Plate III). Below the Sauble oil field the top of the Traverse formation has positive relief of about 30 feet in a half mile wide area. This relief in the Traverse limestone is best explained by reference to the Traverse-Antrim break described by Kirkham (1931, p. 136). He states that, "Evidence derived from the cuttings and logs of wells drilled for oil and brine indicates persuasively that in parts of the Lower Peninsula of Michigan an important erosional unconformity exists at the top of the Traverse formation of Devonian age." This could easily account for variations in relief of the Traverse limestone that at first may be taken as structural folding as doming. The same situation was found by Newcombe (1933, p. 97) in the Dundee formation. He says that "Post-Dundee erosion apparently caused considerable surface relief, for in the central part of the State the formation may vary as much as 200 feet in thickness within a comparatively short distance . . . "

Thus, the very close proximity in location between the gravity and magnetic anomalies and the Sauble oil field is attributed to coincidence. The structure and stratigraphy entrapping the oil in the Sauble field is not believed to be related to the anomalies, which have been attributed to basic Precambrian intrusives.

CONCLUSION

The conclusions of this thesis are the following:

1. The combined analysis method used in conjunction with best-fitting idealized cases gives considerably more information about the depth, dimensions, and composition of the anomalous body.
2. The vertical gradient approximation devised by Baranov is of high accuracy.
3. The anomalous body has a gabbro composition with about 3 per cent magnetite and is believed to be a stock of Precambrian age, probably related to the Keweenawan intrusives. The stock was most likely exposed during erosion of the Precambrian surface.
4. The elevation of the top of the Precambrian in this area is about 8,000 to 9,000 feet below sea level.
5. The close proximity of the Sauble oil field and the Sauble anomaly is attributed to coincidence.

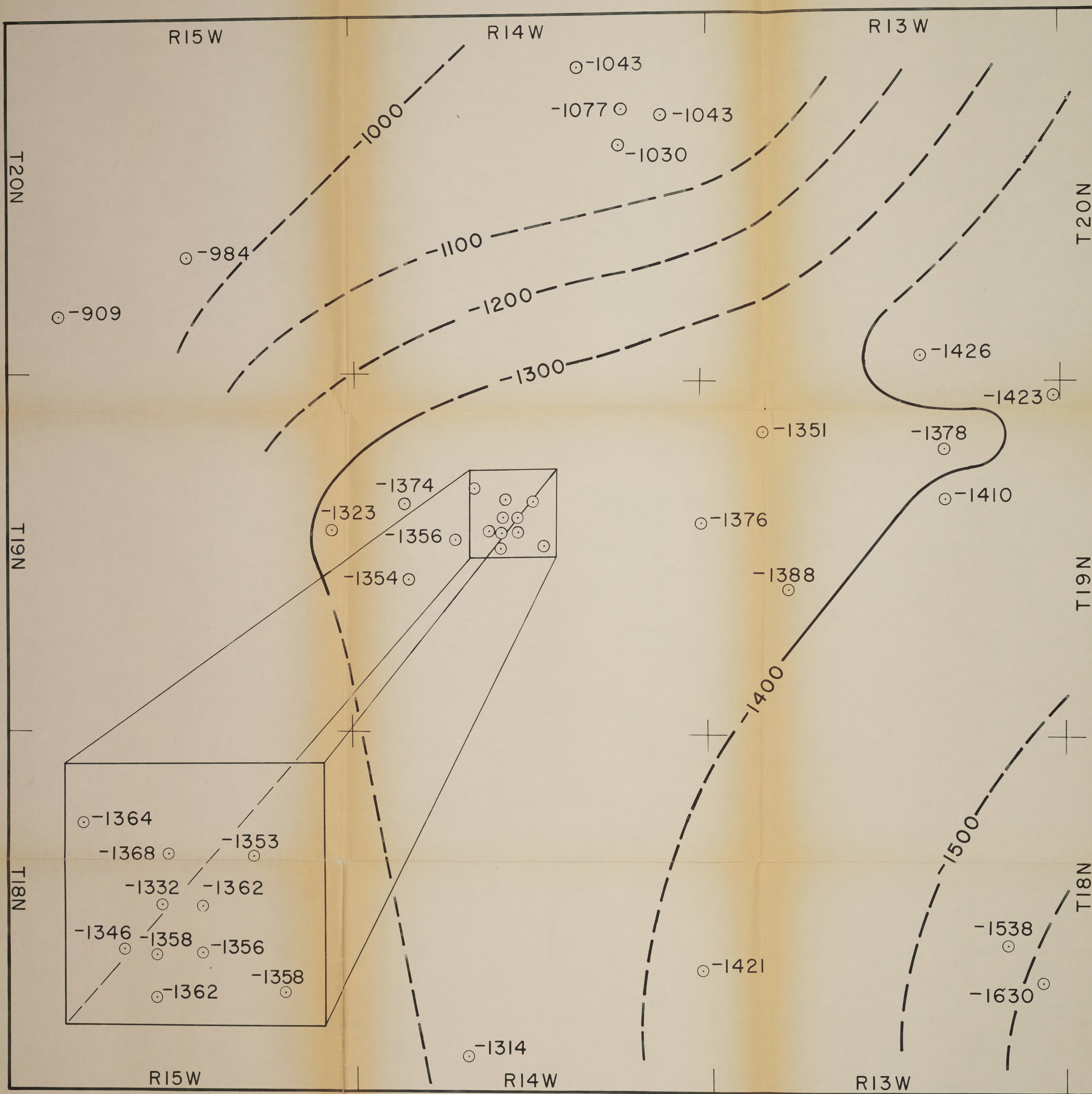
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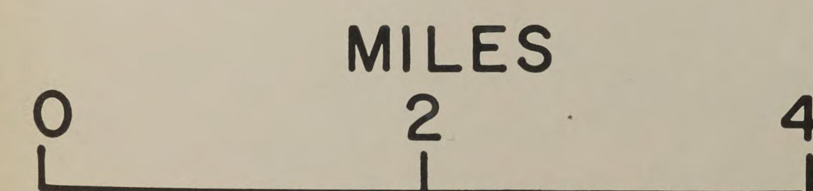
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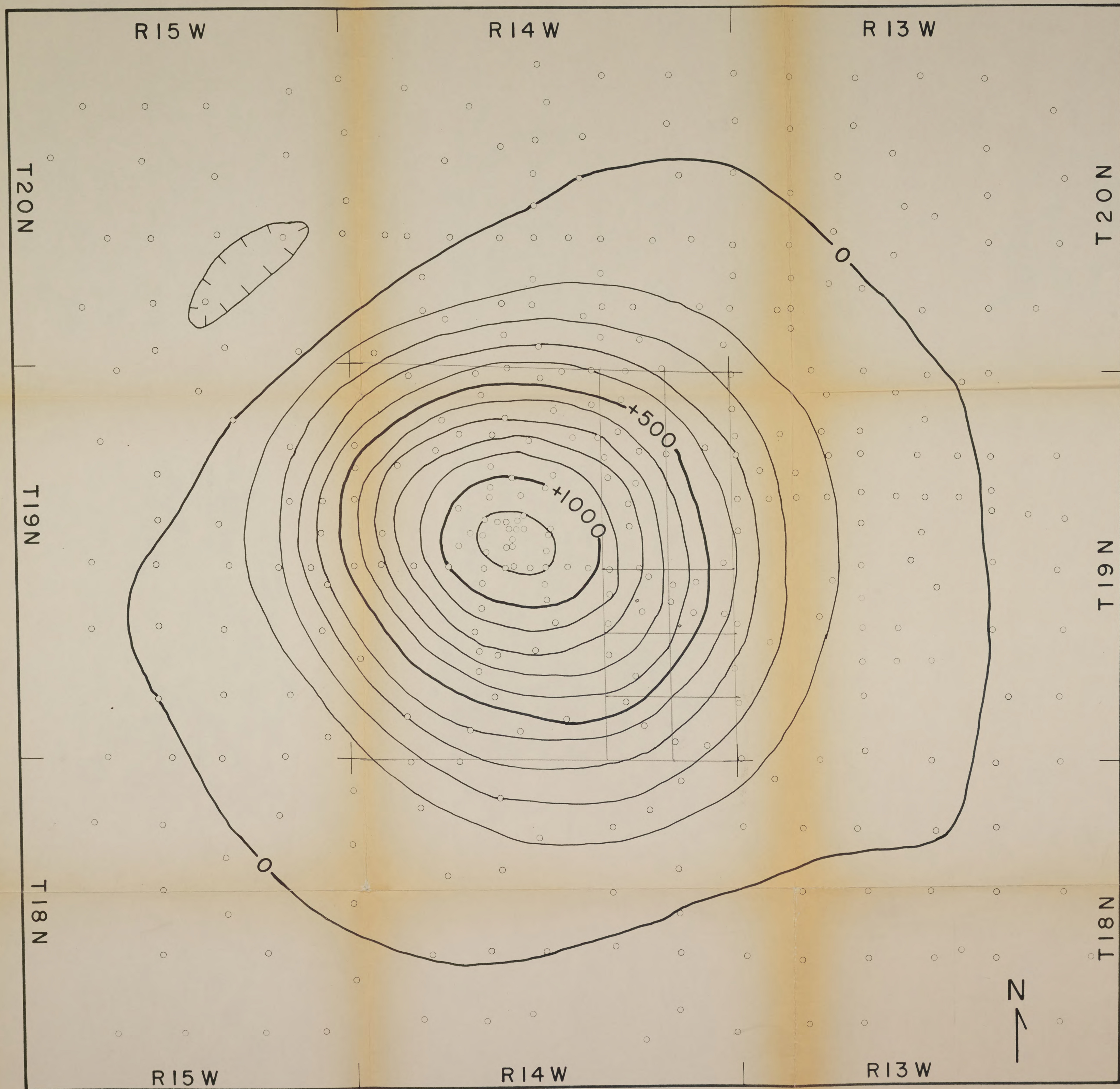


STRUCTURAL CONTOURS ON TOP OF THE TRAVERSE FM.

DATUM MEAN SEA LEVEL
CONTOUR INTERVAL 100 FEET

PLATE I





RESIDUAL VERTICAL MAGNETIC INTENSITY ANOMALY MAP PLATE 5

CONTOUR INTERVAL 100 GAMMAS

MILES
0 2 4

Plate 5

SUPPLEMENTARY
MATERIAL



141
363
THS
Plate 5



RESIDUAL BOUGUER GRAVITY ANOMALY MAP

CONTOUR INTERVAL 2.0 MILLIGALS

PLATE 4

⊖ ELEVATIONS BY BAROMETRIC ALTIMETER

$\sigma = 2.67$

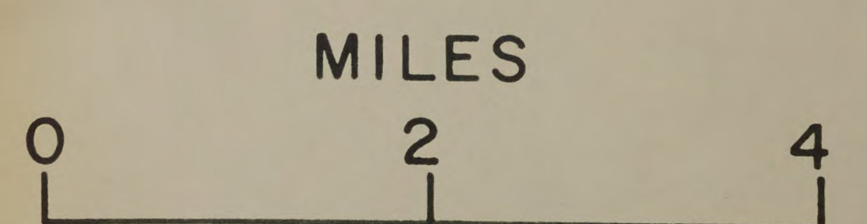


Plate 4

SUPPLEMENTARY
MATERIAL



141
243
T45
Plate 4

