GRAVITY STUDIES OF BURIED BEDROCK TOPOGRAPHY IN NORTHWEST OAKLAND COUNTY, MICHIGAN

THESIS FOR THE DEGREE OF M. S.

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ROGER WAITE PEEBLES

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ABSTRACT

GRAVITY STUDIES OF BURIED BEDROCK TOPOGRAPHY IN NORTHWEST OAKLAND COUNTY, MICHIGAN

By

Roger Waite Peebles

Approximately 360 gravity stations were occupied in a six township area of northwestern Oakland County and in parts of three adjacent townships in Livingston and Genessee counties for the purpose of mapping the topography of the bedrock surface. In addition, two detailed gravity profiles consisting of roughly 260 gravity stations were established in T4N, R7E. Data reduction followed standard procedures and residual gravity anomalies were isolated by the cross-profile method and the least squares polynomial method.

The residual gravity maps indicate that a large bedrock low in T4N, R7E may be closed on its western end. Two other bedrock lows, or valleys, may connect with the large low at its western end, one trending northwest, the other southeast.

In addition to the Oakland County Bouguer gravity survey, a method of measuring the horizontal gravity gradient was evaluated to determine its effectiveness as a reconnaissance tool to locate buried bedrock valleys. The gradient was measured by using a gravity meter to take three gravity readings in a triangular array. Each set of three

gravity stations comprised a gradient station and was treated as an individual gravity survey. Standard gravity reduction techniques were used to determine the Bouguer gravity at each gravity station. Graphical methods were used to determine the horizontal Bouguer gravity gradient.

To evaluate the method, 20 gradient measurements were observed over a sharply defined Bouguer gravity anomaly in western Michigan. An additional 13 measurements were made in Oakland County. All gradients show excellent agreement with the Bouguer anomaly. In particular, the buried valley in western Michigan is successfully defined by the method.

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Roger Waite Peebles

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INTRODUCTION

Much of the ground water for private, municipal and industrial use in Michigan is obtained from the ubiquitous glacial drift. With increasing demand for water, the need for information concerning the location of ground water sources in the drift has increased greatly. Among the best sources of ground water are the sands and gravels often found in buried bedrock valleys. For this reason, a map of bedrock surface topography showing the location of buried valleys can be of great value for ground water exploration.

In the preparation of a bedrock topographic map, the most reliable source of data are well logs that extend to bedrock. Where well logs are scarce or lacking, bedrock topography often can be determined indirectly using geophysical methods. The purpose of this study is to delineate the bedrock topography of an area using conventional gravity methods (Bouguer anomaly survey) and well data. In addition, a method of measuring horizontal gravity gradients will be investigated. It is hoped this method will prove useful in determining the location of buried bedrock valleys.

The area selected for the gravity survey is a six township portion of northwestern Oakland County. Recent population and industry growth have increased greatly the demand for water in this area. All water currently used in these townships is obtained from the glacial drift. Future demands will require greater withdrawals from the drift. Thus, it is felt that a topographic map of the bedrock surface will be of use in future exploration for ground water.

GEOGRAPHY OF THE AREA

The study area, shown in Figure 1, includes six townships in northwest Oakland County and portions of adjacent Livingston and Genessee counties. Except for three villages, Holly, Fenton, and Milford, the area is rural with extensive farming. A network of section line roads covers the survey area. The lowest land surface elevation is approximately 800 feet above sea level; the highest, about 1,100 feet. Locally elevation differences are rarely greater than 75 feet.

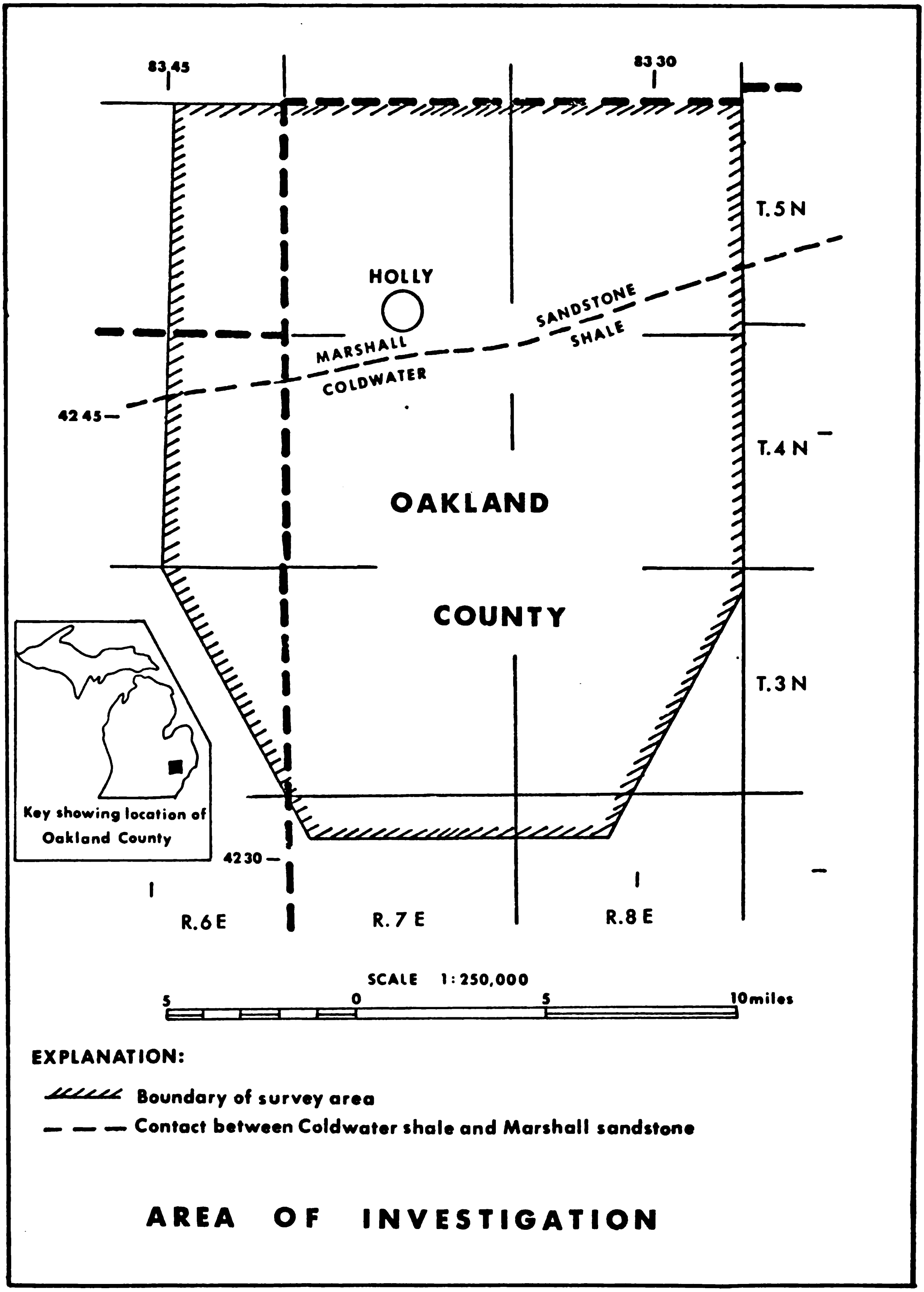


Figure 1. Map showing area of Bouguer anomaly survey.

GEOLOGY OF THE AREA

The survey area is located on the southeastern edge of the Michigan basin. Bedrock consists of sedimentary rock of Paleozoic age, dipping gently to the northwest toward the center of the basin. The subcrops in the survey area, as shown by well logs, are the Marshall Sandstone in the north and the Coldwater Shale in the south. The location and trend of the contact between the formations are shown approximately in Figure 1.

Glacial sediments in the area range from approximately 100 feet to 400 feet in thickness. They were deposited during the Wisconsin in the interlobate area between the Saginaw and Huron-Erie ice lobes. Surface formations consist of outwash, kames, kame complexes and some ground moraine. The greatest proportion of surface sediments appears to be sands associated with kames and kame complexes. Subsurface materials consist of clays, sands, gravels and till. Correlation of any one lithologic type between closely spaced wells is practically impossible in the survey area, indicating that the glacial deposits are heterogeneous in nature.

THE BOUGUER GRAVITY ANOMALY SURVEY

INTRODUCTION

The Bouguer gravity anomaly survey was undertaken in order to map the bedrock topography in northwest Oakland County, Michigan. Well log data suggest that a buried bedrock valley trending roughly east-west is located south of the village of Holly in the northern portion of Rose Township (T4N, R7E). The valley is believed to have a width of between one-half and one mile and a depth of 300 feet. A special attempt will be made to delineate this valley, as well as others that may exist in the area, using the Bouguer anomaly map.

COLLECTION AND REDUCTION OF DATA

Two gravity meters were used in the survey, Worden no. 99 and Lacoste-Romberg no. 103. Both meters are capable of determining relative gravity with an accuracy of 0.01 milligals (mgals) or one part in one-hundred millionth of normal gravity of the earth.

Although the meters are temperature and pressure compensated or controlled, they show variation with time, or drift. The drift of the Worden meter was determined by reoccupying the same base station once every hour. The Lacoste-Romberg meter was observed to follow very closely daily variations in gravity due to lunar and solar tides. In using the meter, a base station was established and reoccupied at the end of a day's survey. A check on the agreement between the meter drift and tides was made at two or three hour intervals by reoccupying intermediate stations.

Gravity data for the Bouguer anomaly map were collected along profiles and at points where elevations are given on U. S. Geological Survey topographic maps. The profiles were located to cross the large buried valley believed to exist in Rose Township. They are shown in Figure 2. All gravity stations were located along roads.

Elevations for the gravity profiles were determined by levelling. The spacing between gravity stations varied from 50 to 800 feet. About 260 stations were occupied along the profiles. Elevations for gravity stations in the remainder of the survey area were obtained from preliminary (unpublished) topographic sheets which show numerous elevations that do not appear on published topographic sheets. About 360 stations were occupied at road corners and intersections of fences with roads.

Gravity readings must be corrected for known gravity variations to obtain the Bouguer gravity anomaly. The corrections are summarized by the following formula:

$$G_b = g_o - g_l + g_f - g_m + g_t$$

where:

G_b = the Bouguer gravity anomaly

g_o = the observed gravity

g_l = the latitude correction

Figure 2. Map showing location of Bouguer gravity profiles.

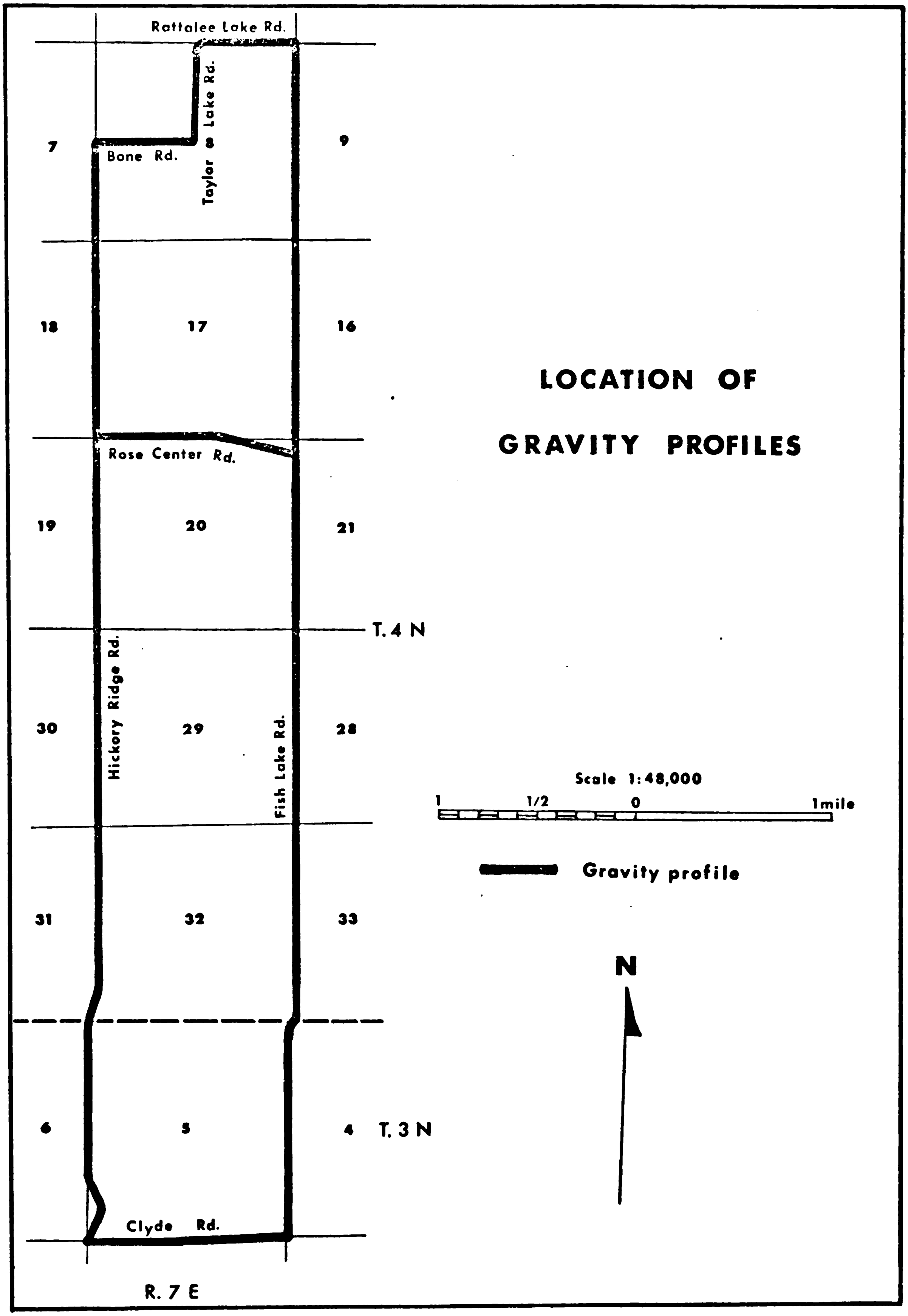

Rattalee Lake Rd.
Taylor 8 Lake Rd.
Bone Rd.
7
9
18
17
16
LOCATION OF
GRAVITY PROFILES
Rose Center Rd.
19
20
21
T. 4 N
Hickory Ridge Rd.
30
29
Fish Lake Rd.
28
Scale 1:48,000
1
1/2
0
1mile
Gravity profile
31
32
33
N
6
5
4
T. 3 N
Clyde Rd.
R. 7 E

Figure 2.

g_f = the free-air correction

g_m = the mass correction

g_t = the terrain correction.

The observed gravity is obtained by multiplying the gravity meter readings, in scale divisions corrected for drift, by the conversion factors of the gravity meters. Drift corrections for the Worden meter were based on observed drift, while the corrections for the Lacoste-Romberg meter were based on a combination of observed drift and solar-lunar tide tables (Geophysical Prospecting, 1967).

Latitude corrections were obtained by calculating the theoretical gravity at latitudes not greater than four miles apart covering the survey area. Distances to stations north or south of a chosen latitude were measured and multiplied by a constant factor, K. According to Nettleton (1940), $K = 1.3067 \sin 2\phi$ mgals/mile where ϕ is the latitude from which the distance to a station is measured.

To eliminate variations in gravity caused by elevation differences between stations, all observed gravity values were related to a sea level datum. This was accomplished by applying the free-air correction, which is calculated by multiplying the elevation of a station above the datum by a constant 0.09406.

In addition to the free-air correction, it is necessary to correct for the mass of the earth materials lying between the gravity station and the datum. To calculate this correction in mgals, the elevation of a gravity station in feet above sea level is multiplied by 0.01267σ, where σ is the estimated density of the earth materials in grams per cubic centimeter (g/cc).

The optimum density value for the mass correction most completely eliminates the effect of surface elevation changes on the Bouguer anomaly. Klasner (1964) determined an in situ density of 2.15 g/cc for a small glacial drift feature in western Michigan using the density profile method of Jung (1953). Densities for glacial till of 2.10, 2.15 and 2.20 g/cc are given by Hall and Hajnal (1962). Lennox and Carlson (1967) give a value of 2.23 g/cc for a glacial till. A value of 2.2 g/cc was chosen for this survey. It is believed the error associated with this value is no greater than $\pm$ 0.2 g/cc.

In applying the mass correction, the assumption has been made that the area surrounding a gravity station is a flat horizontal surface extending an infinite distance in all directions. By disregarding variations in topography, an error is introduced in the calculation of the Bouguer anomaly which can be eliminated by applying a terrain correction. In the survey area, the error introduced by neglecting the terrain correction was very small compared to other sources of error. Consequently, no terrain corrections were made.

ACCURACY OF DATA REDUCTION

There are five sources of error in the calculation of the Bouguer anomaly values: (1) error in the observed gravity (including drift correction error), (2) error in the latitude measurements, (3) error in the elevation measurements, (4) error in the assumed density of earth materials used in the mass correction, and (5) error due to neglecting terrain corrections.

The error in the observed gravity was estimated by calculating the standard deviation of gravity readings taken at the same point at different times. Five gravity stations, reoccupied on the same day or on different days a total of 11 times, have a standard deviation in the drift-corrected observed gravity of ± 0.015 mgals.

Latitude correction errors arise from inaccuracies in measured north-south distances. Along the profiles, where distances were measured by stadia rod interval, the error is estimated to be not more than ± 10 feet or ± 0.002 mgals based on a north-south gradient of 0.0002467 mgals per foot. At other gravity stations, north-south distances can be measured on topographic maps with an accuracy of ± 75 feet, giving an error of ± 0.015 mgals.

Errors in gravity station elevations affect both the free-air and mass corrections. The closure errors on the level loops were 0.05 feet for a nine mile loop and 0.04 feet for an eight mile loop. Assuming an error of ± 0.05 feet in elevations along the gravity profiles, the combined free-air and mass correction error could be as much as ± 0.035 mgals for an assumed density of earth materials of 2.2 g/cc.

According to the Topographic Division, U. S. Geological Survey, elevations at road corners and fence lines have an accuracy of plus or minus one tenth of the contour interval. All maps used in this survey have a contour interval of ten feet, indicating elevations are accurate to plus or minus one foot. To allow for differences between the elevation point and the point where the gravity is observed, an elevation error of ± 3 feet is assumed for all gravity stations not on the profiles. This contributes an error of ± 0.2 mgals in the reduction of data.

Using an incorrect density value for the mass correction can result in a significant error in the Bouguer anomaly values. Assuming the density error to be ± 0.2 g/cc, a one foot difference in elevation between two gravity stations results in an error in the mass correction of ± 0.00256 mgals. In the survey area, where elevations vary locally as much as 75 feet, the error could be as great as ± 0.2 mgals. A visual comparison made between gravity profiles and topographic profiles indicates no apparent correlation between the Bouguer anomaly and topography. Consequently, the error from this source is estimated to be no greater than ± 0.2 mgals.

To estimate the error introduced by neglecting the terrain effect, a terrain correction was calculated for a gravity station located where variations in topography are among the greatest to be found in the survey area. Using Hammer's method (Hammer, 1939), the terrain correction was found to be approximately 0.06 mgals. At most, ten percent of the gravity stations in the survey area would have a correction as great as this value.

The maximum net error, assuming all errors agree in sign, is - 0.28, + 0.22 mgals for the gravity profiles and - 0.45, + 0.39 mgals for other stations. The difference in the plus and minus values is due to the terrain correction error which is always positive in sign. The net error at most gravity stations is probably much less than indicated because only maximum errors have been considered and it is not likely that all errors always agree in sign.

DISCUSSION OF THE BOUGUER GRAVITY ANOMALY MAP

The Bouguer gravity map, Figure 3, shows a very steep gradient from a high in the southwest to a low in the northeast with a range in gravity values of + 4 mgals to - 43 mgals. The gravity contours curve from a northerly direction in the western section of the map to a more easterly direction in the eastern section. The only obvious local anomalies that might be associated with buried bedrock valleys are a change in the gradient just south of the village of Holly and irregularities in the curvature of the contour lines. However, even assuming these anomalies are due to buried valleys, the modifying effect of the steep

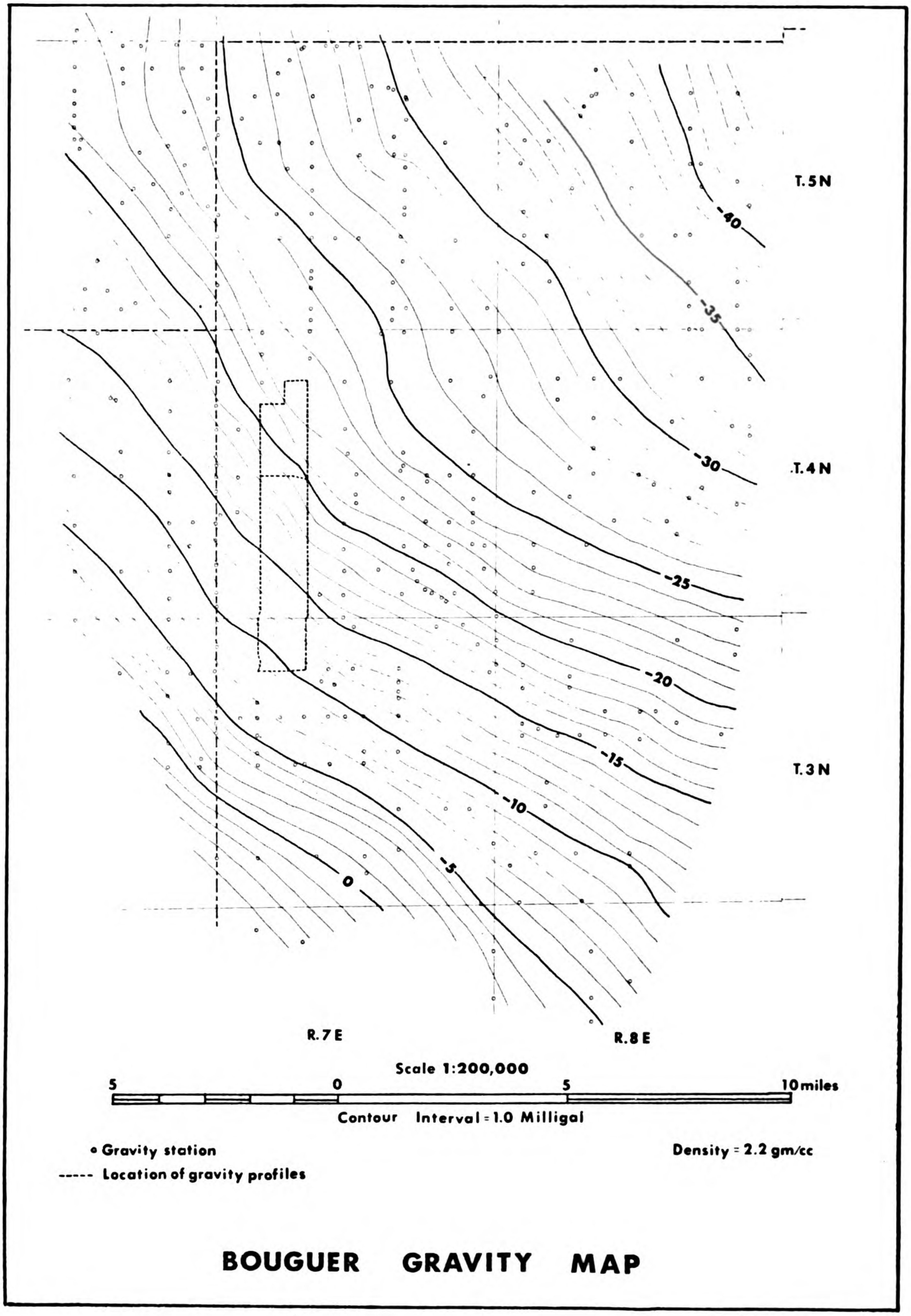


Figure 3. Bouguer gravity anomaly map.

regional gradient makes it impossible to directly determine their configuration.

The Bouguer gravity anomaly profiles, Figure 4, also give no direct information about buried bedrock valleys. Their slight concave-upward shape may indicate a general thickening of the glacial drift over a local bedrock low, but additional gravity and well data are needed to support this hypothesis.

In conclusion, it is necessary to isolate the low-amplitude local gravity anomalies from the steep regional gradient in order to detect and delineate the buried bedrock valleys that may exist in the survey area.

ISOLATION OF BEDROCK ANOMALIES

The steep regional gradient shown by the Bouguer anomaly map probably is due to lateral changes in density of the basement rock. Superimposed on the strong gradient are horizontal variations in gravity due to (1) lateral changes in the density of both the sedimentary rock and glacial sediments and to (2) variations in the elevation of the bedrock surface.

To detect gravity anomalies due to buried valleys with the Bouguer anomaly map, it is necessary to isolate anomalies that have characteristics expected from theoretical considerations. To estimate a probable anomaly magnitude, a hypothetical buried valley was constructed with dimensions approximating the large buried valley that well log data

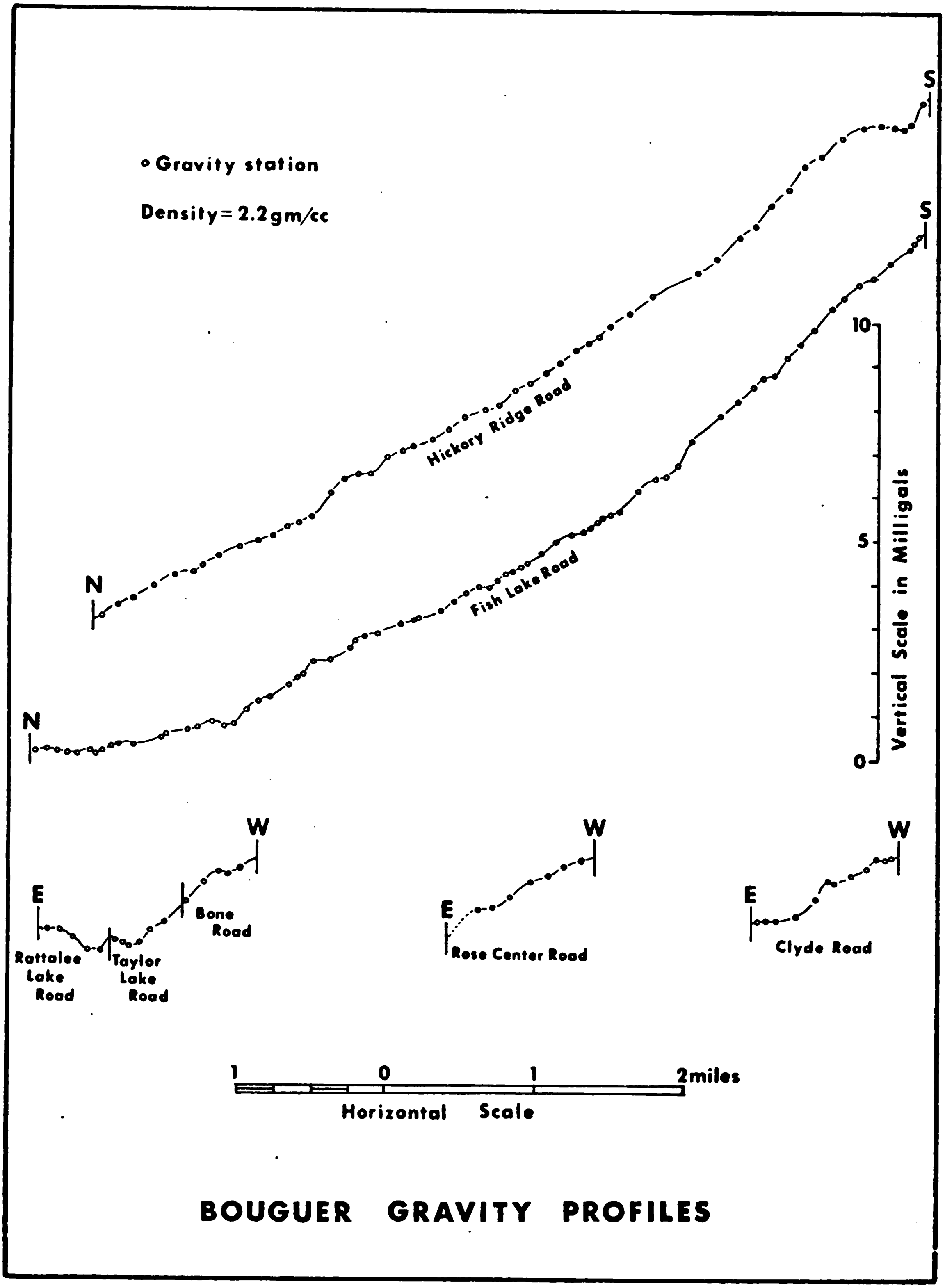


Figure 4. Bouguer gravity profiles.

indicate exists in the northern portion of Rose Township (T4N, R7E). Using a value of 2.50 g/cc to approximate the densities of the Coldwater Shale and Marshall Sandstone (Michigan State University, unpublished data) and a density of 2.20 g/cc for the glacial materials, the density contrast of the buried valley is assumed to be - 0.30 g/cc.

The valley model is symmetrical with a width between the crests of the valley walls of 1,500 feet, a floor width of 500 feet, a depth of 250 feet and an infinite length. The valley walls are assumed to be straight. In addition, it is assumed that a regional overburden 100 feet in thickness covers the valley and the valley fill.

A graticule was used to evaluate the anomaly (Hubbert, 1948a). It was placed at a point over the center of the valley and 100 feet above the crests of the valley walls to allow for the regional glacial overburden. The anomaly has a maximum amplitude of - 0.68 mgals.

To isolate anomalies with magnitudes on the order of 0.68 mgals, it is necessary to remove the large scale regional changes in gravity. Two methods are used to accomplish this, a cross-profile method and a two dimensional least squares method.

Cross-profiling is a graphical technique for fitting a smooth, "regional" surface to the Bouguer gravity values. An orthogonal set of Bouguer gravity profiles are drawn from the Bouguer map. For each Bouguer profile, a smoothed profile is constructed with the restriction that the regional gravity values must agree where any two profiles intersect. The regional is then subtracted from the Bouguer values at each gravity station. The difference is used to construct a residual gravity map, which should show gravity anomalies of the order of magnitude indicated by the buried valley model.

The fitting of a smooth profile to the Bouguer profile by cross-profiling is a subjective process and may result in errors arising from bias on the part of the interpreter. To eliminate this possibility, a two dimensional least squares polynomial fit to the Bouguer map was calculated using the Michigan State University digital computer. A least squares fit is a statistical method that consists of fitting a smooth surface to the Bouguer gravity values (Croxton, 1959). This surface represents the regional gradient. A reasonable regional gravity surface can be obtained by selecting an equation of the appropriate degree. Second through seventh degree equations gave residual anomaly magnitudes most closely approximating the anomaly obtained from the model. Figures 5 and 6 show the residual gravity maps obtained by the cross-profile method and by the fifth degree least squares approximation.

The two residual gravity maps differ in the magnitude and configuration of the anomalies displayed. In the central portion of the survey area, the least squares residual map is judged to better approximate the anomalies predicted by the model. However, because the least squares method is

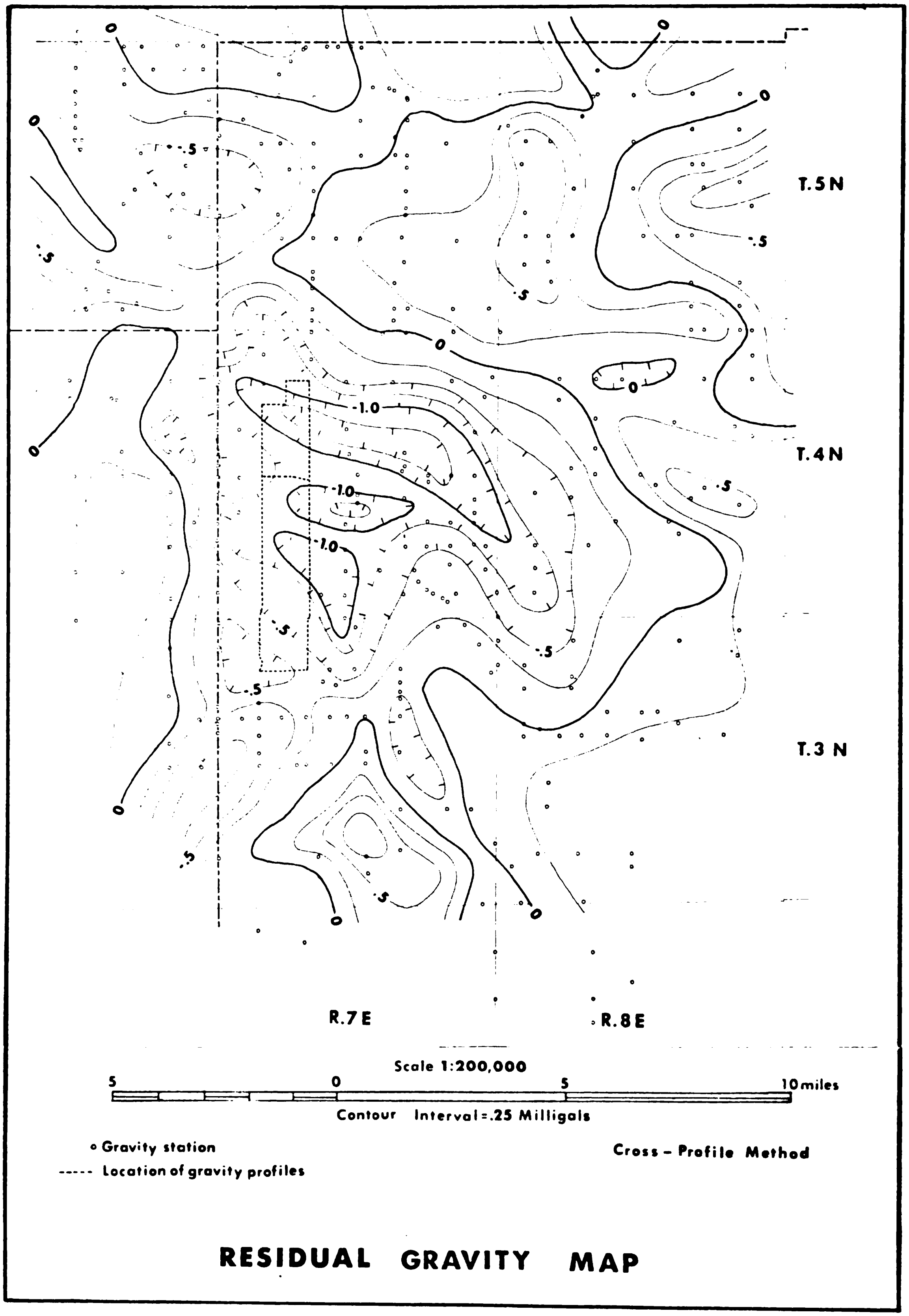
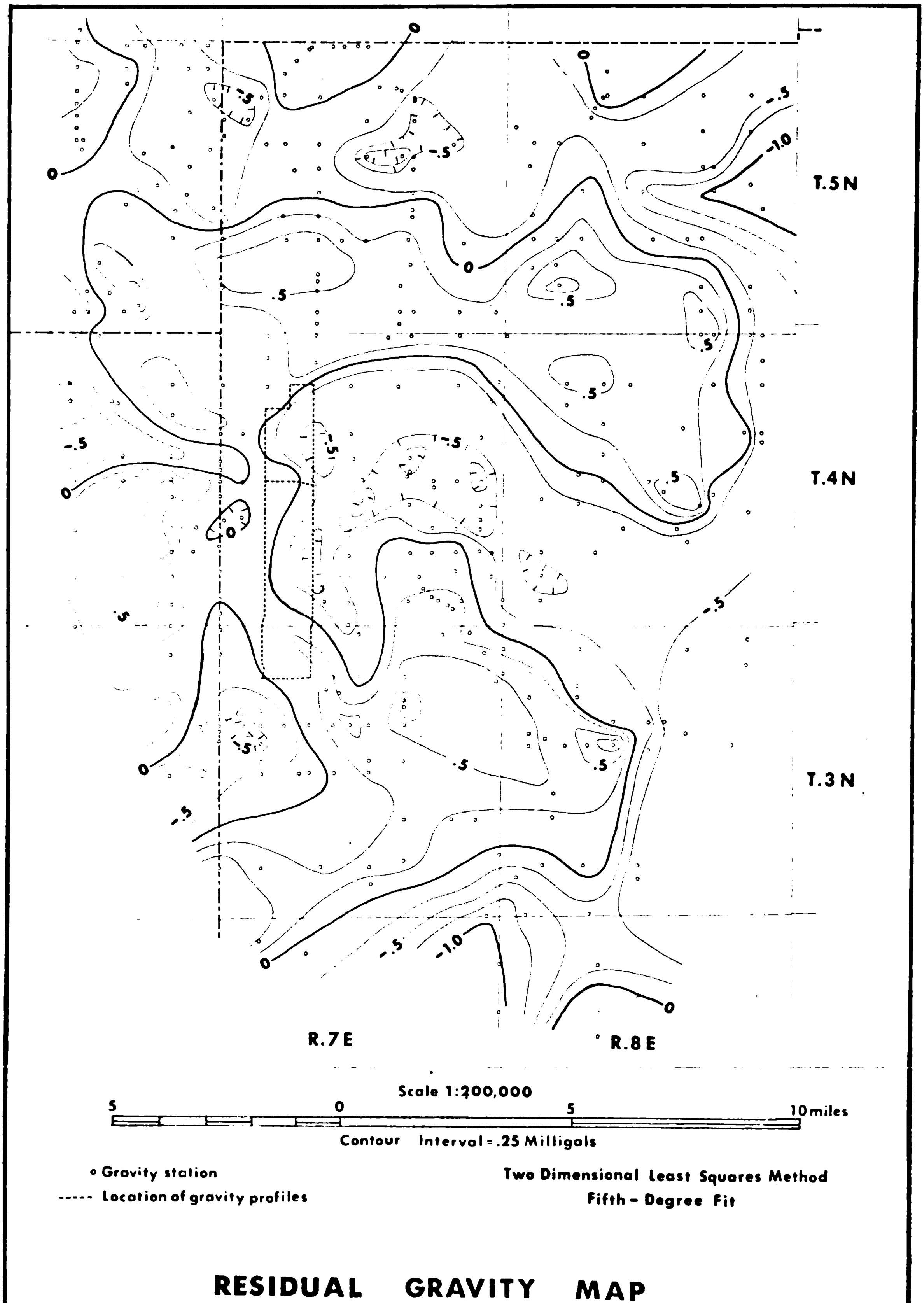


Figure 5. Cross-profile residual gravity map.

Figure 6. Two dimensional least squares residual gravity anomaly map.



RESIDUAL GRAVITY MAP

Figure 6.

subject to errors at the margins, the cross-profile residual map is judged to reflect more accurately the changes in bedrock topography in those areas.

INTERPRETATION OF DATA

The interpretation of the gravity data can be reduced to answering two questions: (1) are the residual gravity anomalies shown on the two gravity maps due to changes in bedrock topography and (2) if they are, what do they indicate the topography to be?

In general, gravity anomalies associated with near-surface features, such as buried bedrock valleys, have horizontal dimensions approximately equal to the area covered by the features. As the depth of a feature increases, the gravity anomaly becomes broader and less sharply defined. Ideally, a residual gravity map over a set of relatively deep and narrow buried valleys would show sharply defined, relatively small (short wavelength) anomalies with linear or sinuous trends. The residual gravity map of the survey area does not show this type of anomaly. Rather, the anomalies are broad and, except for some isolated areas, smooth. While not eliminating the possibility that the gravity anomalies reflect variations in a smooth bedrock topography, it does introduce the possibility that the anomalies may be due to deeper features located in the sedimentary column. Also, it is possible that some of the anomalies may be due to a combination of changing bedrock elevations and structures in the sedimentary rocks.

In an attempt to determine whether the residual gravity maps reflect changes in bedrock topography, two graphs of bedrock elevations from well logs versus the residual gravity anomalies at the well locations were plotted for both the cross-profile and fifth degree least squares maps, Figure 7. A least squares regression line and a correlation coefficient r were calculated for both graphs. The values of the correlation coefficients are 0.406 and 0.550 for the cross-profile and fifth degree graphs respectively. The squared correlation coefficients, or coefficients of determination, r^2, when multiplied by 100 indicate the percentage of the observed variation that can be attributed to a relation between bedrock elevations and residual gravity. These percentages are 16 and 30 for the cross-profile and fifth degree graphs respectively.

Because the coefficients of determination are low, the hypothesis was tested that there is no correlation between bedrock elevations and residual gravity. For the fifth degree graph, the probability that a correlation coefficient of 0.550 is from a population with a true correlation coefficient $\rho = 0$, is less than one percent, indicating that a correlation does exist between the two variables. In the case of the cross-profile map, the probability that no correlation exists lies between ten and five percent, which is judged to be not significant.

The slope of the regression line for the fifth degree

Figure 7. Graphs showing relation between interpolated residual gravity anomalies and bedrock elevation.

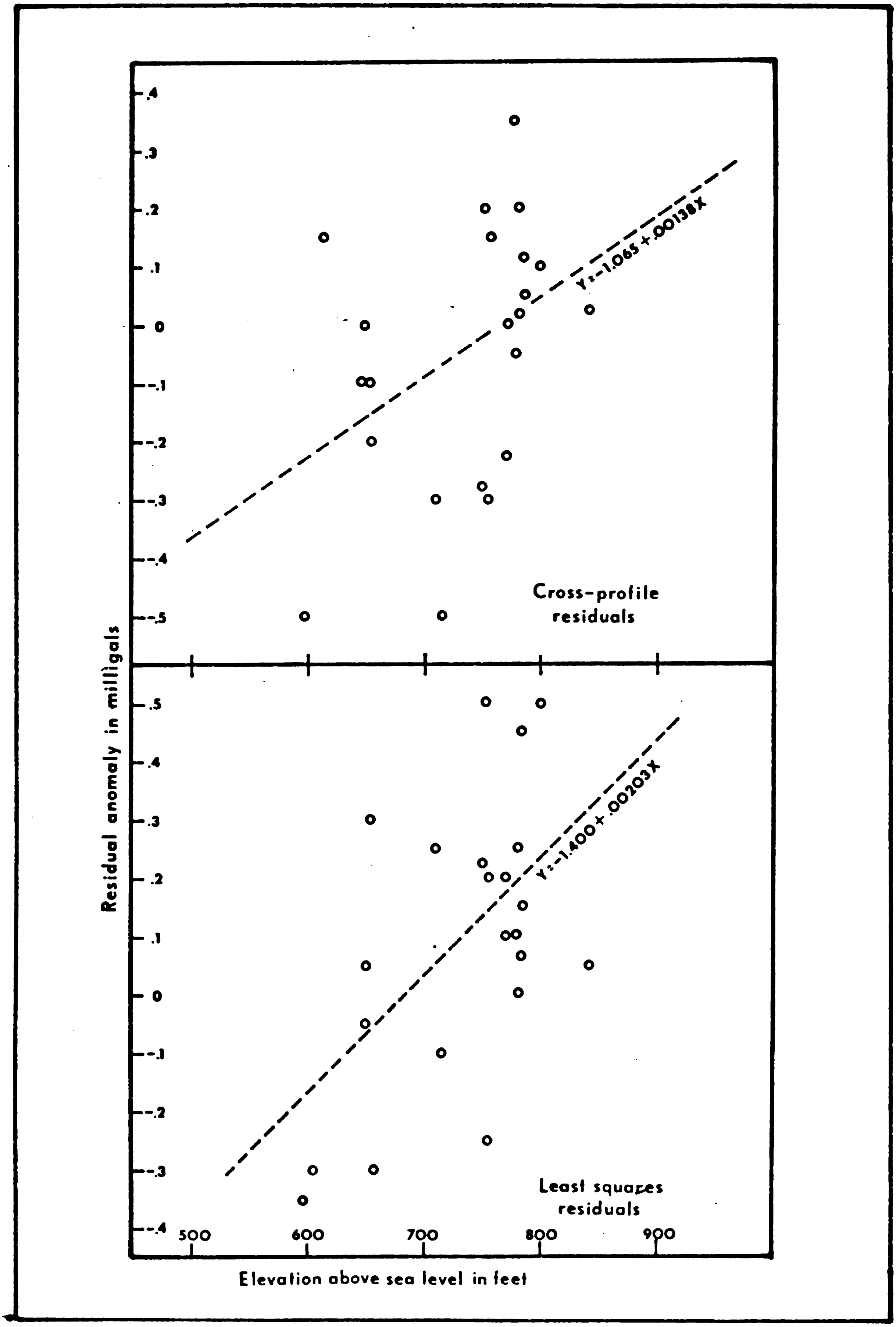

.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
Y=-1.065+.00138X
Cross-profile
residuals
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
Y=-1.400+.00203X
Least squares
residuals
Residual anomaly in milligals
500
600
700
800
900
Elevation above sea level in feet

Figure 7.

graph gives an experimentally determined density contrast between the bedrock and the glacial drift of 0.15 g/cc. A value closer to the 0.3 g/cc used to calculate the expected anomaly magnitude is felt to be more realistic. Because the correlation coefficient for the fifth degree graph is small, the difference in density contrast values can be attributed to a lack of significant correlation between the parameters.

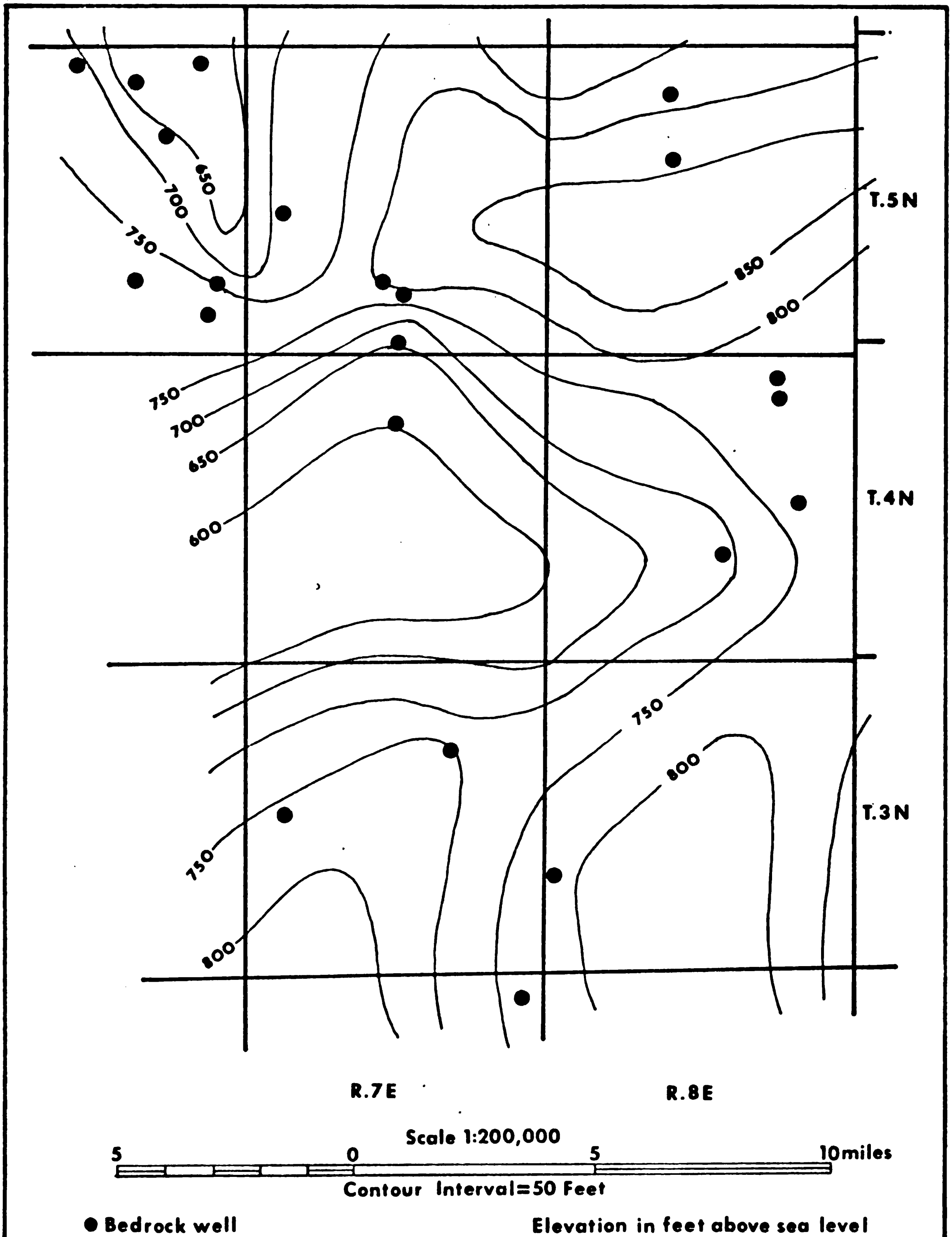
Although the fifth degree graph shows a significant correlation, the coefficient of determination, $r^2 = 0.30$, indicates that 70 percent of the variation is due to factors other than the relation between bedrock topography and residual gravity. Part of this unexplained variation may be due to the fact that at some well locations, the regional defined by the fifth degree polynomial may not coincide with the true regional gradient. Also, residual values at the well locations may be in error because of errors in the interpolation that were necessary to contour the map. Another source of variation may be the location of a well at a point where the bedrock elevation changes drastically. For example, a well located on the edge of a valley could result in a low residual gravity value being associated with a high elevation value. Such sources of error may account for part of the 70 percent unexplained variation in the fifth degree graph.

Based on these calculations, it can be concluded that the fifth degree residual gravity map is related to bedrock elevations but not strongly related. Also, the fifth degree residual gravity map appears to reflect changes in bedrock topography better than the cross-profile map.

Certain prominent anomalies common to both residual gravity maps correlate well with the bedrock elevations on the map of bedrock topography which is a portion of a larger map of Oakland County constructed from well data and information obtained from local well drillers, Figure 8. Both residual gravity maps show a high in the southern portion of T5N, R7E and a low in T4N, R7E that correspond in location to the high and low shown on the bedrock map. Also, a gravity low in the northwest can be correlated with the bedrock low in the same area. This general agreement between the major high and low areas suggests that the residual maps do reflect major changes in bedrock elevation.

Assuming that the residual gravity maps reflect bedrock topography, the bedrock topography should probably be altered in some areas. The residual maps suggest that the bedrock low situated in T4N, R7E may be closed at its western end. The strong gravity low in the southwestern portion of the survey area implies that drainage out of the low may have been through a broad valley to the south or southwest. The gravity map suggests that there may also be a tie between the central low and the bedrock low in the northwest. Either or both of these possibilities would agree with the trend of generally decreasing bedrock surface elevations to the north of Holly toward Saginaw Bay and to the

Figure 8. Map showing topography of the bedrock surface from well log data.



TOPOGRAPHY OF THE BEDROCK SURFACE

Figure 8.

south toward Lake Erie.

THE GRAVITY GRADIENT SURVEY

INTRODUCTION

Measurements of the horizontal gradient of gravity, taken with the torsion balance, formed the basis for the first large scale gravity surveys conducted in the United States. About 1940, the torsion balance was replaced by the more accurate and easily read gravity meter. As a result, gravity surveys based on gravity gradient measurements generally are no longer carried out. This section deals with the investigation of a method of measuring horizontal gravity gradients using multiple closely-spaced gravimeter observations and the application of gradient measurements to ground water exploration.

The motivation for this study arises from the fact that it is unnecessary to determine relative elevation differences between gradient stations. In surveys for buried bedrock valleys, this can result in a considerable saving of time and effort over conventional gravity methods where accurate elevations between gravity stations must be obtained by levelling.

The gradient measured by this method defines the strike and dip of the Bouguer gravity anomaly surface. Consequently, to successfully identify a buried valley, its anomaly would have to be easily recognized on a Bouguer gravity anomaly map.

The accuracy of the method must be sufficient to detect gradient direction and magnitude changes across a buried bedrock valley gravity anomaly. Near surface density variations, of which a buried valley is an example, frequently have sharply defined gravity anomalies. Thus, it is reasonable to expect that the gradient method can be successfully applied to locate and roughly delineate buried valleys that would be evident on a Bouguer anomaly map, possibly for more detailed analysis by conventional gravity methods.

This study will show that horizontal gravity gradients can be determined with relative ease and that the gradients are accurate enough to detect certain buried bedrock valley anomalies.

An easily recognized, sharply defined buried valley anomaly located southeast of Muskegon, Michigan was chosen to evaluate the method. In addition, gradient measurements were made in Oakland County in the area of the Bouguer gravity anomaly survey.

COLLECTION AND REDUCTION OF DATA

The equipment used for the collection of gravity gradient data was a Lacoste-Romberg gravity meter (no. 103), a Zeiss self-levelling level and a stadia rod. Two men were needed to carry out the field work: one to read the gravity meter, the other to operate the level.

Because the gradient can be completely defined by three gravity readings not on a line, each gradient station consists of three gravity stations located at the points of an imaginary triangle. An attempt was made to keep the triangle roughly equilateral with sides at least 300 feet in length. An example of a gradient station is shown in Figure 9.

Prior to taking the gravity and elevation observations at the three gravity stations, the orientation of the three station array was determined by reading an azimuth with the level aligned in a north-south or east-west direction. The procedure followed in this survey was to place the level on the edge of an east-west of north-south section line road, take a sight along the road edge and record the azimuth. The reading of the gravity stations began by carrying the gravity meter to a point selected for the first station, generally along the edge of the road about 150 to 200 feet from the level. The base plate was placed in the ground and elevation, distance and azimuth readings were taken with the rod resting on the base plate. A gravity observation was made and the time was recorded. An additional note was made of the distance between the ground and base plate, which may vary from station to station. The same procedure was repeated at a second station located off the road at a point judged to lie on a perpendicular to the road passing through the level.

At the third station, the gravity was read before level readings were taken. This served to reduce drift by shortening the time between the first and third gravity readings. When using a meter that has unpredictable drift characteristics, the drift can be obtained by taking a

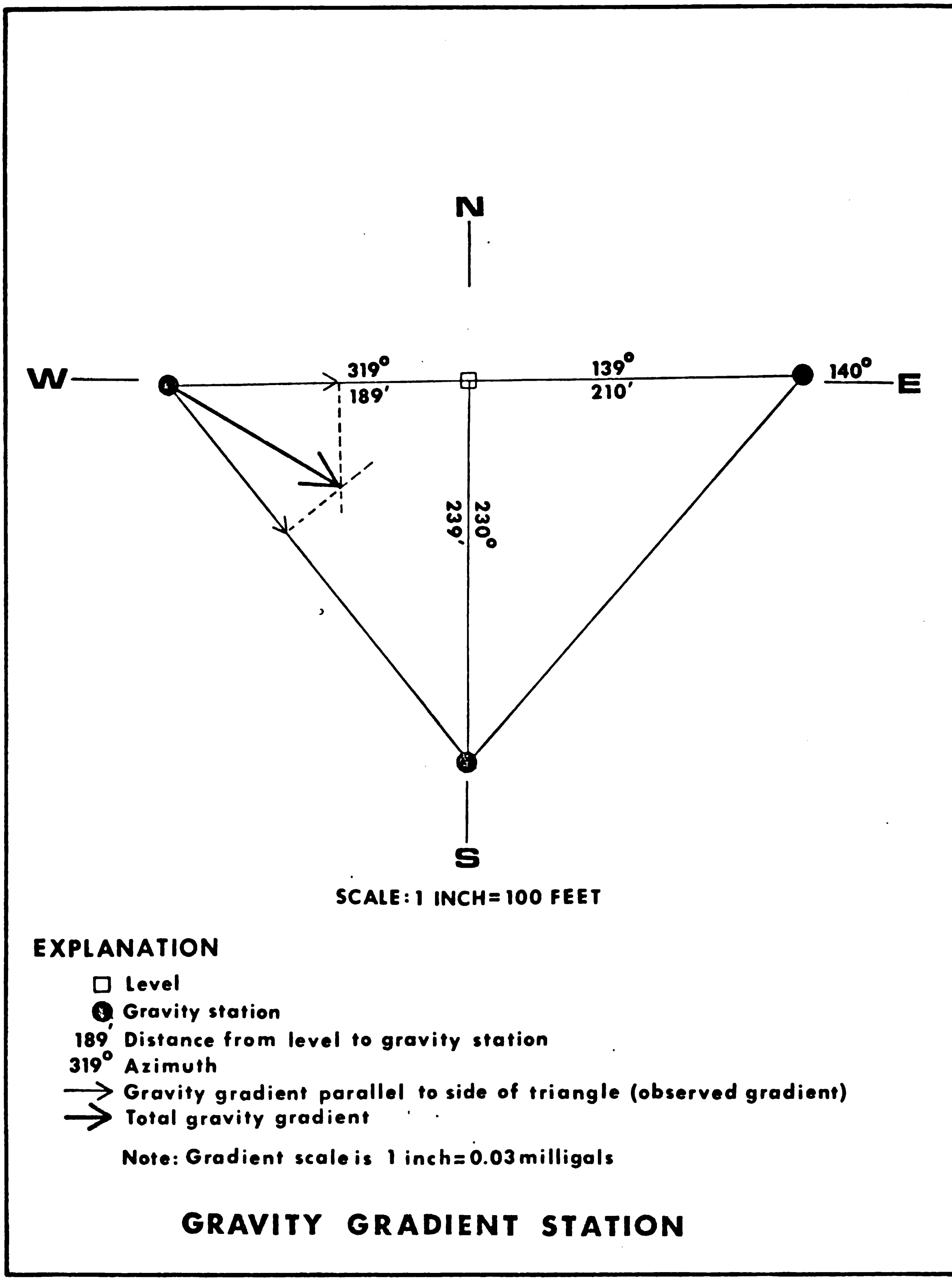


Figure 9. Example of gravity gradient station.

fourth gravity reading at the first station occupied. This was not done in this survey because previous work with the Lacoste-Romberg meter indicated drift was due only to lunar and solar tides. The readings at each gradient station took about 15 to 20 minutes to complete. In some cases, a gravity station used in one gradient station was included in a second gradient station and only five gravity readings were needed to obtain two gradient measurements. The data collected by the level operator and by the gravity meter operator are summarized in Table 1, which shows suggested formats for data collection sheets and some sample data.

For the reduction of data, each gradient station was treated as a small gravity survey. The procedures followed were the same in principle as those used in the Bouguer gravity anomaly survey. The techniques used to obtain the reductions are described below.

The first step was to draw to scale on a sheet of paper the array of gravity stations using the distances and directions (azimuths) recorded by the level operator. The array shown in Figure 9 was constructed from data in Table 1. One of the three gravity stations was designated a base station. In the example, this was station "west" (W). The other two stations were corrected for drift relative to the base, W, by using tidal curves. Latitude corrections were made by measuring the north-south distances between the base and the other two stations and multiplying this distance by the constant factor K explained previously. The

Table 1. Data collection formats for gravity gradient survey.

DATA COLLECTED BY LEVEL OPERATOR

GRADIENT STATION: 109

N(S) OR E(W) AZIMUTH: 320° W

GRAVITY STATION	ELEVATION	DISTANCE		AZIMUTH
W	4.55	5.50	3.61	319
S	5.15	6.35	3.96	230
E	4.57	5.62	3.52	139

DATA COLLECTED BY GRAVITY METER OPERATOR

GRADIENT STATION: 109

GRAVITY STATION	METER READING	TIME	DISTANCE BASE PLATE TO GROUND	REMARKS
W	3794 870 870	13:14	2"	
S	3794 760 760	13.17	0	
E	3794 760 760	13:26	1"	

free-air and mass corrections were made relative to a datum chosen arbitrarily at one foot below the lowest gravity station. The elevation used for the free-air and mass corrections was the distance from the datum to the base plate, except where the distance from base plate to ground surface varied between gravity stations. In this case, the thickness of material used for the mass correction was the distance from datum to ground surface. A density of 2.0 g/cc was used for the mass correction. No terrain corrections were made.

The sequence of calculations is shown in Table 2 using the sample data from Table 1. The last column shows two observed gradient values directed along two of the three sides of the triangle. These are scaled off as vectors along the sides of the triangle and a perpendicular is constructed from the end of each vector. The intersection of the perpendiculars defines the magnitude and direction of the calculated, or total gradient, shown as the heavy arrow in Figure 9.

ACCURACY OF DATA REDUCTION

Errors in the observation and reduction of data for the gradient method occur at individual gravity stations. The Lacoste-Romberg gravity meter was used for all gravity measurements. At each station, gravity was read until two readings agreed to the nearest one-half scale division, which is roughly equal to 0.005 mgals. Drift corrections

Table 2. Data reduction format for gravity gradient survey.

GRADIENT STATION NO: 109 DATUM: 6.15' BASE STATION: (W)

GRAVITY STATION	ELEVATION BASE PLATE ABOVE DATUM (FEET)	FREE AIR CORRECTION (MGALS) A	ELEVATION LAND SURFACE ABOVE DATUM (FEET)	MASS CORRECTION (MGALS) B	FREE AIR + MASS CORRECTION (MGALS) (A + B)	FREE AIR + MASS CORRECTION RELATIVE TO BASE (MGALS) C	OBSERVED GRAVITY RELATIVE TO BASE -DRIFT CORRECTED (MGALS) D	DISTANCE NORTH (+) OR SOUTH (—) OF BASE (FEET)
W	+1.60	-.150	+1.43	+.036	-.114	—	—	-
S	+1.00	-.094	+1.00	+.026	-.068	+.046	-.118	-238
E	+1.58	-.149	+1.50	+.038	-.111	+.003	-.124	0

LATITUDE CORRECTION (MGALS) E	(C + E) F	GRADIENT BETWEEN BASE AND STATION (MGALS) (B − F)	DISTANCE BASE TO STATION (FEET)	GRADIENT BETWEEN BASE AND STATION (MGALS/100 FT)	MAGNITUDE AND DIRECTION OF GRAVITY GRADIENT (MEASURED FROM THE DIAGRAM)
—	—	—	—	—	
-.059	-.013	-.105	303	-.035	.038 mgals/100'
0	+.003	-.127	399	-.032	33° S of E

were taken from tidal curves. The combined error from both sources is estimated to be no greater than ± 0.01 mgals.

Gravity station elevations were measured with an accuracy of ± 0.01 feet. The resulting error in the combined free-air and mass corrections is less than ± 0.001 mgals.

Distance north or south of the base station was determined graphically to the nearest 10 feet, giving a latitude error of + 0.002 mgals.

The elevation difference between gravity stations at each gradient station did not exceed five feet. Using this value and assuming an error in the assumed density value of ± 0.2 g/cc, the error in the mass reduction is ± 0.013 mgals.

The terrain error will be considered in two parts: the error due to local terrain variations and the error resulting from more distant topographic features. All gravity gradient stations were located where local terrain variations were minimal. The greatest terrain variations encountered locally were ditches along roads where gravity readings were taken. Graphs of the terrain effect from Hubbert (1948b) were used to estimate the error. The model ditch, located six feet to one side of the gravity station, was three feet deep and had side slopes of 45 degrees. The error from this source was ± 0.005 mgals.

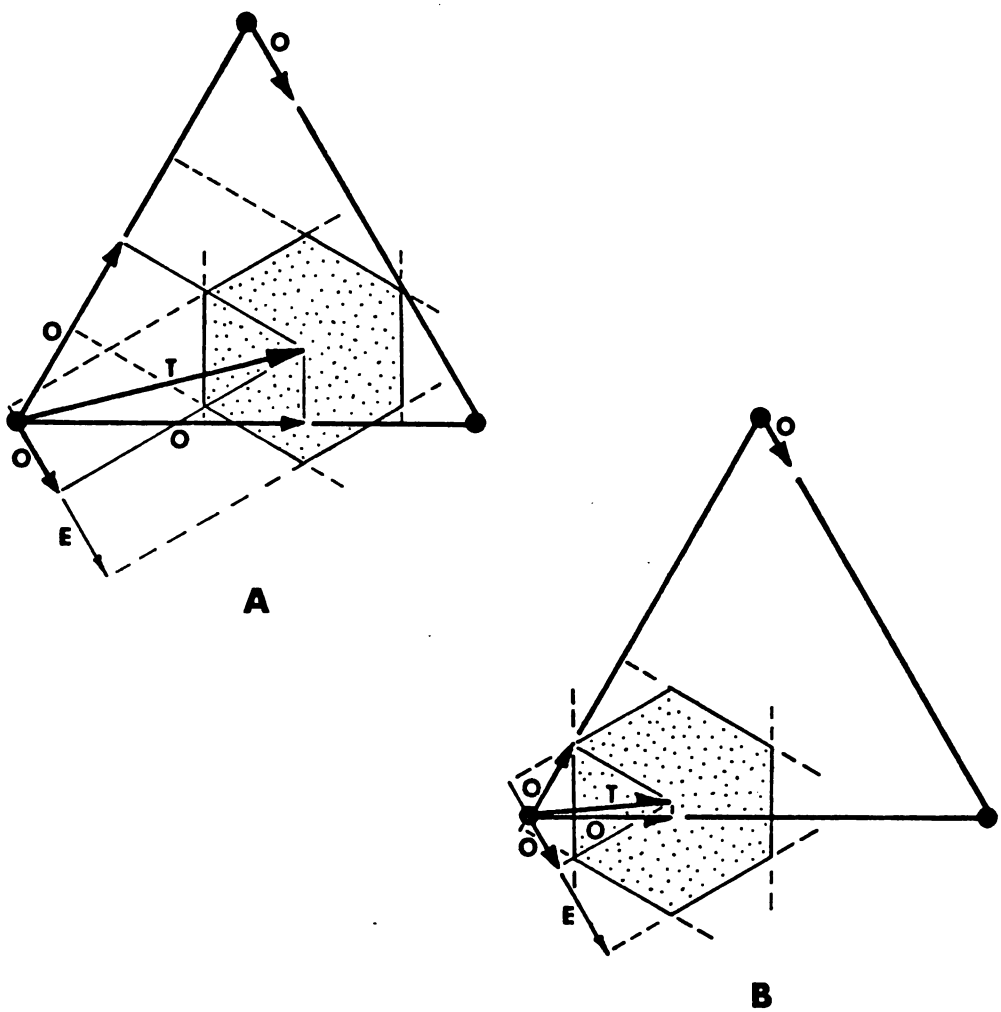
Terrain error associated with more distant features was not calculated because in both areas where gradients were measured, topographic irregularities greater than 50 feet did not occur within 500 to 1000 feet of most gradient stations. At each gradient station, the relatively short distances between the gravity stations has the interesting consequence that distant topographic features tend to affect equally each gravity station. For this reason, the terrain effect of distant features on separate gravity observations was disregarded.

The sum of all sources of error, assuming all agree in sign, was + 0.031 mgals and - 0.026 mgals. The difference in values is due to the terrain correction error, which is always positive.

Having determined the error at any gravity station, it is necessary to evaluate its effect on the total gradient. As shown in Figure 9 the total gradient was determined from gradients along two sides of the triangular array. Considering only one side of the array, a gravity gradient can be said to exist parallel to the side only if the observed gradient exceeds the error gradient along the side. The error gradient is the sum of errors at the two gravity stations that make up the side. For the hypothetical array, this error was ± 0.057 mgals/300 feet or 19 microgals/100 feet. Note that the error gradient depends in part on the distance between the two gravity stations.

The relation between the error in the three observed gradients and the total gradient error was obtained by the following graphical method. The three observed gradient vectors were placed at a common origin. Then, for each observed vector, two additional vectors were constructed:

Figure 10. Diagram showing graphical method of determining total gradient errors.



● Gravity station
O Observed gradient vector
T Total gradient vector
Error region. Delineates total gradient vector magnitude and direction errors.
E Error gradient vector. A constant added to and subtracted from observed gradient to construct error region.

Figure 10.

the observed plus the error gradient and the observed minus the error gradient. Lines perpendicular to the ends of these six new vectors were drawn and the area enclosed by the intersection of the six perpendiculars defined the total gradient error region.

Figure 10 illustrates two examples of the error region. By comparing part A and B of this figure it can be seen that as the difference between the total gradient and the error gradient increases, both magnitude and direction errors decrease. It is interesting to note that at B only one observed gradient exceeds the error gradient yet it is still possible to place limits on the direction and magnitude errors of the total gradient. If all three observed gradients are less than the error gradient, no limit can be placed on the direction error, which implies that the total gradient may be entirely a result of errors in the observation and reduction of data at the gravity stations.

In this study all errors were determined graphically, although it is possible to develop an analytical expression to calculate errors in total gradient direction and magnitude. Where a large number of gradient stations exists in a relatively small area, spurious readings usually can be eliminated by inspection and the determination of error regions becomes unnecessary. However, where two or more of a few closely spaced total gradients appear to differ significantly, the construction of error regions at the stations in question could give immediately a quantitative estimate of the significance of observed differences.

DISCUSSION OF OBSERVED GRADIENTS

The first step in the measurement of gravity gradients was to choose a suitable Bouguer gravity anomaly for a test of the method. The criteria for choosing an anomaly were (1) that the dimensions of the anomaly should be roughly those that would be caused by a buried bedrock valley, and (2) that the anomaly should be sharply defined (i.e., high amplitude/wavelength ratio). These conditions were satisfied by a gravity anomaly located a few miles southeast of Muskegon, Michigan. In addition, the terrain in this area was very flat which eliminated error due to terrain irregularities. The Bouguer anomaly map of the area is based on a grid of gravity stations located at one-quarter mile intervals along section line roads. Gradient measurements were made along two east-west lines crossing the anomaly, which trends roughly north-south. The anomaly and total gradients are shown in Figure 11.

In Oakland County, the original intention had been to measure gradients across buried valley anomalies, but the Bouguer anomaly survey revealed no distinct anomalies of this type. Instead, thirteen total gradients were measured where the Bouguer anomaly has a relatively constant rate of change to gather more data on the agreement between total gradients and the Bouguer anomaly. Certain of these total gradients also were of interest due to adjacent topographic

Figure 11. Map showing gravity gradients near Muskegon, Michigan.

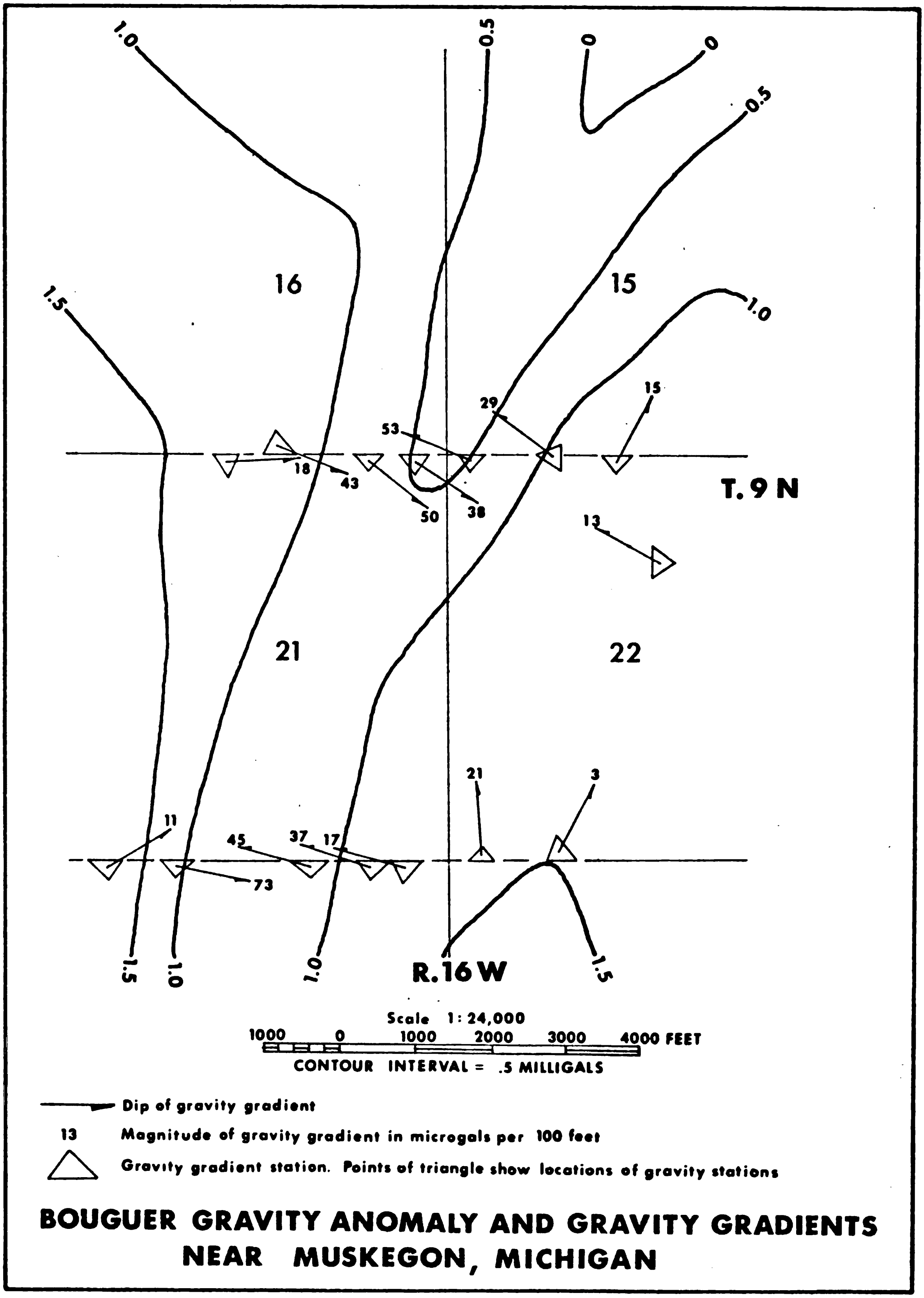

1.0
0.5
0
0
0.5
16
15
1.5
1.0
29
15
53
18
43
50
38
T. 9 N
13
21
22
21
3
11
45
37
17
73
1.5
1.0
1.0
R. 16 W
1.5
Scale 1 : 24,000
1000 0 1000 2000 3000 4000 FEET
CONTOUR INTERVAL = .5 MILLIGALS
Dip of gravity gradient
13 Magnitude of gravity gradient in microgals per 100 feet
Gravity gradient station. Points of triangle show locations of gravity stations
BOUGUER GRAVITY ANOMALY AND GRAVITY GRADIENTS
NEAR MUSKEGON, MICHIGAN

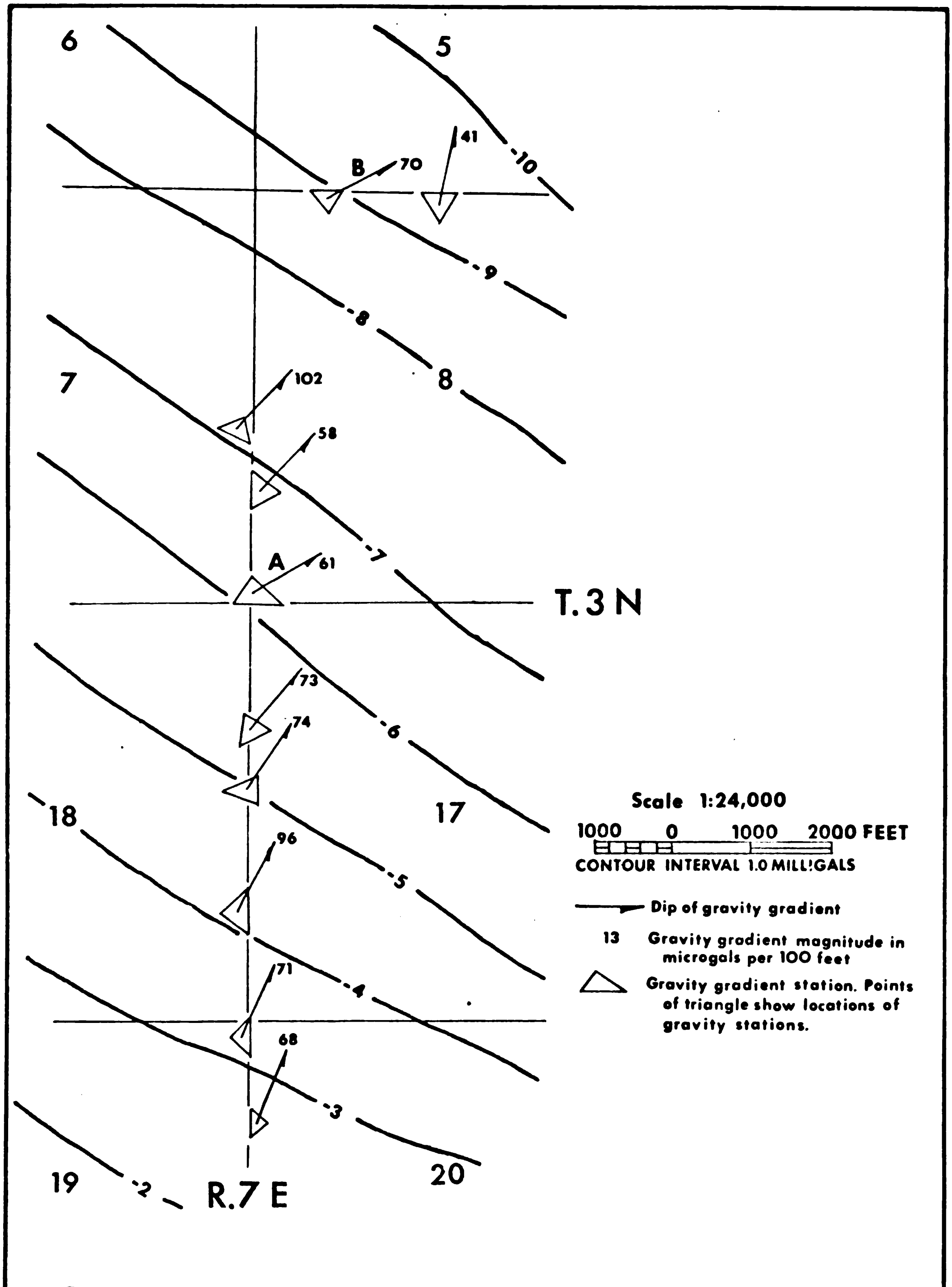
Figure 11.

features that exceeded variations encountered at other stations in the county and stations located near Muskegon. The Bouguer anomaly and gradients measured in Oakland County are shown in Figures 12 and 13.

The total gradients in western Michigan show excellent agreement with the gradients obtained from the Bouguer anomaly. Not only is the reversal of gradient across the anomaly detected, but the gradient directions also agree closely with the direction of dip of the Bouguer surface. This is also true of the total gradients measured in Oakland County.

In Figure 12, ten total gradients were measured over an area of the Oakland County gravity survey where the rate of change of the Bouguer gradient is relatively constant. Inspection of the map shows a close agreement between the total gradients and the Bouguer gradient. To obtain a rough quantitative measure of the difference between the observed total gradients and the Bouguer anomaly gradient, the standard deviation was calculated of the differences between the observed total gradients and the mean gradients measured directly from the Bouguer anomaly map. The gradients from the Bouguer anomaly map were measured using a scale distance of one-half mile parallel to the dip of the Bouguer surface at each gradient station location. The standard deviation of the differences is 23 microgals/100 feet. It should be noted that this difference is based on ten gradient stations and does not take into account

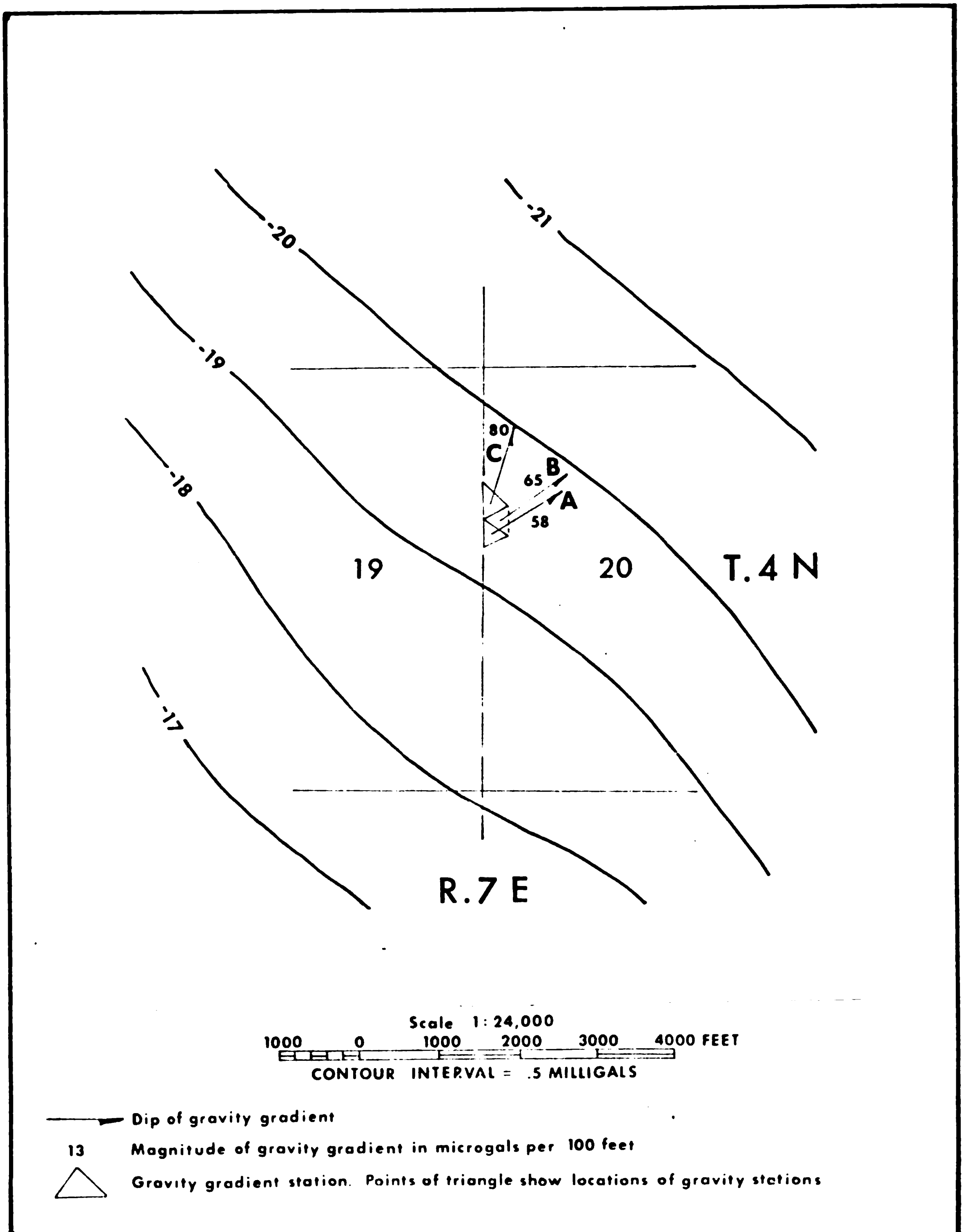
Figure 12. Map showing gravity gradients in Oakland County, Michigan.



BOUGUER GRAVITY ANOMALY AND GRAVITY GRADIENTS
OAKLAND COUNTY, MICHIGAN

Figure 12.

Figure 13. Map showing gravity gradients in Oakland County, Michigan.



BOUGUER GRAVITY ANOMALY AND GRAVITY GRADIENTS
OAKLAND COUNTY, MICHIGAN

Figure 13.

differences between the direction of the total gradient and the dip direction of the Bouguer anomaly surface.

The terrain effect on total gradients located close to apparently significant terrain variations was evaluated at two gradient stations in Oakland County. At the station designated A in Figure 12, the east gravity station is about 50 feet from a 20 foot depression. This would result in a too low Bouguer value for that station causing the gradient vector to be deflected in an easterly direction. This expected deflection is observed at the station.

To determine whether the observed deflection of this gradient was due to terrain variations, the terrain correction was calculated for each gravity station using Hammer's method (Hammer, 1939). The maps used have a scale of 1:24,000 and a contour interval of 10 feet. Terrain error was calculated for the B through the E rings. A terrain corrected total gradient was constructed and compared with the uncorrected total gradient. The direction and magnitude differences were only three degrees and three microgals/100 feet respectively, indicating the observed deflection of the total gradient to the east is due to other factors. Construction of the error region for the uncorrected total gradient showed that the direction and magnitude errors are roughly $\pm$ 20 degrees and $\pm$ 20 microgals/100 feet. Thus the observed deflection is not caused by the terrain variations, but by errors in the observation and reduction of data.

At the station designated B, a 100 foot topographic rise occurs approximately 300 feet west of the station. The expected result, assuming the total gradient has been affected by terrain variations, would be a total gradient deflection to the west. No westerly deflection is observed. Based on these considerations, the conclusion is that terrain error at any gradient station is insignificant compared to observation and reduction errors.

Figure 13 shows three gradients determined from two gradient stations. Because the topography is very flat in the area and the change in the Bouguer gradient does not appear to vary greatly, the observed difference between the northernmost gradient and the other gradients is probably due to a spurious reading at one of the gravity stations. However, there is a possibility that the difference is due to local density changes in the glacial drift that do not appear on the Bouguer map. It is of interest to note that if the density change is real, it must occur at the northernmost gravity station. That is, total gradient C only differs from total gradient B by the one north gravity station.

Total gradients A and B in Figure 13 show that a square array of four gravity stations allows the computation of two semi-independent total gradients. The term semi-independent is used because the two total gradients differ by only one gravity station. The agreement between two semi-independent total gradients can be evaluated by constructing a compound error region consisting of the intersection of the two error regions associated with the two total gradients. This compound error region will be smaller than either of the two separate error regions, increasing the accuracy of the combined total gradients. Four gravity station arrays could be used where greater survey accuracy is required.

DISCUSSION OF THE GRADIENT METHOD

The optimum conditions for the application of the gradient method exist when the magnitude of the buried valley anomaly is sufficiently large to cause a reversal in the Bouguer gravity gradient direction. In this case, the only factor limiting the application of the method is the magnitude of the gradient change. Ideally, total gradients over the anomaly should have error regions that do not overlap the error regions of the surrounding regional gradients.

Problems arise when the magnitude of the buried valley anomaly is too small to cause a reversal of gradient. If the anomaly strikes parallel to or at a low angle to the strike of the regional Bouguer anomaly gradient, total gradients must show significant magnitude changes to identify the anomaly. Where the anomaly strikes at a higher angle to the strike of the regional gradient, it may be possible to use total gradient direction changes as well as magnitude changes to identify the anomaly.

Prior to conducting a gradient survey, the ability of the gradient method to detect expected gradient and magnitude changes should be evaluated. If the buried valley is to be identified primarily on the basis of direction changes in the total gradient, the magnitude of the regional gradient should be taken into consideration. This can be demonstrated by referring to Figure 10, which shows that a significant direction change at A could be much less than a significant change at B. This is a result of the different angles subtended by the error regions at A and B.

When evaluating the applicability of the method, it is necessary to consider also the characteristic linear or sinuous trend of buried bedrock valley anomalies. It may happen that the identification of a buried valley anomaly will be based on a combination of total gradient reversals, magnitude changes and direction changes.

In conclusion, three factors should be considered prior to conducting a gravity gradient survey: (1) the magnitude and direction changes (including reversals of gradient) associated with the anomaly, (2) the magnitude of the regional gradient and (3) the expected trend and shape of the buried valley anomaly.

CONCLUSION

The measurement of the horizontal gravity gradient by the use of a triangular array of gravity stations appears to be a feasible gravity exploration technique. The successful application of the method as a means of delineating buried bedrock valleys for ground water exploration purposes depends on both the configuration of the buried valley anomaly and the magnitude of the gradient changes associated with the anomaly.

Where well log and geologic data indicate a buried valley may exist, a profile of gradient stations across the valley could serve as a relatively simple aid in confirming the existence of the valley. It is also possible that a gradient survey could be used to roughly delineate a major buried valley prior to using more accurate conventional techniques for a detailed mapping of the valley. For example, by outlining the trend and configuration of the buried valley in western Michigan with gradients, considerable time and effort could be saved if a detailed conventional survey were subsequently conducted.

It is also evident that gradients show promise as a method to be used for large scale gravity reconnaissance surveys, particularly where it is difficult or impossible to obtain the elevation control necessary to apply conventional methods. Because gradients provide the dip of the Bouguer anomaly gradient at the observation point, they could also be used to aid in the contouring of a Bouguer anomaly map where gravity stations are widely spaced.

Further study of the gradient method might cover the following:

--Test the ability of the method to delineate known buried valley anomalies that do not show a reversal of gradient.

--Development of an analytical expression for total gradient error computation.

--Investigation of the use of four gravity station arrays as a means of increasing accuracy.

--Application of statistical methods to a set of gradient measurements.

SUMMARY

The Bouguer anomaly survey was moderately successful in defining the bedrock topography in northwestern Oakland County. Residual gravity maps obtained by the cross-profile and least squares methods were generally in agreement with the map of bedrock topography constructed from well logs. Some changes in the bedrock map were suggested by the residual map. Over the majority of the survey area, the residual gravity map judged to best reflect the bedrock topography was the fifth degree least squares approximation. It showed a better statistical correlation between residual anomalies and bedrock elevations than the cross-profile residual map.

A large bedrock low is believed to occur in the central portion of the survey area. Two other smaller lows, or valleys, probably tie in with this low. These are located in the northwest and southeast and possibly reflect pre-glacial drainage out of the central low to the north and south.

The gravity gradient method proved successful as a tool in determining the Bouguer gravity gradient. The survey techniques were simple and individual gradient measurements were made fairly rapidly (15 to 20 minutes per gradient measurement). The anomaly selected for a test of the method, an assumed buried valley in western Michigan, was adequately defined. Gradients measured in Oakland County further showed the ability of the method to determine the Bouguer gravity gradient. As applied to ground water exploration, although the method does not have the accuracy of conventional gravity techniques applied where accurate elevations are carried by levelling, it does appear to hold promise as a quick and relatively simple method of defining distinct buried bedrock valley anomalies. The method also shows promise as a tool to be used for large scale gravity reconnaissance surveys.

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