ROUND LAKE GRAVITY ANOMALY, DELTA COUNTY, MICHIGAN

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
TERRY DENNIS ANDERSON
1974

ABSTRACT

ROUND LAKE GRAVITY ANOMALY,
DELTA COUNTY, MICHIGAN

By

Terry Dennis Anderson

The Round Lake Gravity and Magnetic Anomaly was investigated in order to approximate such parameters as total mass, density, volume, depth, shape, magnetic susceptibility, and magnetite content.

The gravimetric survey consisted of occupying 403 gravity stations and applying subsequent gravity reductions and corrections to the data obtained. The interpretation of the anomaly by simple models was begun by curve fitting various size spheres with an assumed density contrast of 0.3 gm/cm^3. This resulted in a fixing of the size (384.5 cubic kilofeet) and mass excess (3.223×10^{15} gm) of the model. The average observed gravity profile was upward continued on the vertical axis for comparison with vertical gravity values over the top of cylindrical models. Using the constraints of constant volume and constant mass excess, curves were calculated for a family of vertical cylinders at several depths to determine which of these fit the observed upward continued gravity profile best.

On the basis of the above study, a maximum depth to the top of the anomalous body, approximated by a vertical cylinder, was calculated to be 750 feet. Assuming that the magnetic anomaly is produced by a spherical body whose volume is the same as for the vertical cylinder, and neglecting remanent magnetization, a susceptibility of $26{,}450 \times 10^{-6}$ emu/cm^3 was calculated. From this value the volume percent magnetite is estimated to range from 3.3 to 8.8.

ROUND LAKE GRAVITY ANOMALY,

DELTA COUNTY, MICHIGAN

By

Terry Dennis Anderson

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1974

G87015

ACKNOWLEDGMENTS

I would like to thank Dr. Hugh Bennet for criticisms and assistance in the writing of this thesis. I would also like to thank Bob Reed of the Michigan Geological Survey for his suggestion of the Round Lake Anomaly as a basis for a geophysical study, and for the magnetic maps he provided.

Lastly I would like to thank my father, Ralph Anderson, for his invaluable assistance during the gravity survey.

TABLE OF CONTENTS

LIST OF FIGURES

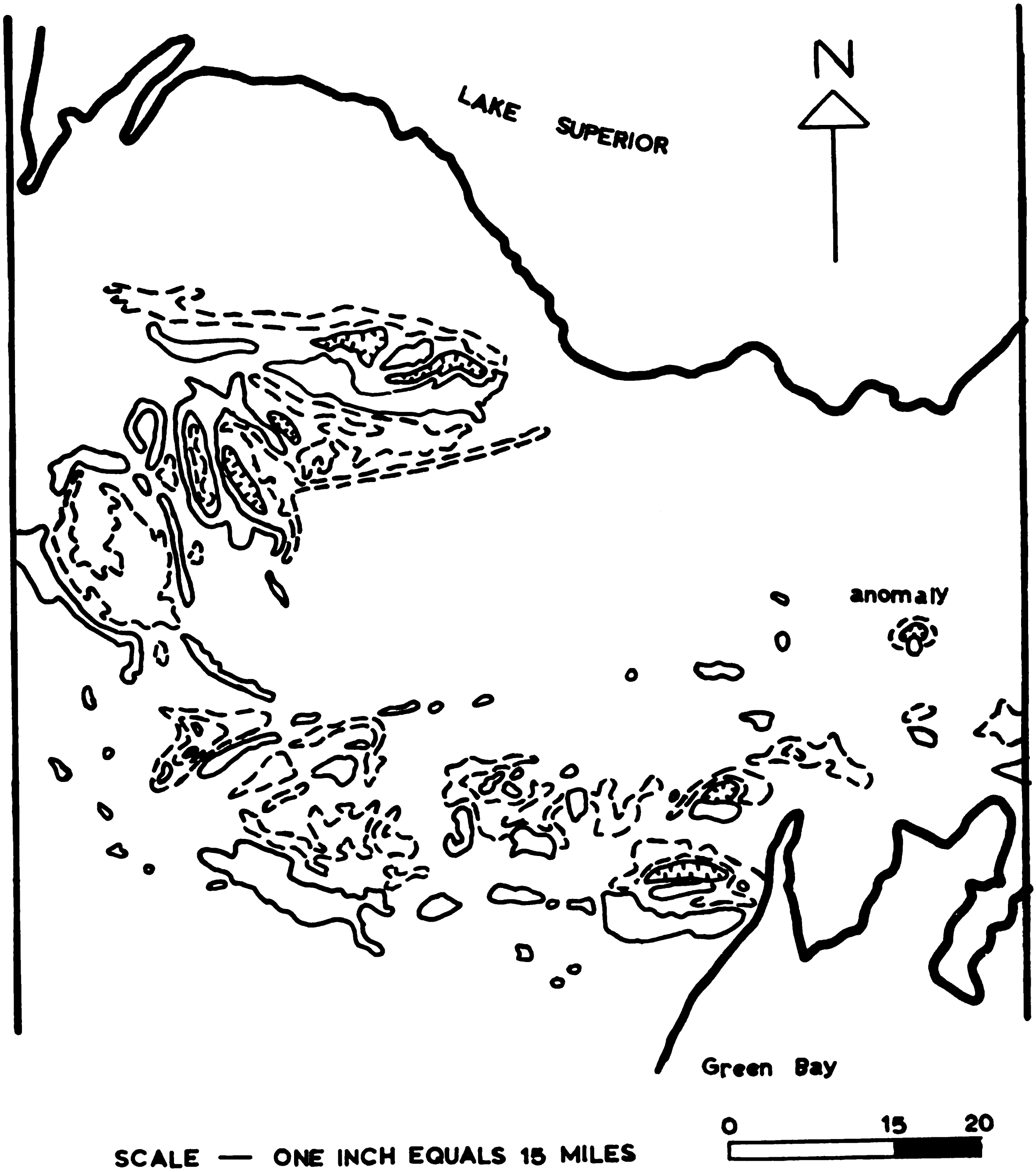
CHAPTER I

INTRODUCTION

The Round Lake Gravity and Magnetic Anomaly is located at eighty-six degrees forty-three minutes west longitude and forty-six degrees seven minutes north latitude, in the northern part of Delta County of the Upper Peninsula of Michigan. It is spatially located approximately twenty-five miles southwest of Munising and forty miles northeast of Escanaba. Figures 1 and 2 show the total field magnetic map of the anomaly and its location. It is geomorphologically located in an area of glacial moraines surrounded in part by low land swamps, which drain into the Whitefish River in the west and the Sturgeon River to the east.

Most of Delta County, north of Little and Big Bay De Noc, has been set aside as National Forest Land as part of the Hiawatha National Forest. Land use of these areas is controlled by the government. In the Park area, roads and campgrounds are maintained by the Forest Service for recreational use.

Although the area of the Round Lake anomaly is entirely within the boundaries of the Hiawatha National Forest, much of this area is privately owned. Some tracts

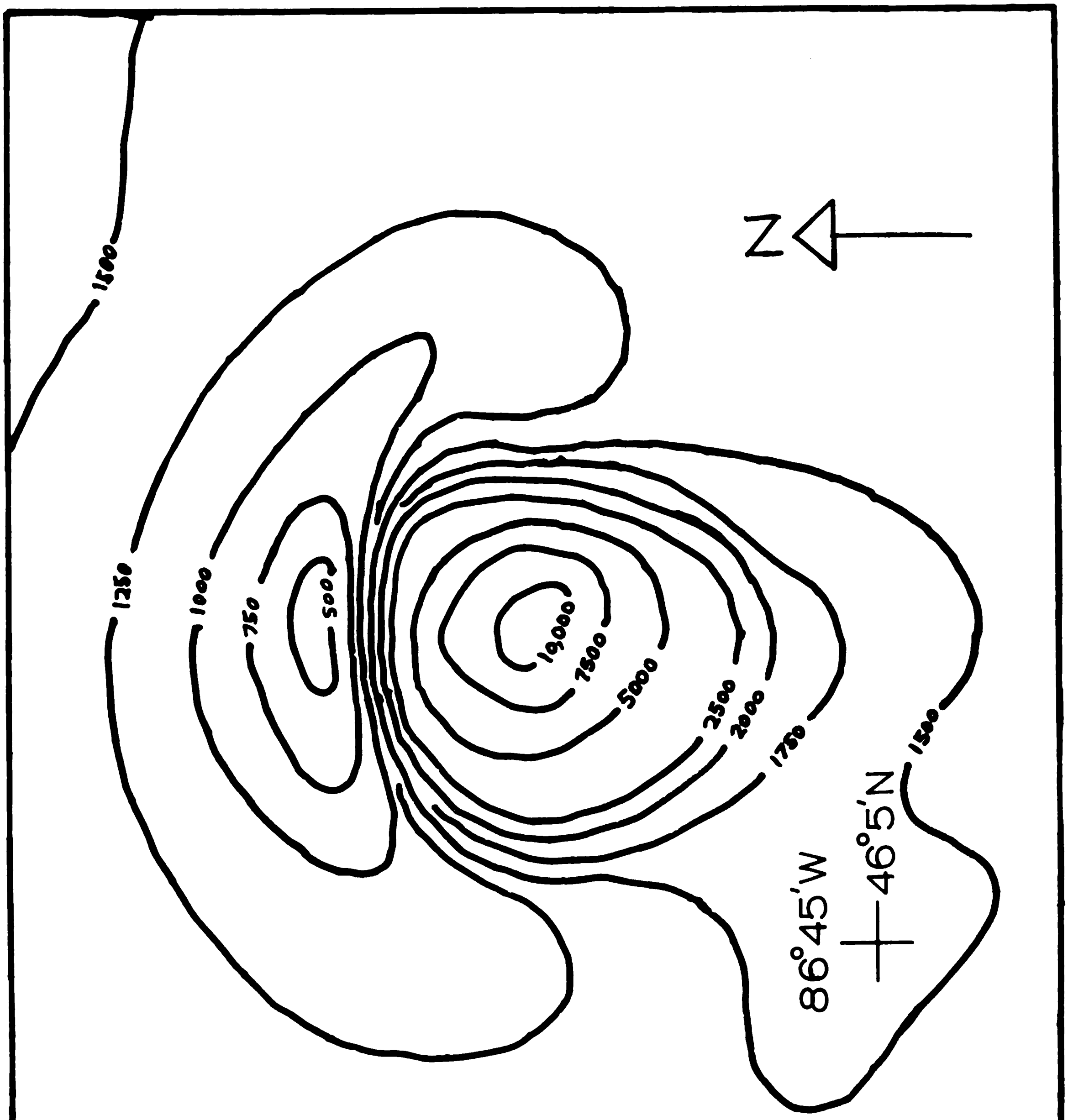


SCALE — ONE INCH EQUALS 15 MILES

GAMMA DATUM — ARBITRARILY SET BY U.S.G.S.

CONTOUR INTERVALS —
—— above 11,800 Gammas
– – – 10,400 – 10,600 Gammas
below 9,800 Gammas

Figure 1. TOTAL FIELD MAGNETIC MAP (U.S.G.S. MAP, 1969)



0 1 1½

SCALE — ONE INCH EQUALS ONE MILE

CONTOUR INTERVAL — AS SHOWN (GAMMAS)

Figure 2. ROUND LAKE TOTAL FIELD MAGNETIC ANOMALY
(U.S.G.S. MAP, 1969)

of land were retained privately for the logging of groundwood, which are owned by the Mead Corporation, while others were retained for use as sites for cottages and hunting camps.

The magnetic anomaly first drew serious consideration from geologists and geophysicists after it was detected by an aeromagnetic survey, although hunters in the area and land owners trying to establish property lines noticed abnormal deflections of magnetic compasses. Aeromagnetic data was collected from 1948 to 1967 and was made available in contoured magnetic maps by the United States Geological Survey in 1971. The magnetometer was flown at an elevation of five hundred feet and at one-half mile flight line spacings in North-South directions.

The Round Lake magnetic anomaly is unique among others occurring in the western Upper Peninsula for several reasons. See Figures 1 and 2. The anomaly shows strong circularity as opposed to the irregular shapes and general linearity, trending East-West, of other anomalies. The areal size of the anomaly is relatively small in relation to other anomalies of comparable magnitude. The magnitude, which is the highest of any in the immediate area, has a maximum field value of 11,204 gammas and a minimum field value of 471 gammas, relative to an arbitrary contour datum, established by the United States Geological Society. These reasons, plus the fact that the Round Lake anomaly is isolated from the effects of other anomalies, indicate that this anomaly would make a good subject for a gravity survey and interpretation.

CHAPTER II

GEOMORPHOLOGY AND VEGETATION OF THE AREA

Terrain

The area about the Round Lake anomaly is governed geomorphologically by post-glacial influence, primarily of the multi-lobate Wisconsin age ice sheet (S. G. Bergquist, 1936). The lobate forms were present during the advance of the ice sheet and retained their forms during the retreat of the ice sheet. The Green Bay lobe was located in an area west of the Au-Train Whitefish River depression, but after retreat of the glacier to the Lake Superior basin a new lobe advanced over the area, the Lake Superior lobe. The moraines left by the glacier constitute the terrain of the area. The moraines are irregular in shape and cover approximately fifty percent of the land area in the vicinity of the anomaly. The elevation of the moraines varies between 780 feet and 860 feet. The maximum relief is 80 feet.

After the final retreat of the glacier, the area was inundated and altered by glacial lake waters, and drainage later was established between the Superior and Michigan basins via the Au Train-Whitefish depression. Evidence for glacial lake inundation and drainage alteration are: presence of cross bedding and sorting seen in road cuts, patches of relatively high clay sands on moraines suggesting lacustrine deposition, and smoothing of irregular sides of moraines by lake and river action.

Vegetation

Approximately fifty percent of the immediate area of the anomaly is occupied by swamps. Vegetation in the swamps usually occurs as a combination of cedar, spruce and alders in a dense, wet environment or as a small spruce tree and moss combination of relatively open area.

Vegetation of the higher morainal ground represents almost entirely a second growth of trees, dating back to the major logging periods of the 1800s and the 1930s. In some areas popular and pine are of sufficient size for logging but generally the poplar, birch, pine, maple and oak are of a small and sometimes scrub wood-like nature.

CHAPTER III

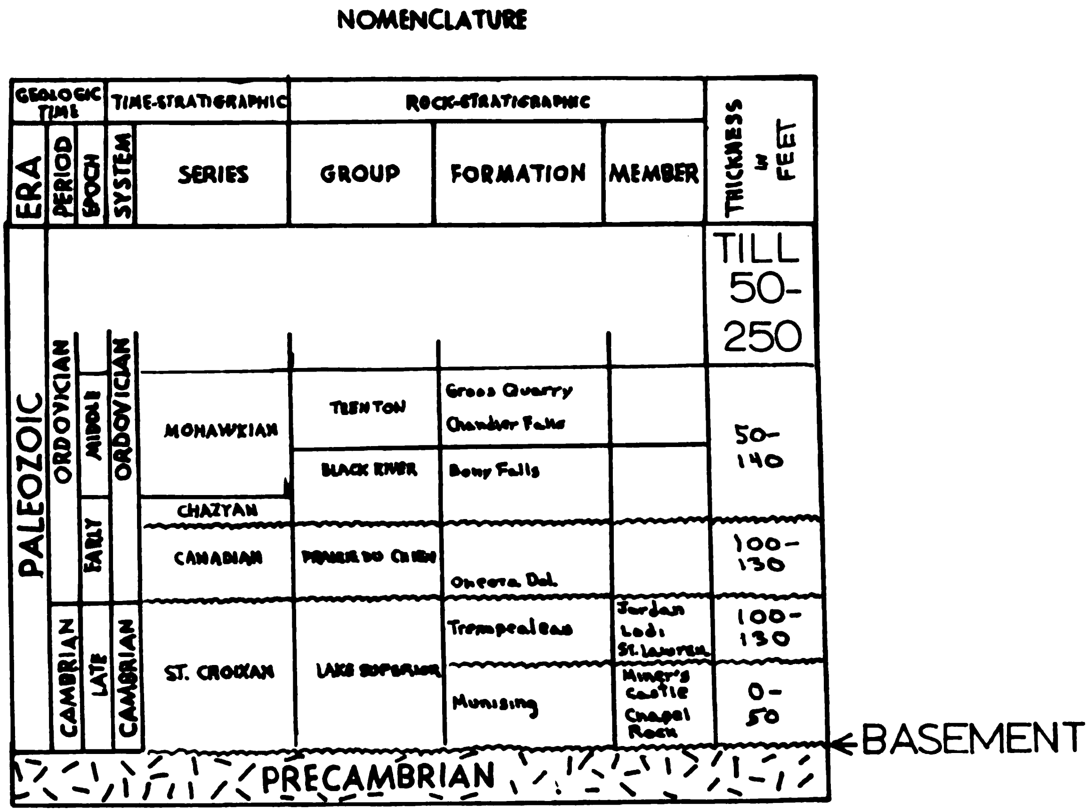
GENERAL GEOLOGY OF THE AREA

Phanerozoic

The Cambrian period of geological history in this area is represented by the Munising and Trempealeau formations. See Figure 3. As close as can be interpolated the Munising varies between zero and fifty feet in thickness in the area and increases in thickness to the north and the south (Hamblin, 1958). The Trempealeau appears to vary between 100 and 130 feet and is dipping in a southeast direction.

The Prairie Du Chien, Black River and Trenton groups constitute the period of the Ordovician. The Prairie Du Chien is represented by between 100 and 130 feet of dolomite which dips to the southeast. The Trenton and Black River rocks, combined in thickness, are between approximately 50 and 140 feet, and dip to the southeast.

Because of the veneer of glacial till in this area, subsurface geology must be interpolated from well logs, which are sparse, and outcrops that occur away from the area. Depth to the Precambrian basement has been assumed to be 500 feet, using the available data.



STRATIGRAPHIC
COLUMN

FIGURE 3

Precambrian

The Precambrian geology, like the geology of the Phanerozoic, must be inferred because of the lack of basement rock outcrops and well logs in the area. Precambrian rocks begin outcropping approximately 35 miles west of the Round Lake anomaly. These rocks consist mainly of granites. It is assumed that the general Precambrian basement rock in the area of the anomaly is granite.

The average depth to sea level in this area is 800 feet. Approximately two-thirds of this distance consists of Precambrian and Early Paleozoic rocks. For this reason a density of 2.67 gr/cm^3 has been assumed as a reasonable general density for this geologic section.

CHAPTER IV

GRAVITY FIELD SURVEY

Equipment

Gravity stations were read using the LaCoste and Romberg Model G Geodetic Gravity meter number one-eighty. It has a range of over 7,000 milligals, a repeatable reading accuracy of 0.01 of a milligal and an instrument drift of less than one milligal per month. The instrument is pressure compensated and temperature controlled requiring a twelve-volt battery source. A nickel cadmium rechargeable batter was used during this survey. Charging of batteries was done the night before the gravity meter was to be used, and at other times it was stored using normal outlet current to maintain the temperature. The best operating temperature is 48°C and the reading line is 2.60 on the scale. Extreme care was used in handling the instrument to avoid sudden jars and tilting of the instrument. The reading line was always brought in from the right side of the scale to prevent hysteresis. The error in reading accuracy is plus or minus 0.01 milligal. Instrument drift and tidal effects were removed using correction curves that were made by reoccupation of base stations.

Three Aneroid altimeters were utilized during the survey to measure the elevations of the gravity stations. One or two of the instruments were used as base altimeters to record the changes of elevation caused by changes in barometric pressure. The reading scale on one altimeter was 2 feet per division and on the others 5 feet per division. Reading accuracy is within plus or minus 2 feet.

Because of the deflection effects of the anomaly on a magnetic compass, a sun compass was used. The compass was constructed for use at 46° latitude. To achieve accurate readings, true north was located to placing two stakes in line with the north star and then during a continuously sunny day a correction chart was constructed by recording readings every fifteen minutes, to determine the location of north during the survey. A new chart was plotted about every two weeks. Handling and reading of the sun compass was cumbersome in that it requires leveling so that a Jacob's staff had to be used with it and it does not have a sighting device so that taking a reading was time consuming. The error in reading the sun compass is plus or minus 2 degrees.

Measurements between stations were either obtained by pacing or by tape and the station locations were marked either by stakes or strips of cloth. Tapes of 200 feet and 600 feet provided the most accurate measurements, but they were time consuming and required two people. The 200 foot tape was used when trails or rail grades curved greatly. Stakes were used for station locations along roads where this was the only means of marking the station. Numbered strips of cloth were used to mark stations in order that they not be confused with plastic strip markers on snowmobile trails. The error in pacing was determined to be 2.5 feet per 100 feet and the error in tape measurement 6 inches per 100 feet.

Survey Sampling Area

The optimum station spacing array would be a grid system consisting of ten or more traverses in each of the two perpendicular directions over the anomaly, with additional stations placed outside the area of the effect of the anomaly in order to represent the regional gravity accurately. This array would then provide 100 or more stations over the anomaly and each profile limb of the anomaly would have approximately five stations to represent it and thus define the anomaly in detail.

In the Round Lake anomaly area a uniform grid spacing array could not be used because of the impossibility of establishing stable station locations in the swamps and the terrain error involved in reading gravity on or close to moraines of high relief. Old rail grades, remnants of the past logging eras, provided the only stable access into the swamps. The rails of these grades were removed during the second World War so that many of the grades have become overgrown and were difficult to find and required clearing. Reading in the vicinity of moraines were taken as near the edge of the adjacent swamp or level ground as was feasibly possible to remove the gravity terrain effect of these areas. The maximum terrain effect is estimated to be 0.13 milligals based upon a "two dimensional" model approximation to a nearby moraine. Where the optimum grid spacing mentioned above would have provided a station every quarter of a mile, actual station spacings were concentrated in 600 and 400 feet intervals in readable areas in order to extract the most information possible as to the gradient of gravity change and directions of increasing or decreasing gravity. With this smaller network of stations in areas that were practical for reading gravity, higher frequency gravity changes not due to the anomaly itself but probably due to lithologic and structural changes within the near surface sediments were recorded. These changes were smoothed over on the contour maps and profiles as their effects are not of interest. A total of 403 gravity stations were occupied.

Data Acquisition

The beginning of the gravity survey consisted of establishing several long and easily accessible traverses in order to gain an approximation to the areal size of the anomaly and to establish a network of base stations for future use. A system of triple looping along the traverses, where each station is occupied within 60 to 90 minutes at three different times, provided the drift correction data necessary to establish the base stations. The average interval between these base stations was 2,500 feet. During the rest of the gravity survey one of these base stations was read every 60 to 90 minutes to provide drift correction data.

Because a maximum elevation change, caused by changing barometric pressure at the same known elevation, of 5 feet in 5 minutes was recorded, a base station altimeter was ready every five minutes at a known elevation during the elevation survey. An additional person was required to record these readings. All elevation data was corrected using base station altimeter graphs. The base station altimeter was always located at bench marks, road or rail grade intersections where the elevation is known, or in a few instances at a gravity station, where the elevation had been previously determined. The maximum error expected for elevation determination was plus or minus 5 feet, including the previously mentioned reading error of 2 feet.

CHAPTER V

REDUCATION OF DATA TO YIELD THE BOUGUER GRAVITY RESIDUAL

Drift Correction

The inherent drift of the gravity meter and the tidal drift of gravity caused by the sun and moon were removed by the use of drift correction graphs. These were constructed by reoccupying base stations every 60 to 90 minutes and plotting the meter reading versus time. The corresponding drift correction for each station read within that time interval was added or subtracted to that station's reading. After this was done the appropriate conversion factors obtained from the LaCoste and Romberg instruction manual were applied to convert the meter reading to gravity readings in milligals. The maximum correction made for drift was 0.14 milligals. This correction was made by the computer as were the corrections for elevation, Bouguer mass effect and latitude.

Combined Correction for Elevation and Mass Effect

The free air correction was used to compensate for the differences in elevation of the stations. All stations were adjusted to a sea level datum. The correction involves adding 0.094 milligals per foot above sea level to the observed gravity.

To remove the gravity effect of the mass between each station and sea level, the Bouguer correction was applied. Using 2.67 gm/cm^3 as the average density of this mass of rocks, the Bouguer correction was 0.034 milligals per foot and is subtracted from the observed gravity. The error of the combined free air and Bouguer corrections is plus or minus 0.30 milligals.

Latitude Correction

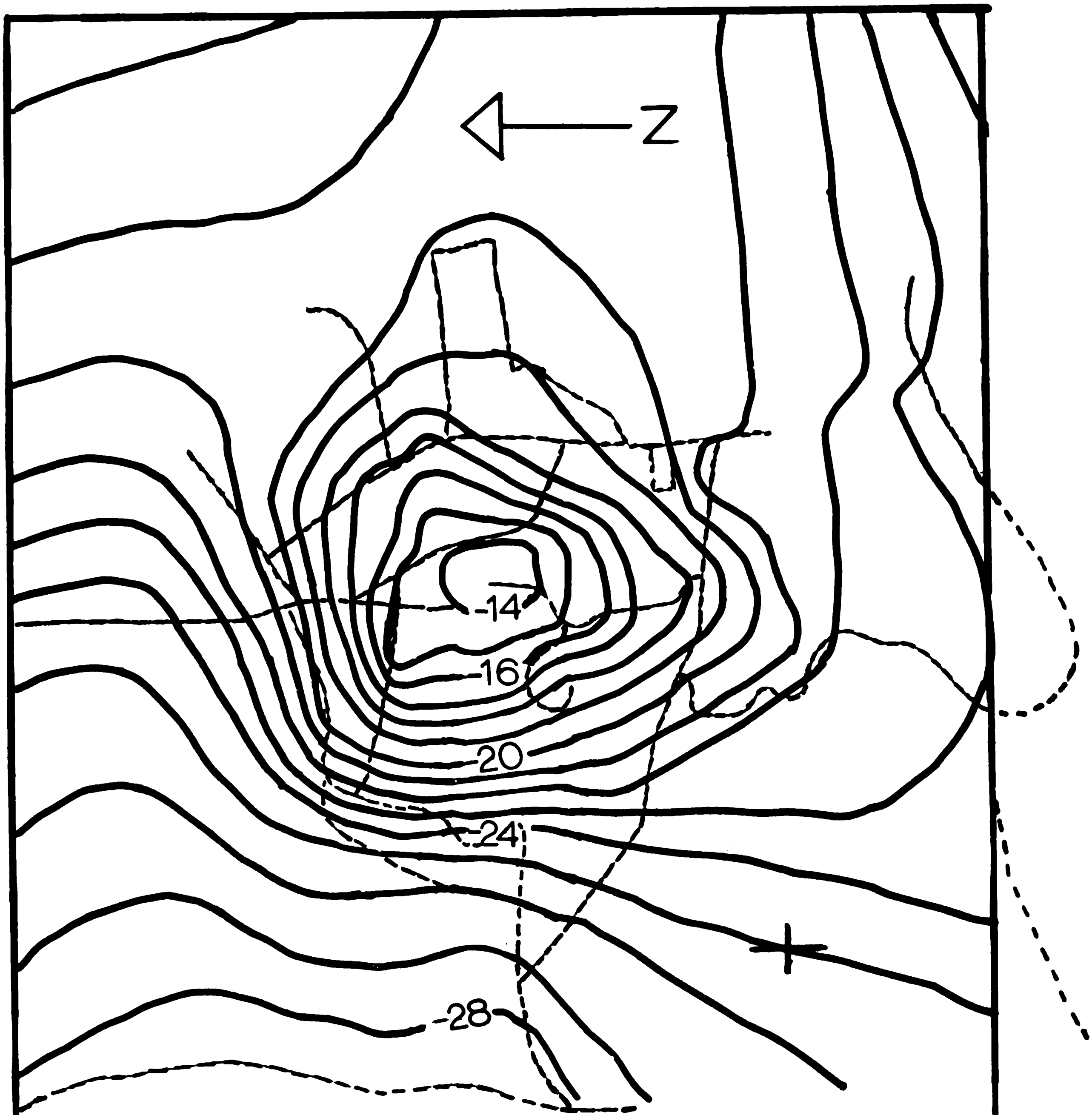
The values of gravity between the equator and the poles vary at the rate of $1.307 \times \mathrm{SIN}\ 2\phi$ milligals per mile, where ϕ is the latitude and indicates that the gravity at the equator is 5,300 milligals less than at the poles and the increase of the component of centrifugal force opposing gravity from the poles to the equator. In the Round Lake anomaly area, the change was 0.1 of a milligal per every 400 feet and was added for stations to the south and subtracted for stations to the north. Latitude distances were measured and mapped with a maximum error of 134 feet, causing a gravity error of plus or minus 0.033 milligals.

Removal of Regional Gravity

Regional gravity variations are caused by density variations deep within the earth and are usually of long wavelength. These changes distort the actual shape of the anomaly. In order to isolate the gravity anomaly from gravity effects other than those caused by the anomalous body it is necessary to remove the regional gravity effects. The cross profile method was used. A grid system of 22 profiles in perpendicular directions was constructed over the area of the anomaly. Regional gravity lines were connected across the interval of the anomaly on each profile with the provisions that the difference of regional and anomalous gravity at each point on the profile, corresponding to a perpendicular profile, is the same. The regional gravity was then subtracted from each profile. This procedure can also be used to remove the effects of other nearby anomalies that interfere with the anomaly of interest. Figure 4 is a raw gravity contour map of the anomaly after all corrections have been applied but before the regional gravity has been removed. Figure 5 is a contour map of the regional gravity that was subtracted from the observed gravity to obtain the residual gravity values. The residual Bouguer contour map is shown in Figure 6.

Estimation of Maximum Gravity Error

A number of sources of error occurred during the survey. The reading of the gravity meter is accurate to plus or minus 0.01 milligal. The error in elevation is a maximum of 5 feet and leads to an error of plus or minus



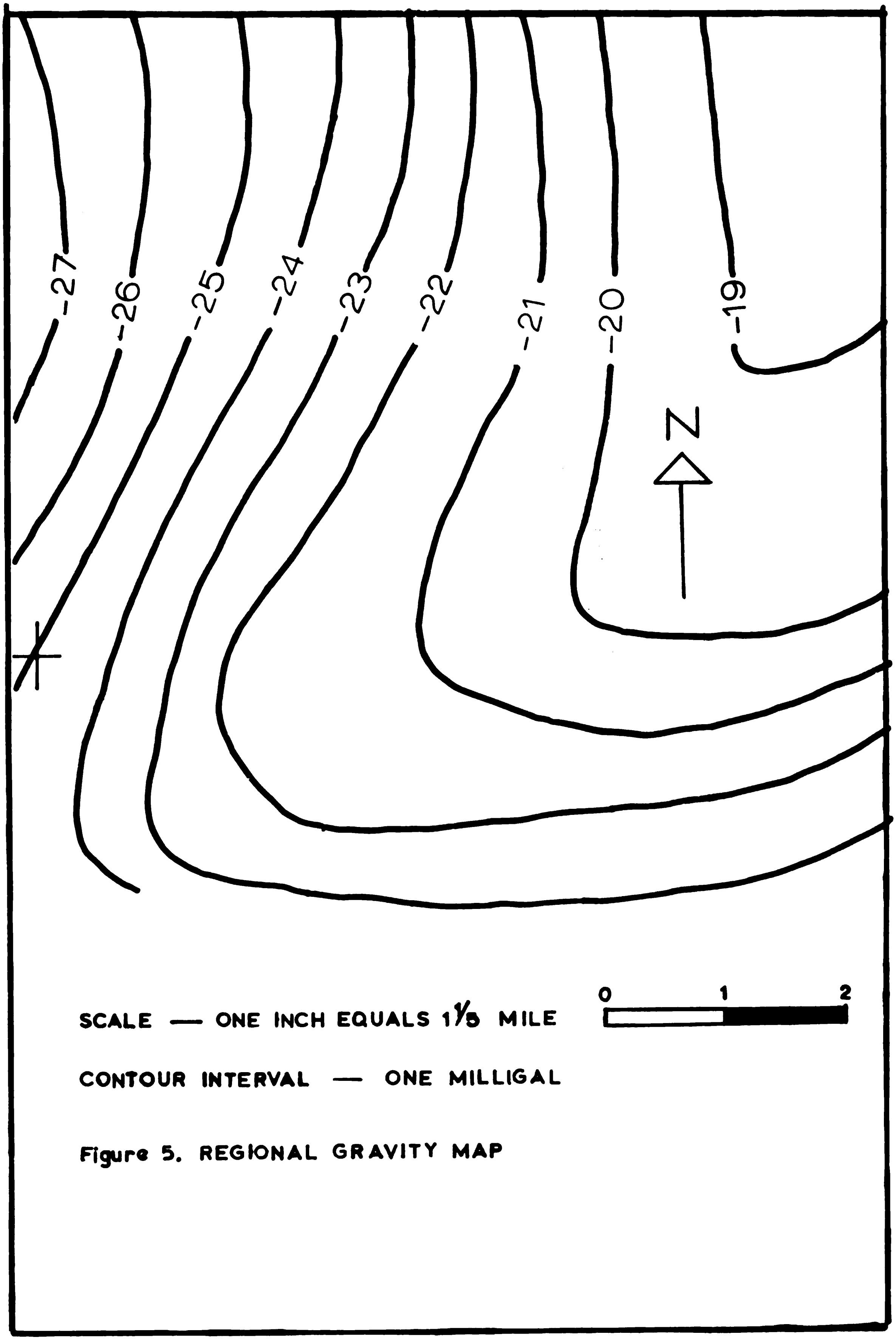
0 4000

SCALE — ONE INCH EQUALS 4,000 FEET

CONTOUR INTERVAL — ONE MILLIGAL

TRAVERSE LINES ------

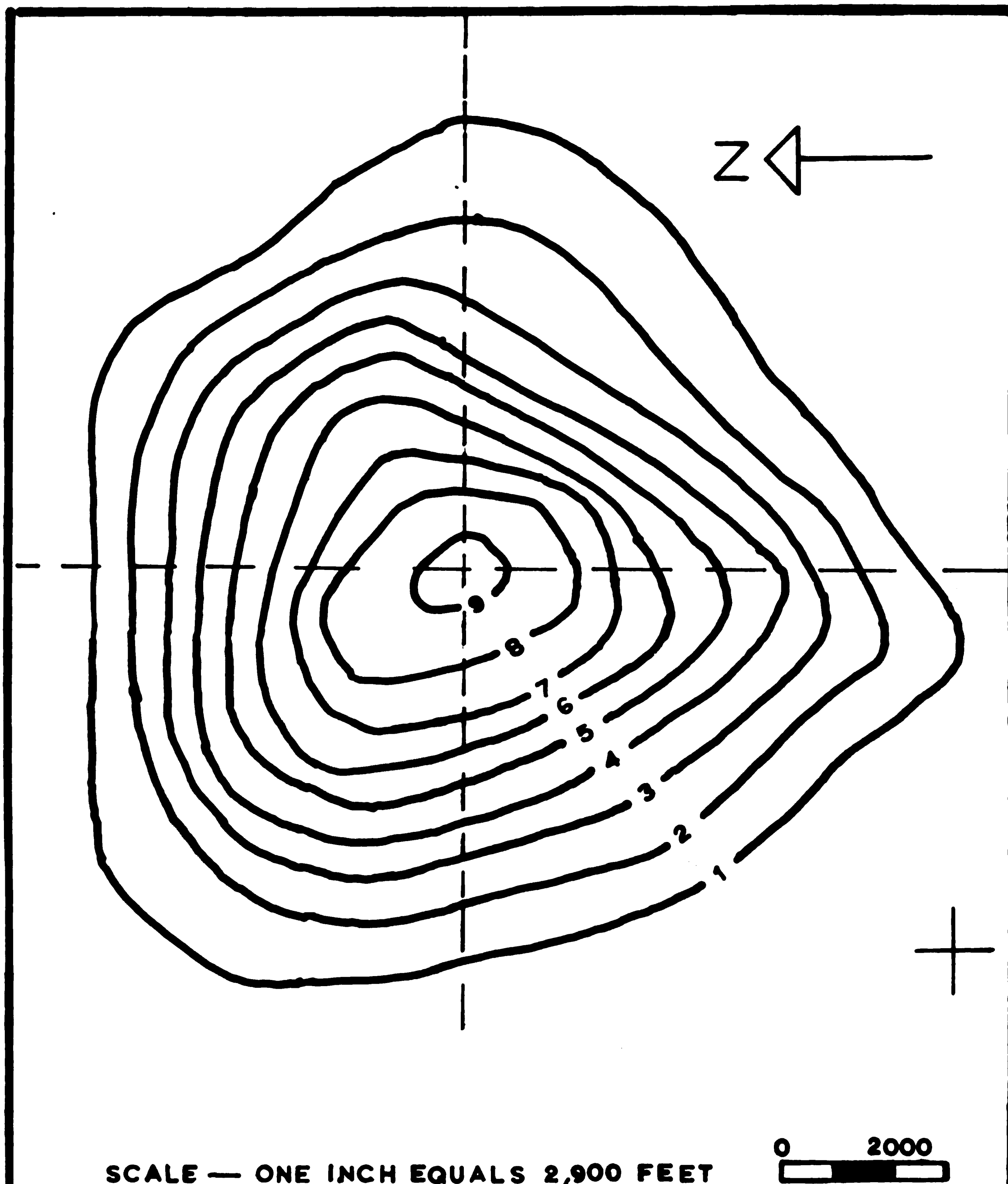
Figure 4. BOUGUER GRAVITY MAP



SCALE — ONE INCH EQUALS 1⅕ MILE

CONTOUR INTERVAL — ONE MILLIGAL

Figure 5. REGIONAL GRAVITY MAP



SCALE — ONE INCH EQUALS 2,900 FEET

CONTOUR INTERVAL ONE MILLIGAL

— — — ORTHOGONONAL AXES (AVER. PROFILE)

Figure 6. RESIDUAL GRAVITY MAP

0.30 milligals to the combined correction for elevation and mass effect. Mapped station locations are accurate to within 134 feet, causing a gravity error of plus or minus 0.033 milligals. The total maximum error is 0.47 milligals including terrain errors of plus or minus 0.1 milligal and arises mainly from the error in elevation determination.

CHAPTER VI

GRAVITY INTERPRETATION BY SIMPLE MODELS

Approximation by a Sphere

The first shape used to approximate the observed gravity was that of a sphere. There are a number of reasons why this is a good first choice. The residual anomaly exhibits closure of the contours and circularity about a central vertical axis. A sphere is equal dimensionally in all directions, the only dimensional variable being the radius, so that changes in width or thickness do not have to be considered. The gravity effects are easily calculated on the radial profile for various size spheres and different depths to the sphere. Once a best fit is established the excess mass and the volume can be calculated easily.

Approximation by a sphere to best fit the observed radial profile was done by calculating radial profile values of gravity at various depths and radius. A density differential of 0.3 grams per cubic centimeter was used as the most suitable differential to represent the upper limits of geologically reasonable densities. This value of 0.3 would make the anomalous mineral density 2.97 gm/cm^3. The formula used for calculating gravity over a sphere is:

$$g_z = \frac{8.53\ \Delta\sigma R^3}{z^2} \quad \frac{1}{[1 + (x/z)^2]^{3/2}} \qquad [6.1]$$

where g_z is the vertical gravity in milligals, $\Delta\sigma$ is the density differential, R is the radius, z is the depth to the center of the sphere and x is the radial distance (Dobrin, 1960). All distances are in kilofeet.

The calculated prfiles of gravity over the spheres were compared to an average radial profile of two sets of orthogonal profiles on the residual anomaly as the anomaly is not perfectly circular. See Figure 6. The sphere that best fits has a radius of 4.515 kilofeet, a depth to the center of 5.015 kilofeet and a depth to the top of 0.5 kilofeet. See Figure 7A.

This close fit of calculated and actual gravity permits the calculation of the excess mass of the spherical model which closely approximates the actual excess mass of the body. The excess mass of the sphere was determined by:

$$X_{mass} = V\Delta\sigma = 4/3\ \pi R^3 \Delta\sigma \qquad [6.2]$$

where X_{mass} is the excess mass and V is the volume. The excess mass is 3.223×10^{15} grams. Total mass is the mineral density divided by the density differential times the excess mass, and has the value of 3.2×10^{16} grams. The volume is easily determined once the mass is known and the density differential assumed. The volume of the sphere is 384.5 cubic kilofeet.

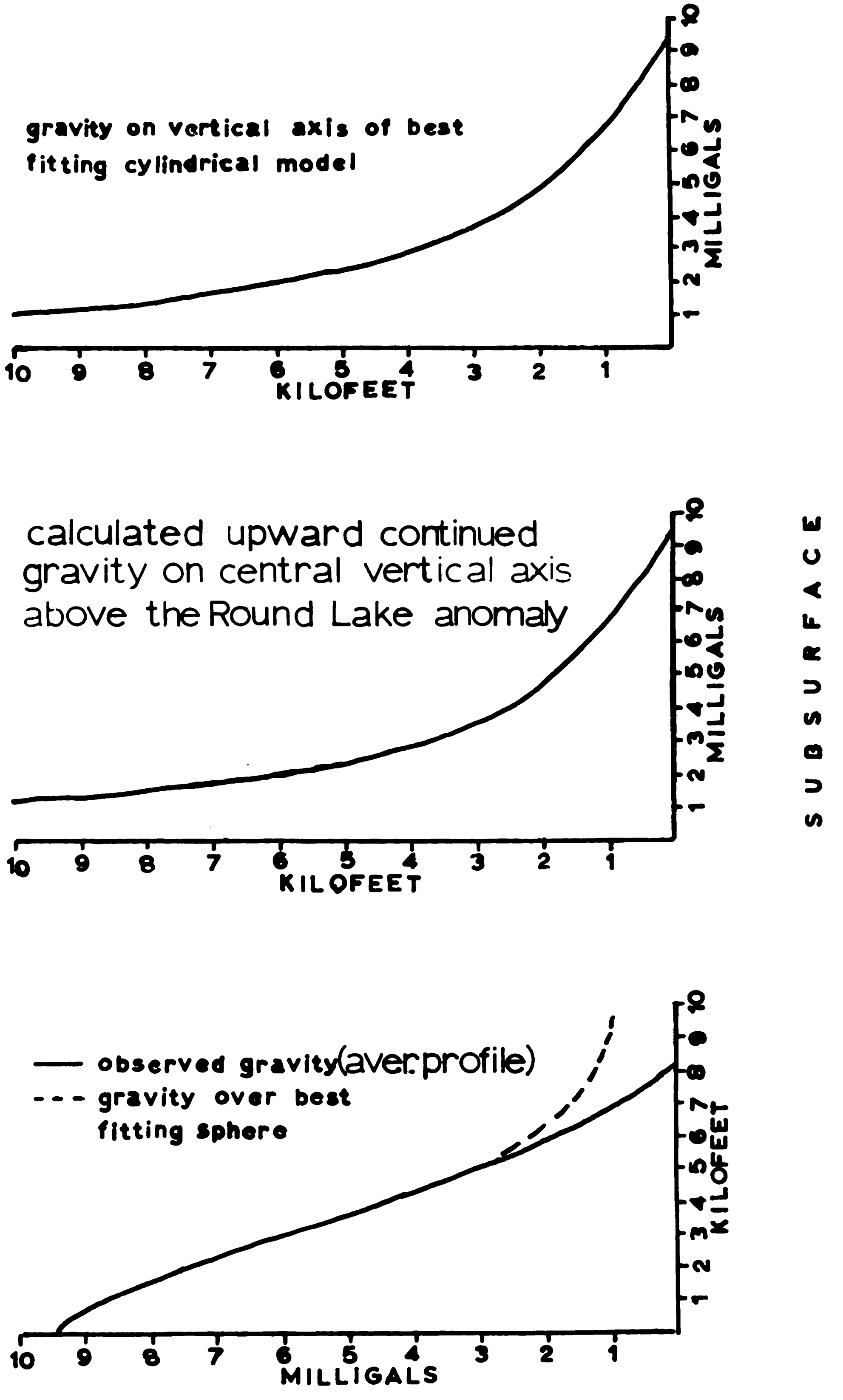


Figure 7. RADIAL AND VERTICAL PROFILES OF GRAVITY

The total anomalous mass is a unique quantity in that when the surface integral of the normal attraction of the mass on the surface is calculated over the mass, the excess mass is determined uniquely. This is from a theorem of Gauss' (Garland, 1965).

$$\int \Delta g(x,y)dxdy = 2\pi GM \qquad [6.3]$$

where G is the gravity constant and M is the excess mass. Thus the volume under the curve of a gravity profile, for a symmetric body about a vertical axis, will always be the same, regardless of the shape, depth or density of the body. If then the excess mass is unique the volume of the body is unique for an assumed density. This constraint of constant volume is a powerful tool when other models are considered as approximations to the anomalous body.

Approximation by Vertical Cylinders

The use of vertical cylinders as models was done for several reasons. The residual anomaly exhibits closure and circularity that would be expected of the gravity over a cylinder. A cylinder is geologically reasonable as a simple model. With a cylinder there is the added dimensions of thickness and diameter. Any cylinder used is constrained to have a constant volume of 384.5 cubic kilofeet as determined by the sphere approximation.

Because gravity is difficult to calculate on a radial profile over a vertical cylinder, but easily calculated on the vertical axis above a cylinder, a method of upward continuation of observed radial gravity to the vertical axis was programmed for use on the computer (Paul, 1972). This method works only for those gravity anomalies showing approximate symmetry about a vertical axis. The method consists of a numerical evaluation presented by Paul of the formula:

$$g(o,z) = z \int_{o}^{\infty} \frac{rg(r,o)}{(r^2+z^2)^{3/2}} \qquad [6.4]$$

which is the upward continuation formula. The end correction for the effect of gravity beyond the extent of gravity stations is based upon the assumption that the gravity field at large distances is in effect caused by a point source. This end correction:

$$\delta g(o,z) = z \int_{R}^{\infty} \frac{rg(r,o)}{(r^2+z^2)^{3/2}} \qquad [6.5]$$

where R is the last gravity value in a radial profile was calculated for z ranging between one and ten kilofeet and was found small enough to be neglected. The upward continued profile of the residual gravity is shown in Figure 7.

Gravity on the axis above vertical cylindrical models was calculated for cylinders ranging in radius from 100 feet to 8,000 feet by intervals of 100 feet, and depth to the top ranging from 100 feet to 32,000 feet by intervals of 100 feet. A computer program was used that calculated the gravity values at heights of zero to ten kilofeet by one kilofoot intervals above the top surface of the models. The program consisted of calculating the formula:

$$g_z = 12.77\ (\Delta\sigma)\ (c_2 - c_1 - \sqrt{R^2+c_2^2} + \sqrt{R^2+c_1^2} \qquad [6.6]$$

for the various cylinders. g_z is the vertical gravity on the axis of the cylinder, c_2 is the depth to the bottom of the cylinder, c_1 is the depth to the top of the cylinder, R is the radius and all distances are in kilofeet. See Figure 8.

Using the constraints that cylindrical models maintain a constant volume of 384.5 cubic kilofeet and exhibit a maximum gravity value of 9.4 milligals, a pair of cylinders at each interval depth met the constraints. At increasing depth intervals the pairs of cylinders merge toward the same shape. See Figure 9. At 750 feet depth only one cylinder fits the constraints and below 750 feet no cylinder fits.

The best fitting vertical gravity profile of a cylindrical model with the upward continued vertical profile of the observed gravity was that representing a cylinder occurring at 500 feet depth to the top, 11,000 feet to the bottom, and having a radius of 3.4 kilofeet. The fit of the upward continued gravity curve with the observed gravity is shown in Figure 7B, C.

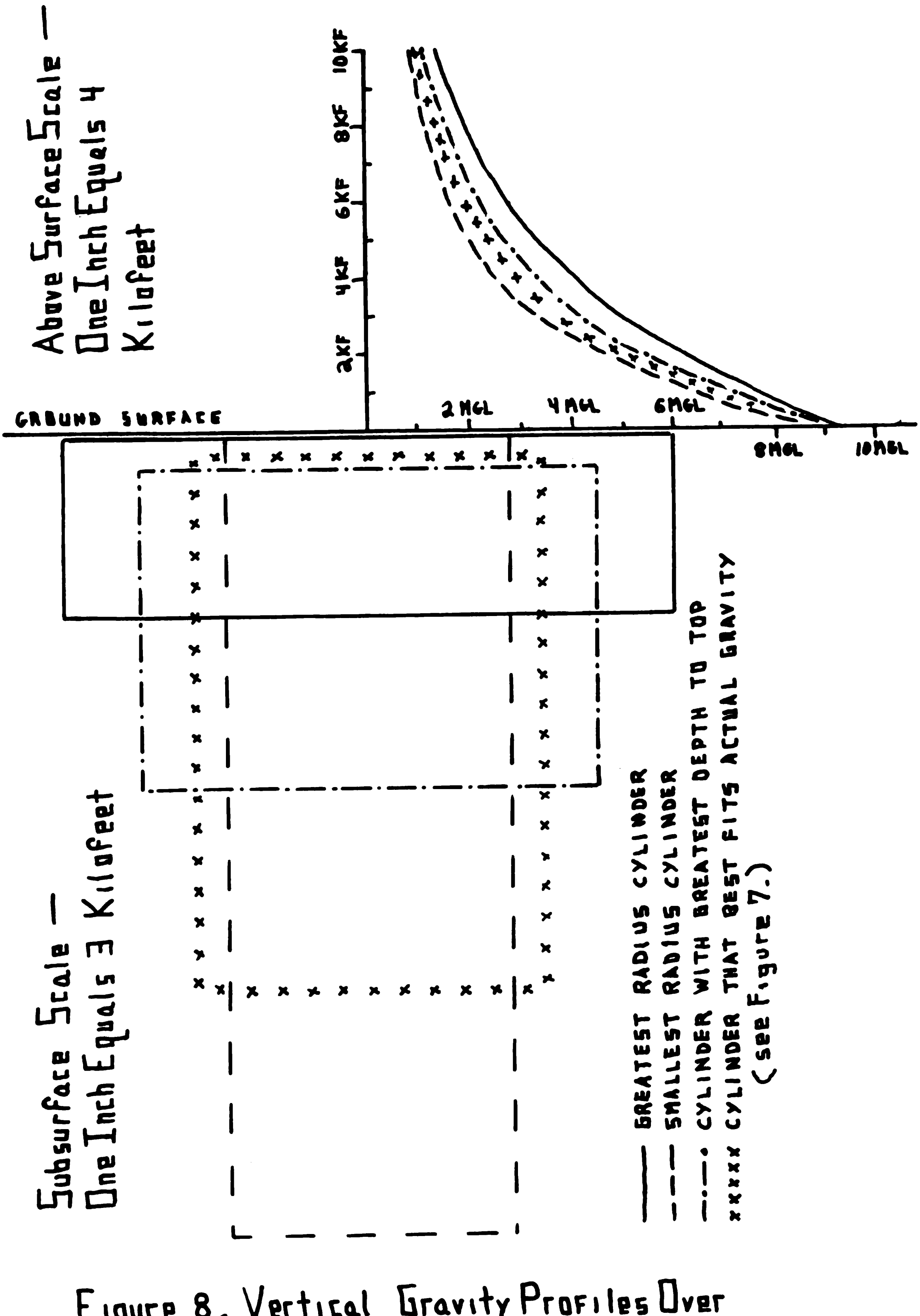


Figure 8. Vertical Gravity Profiles Over Cylindrical Models

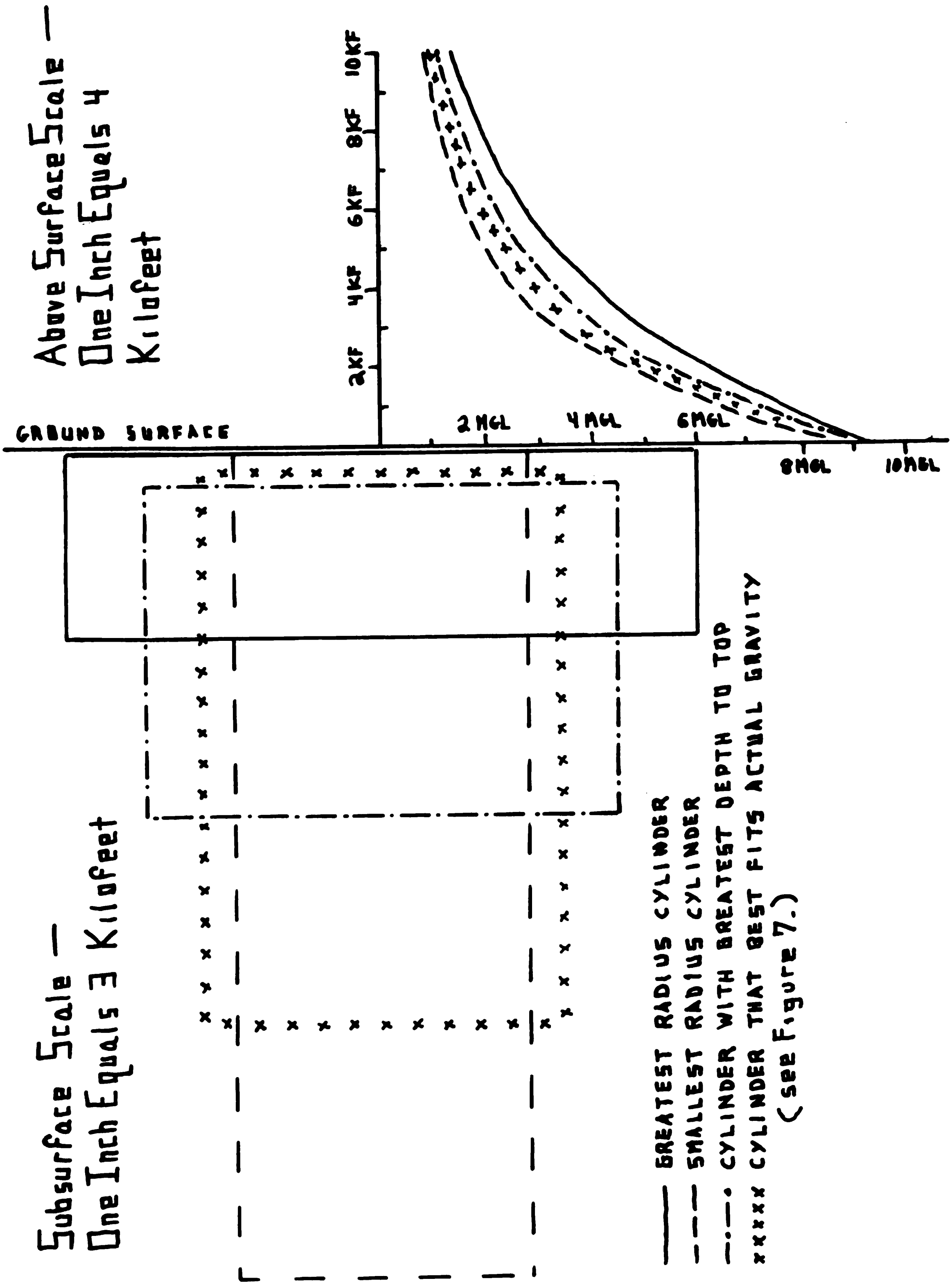
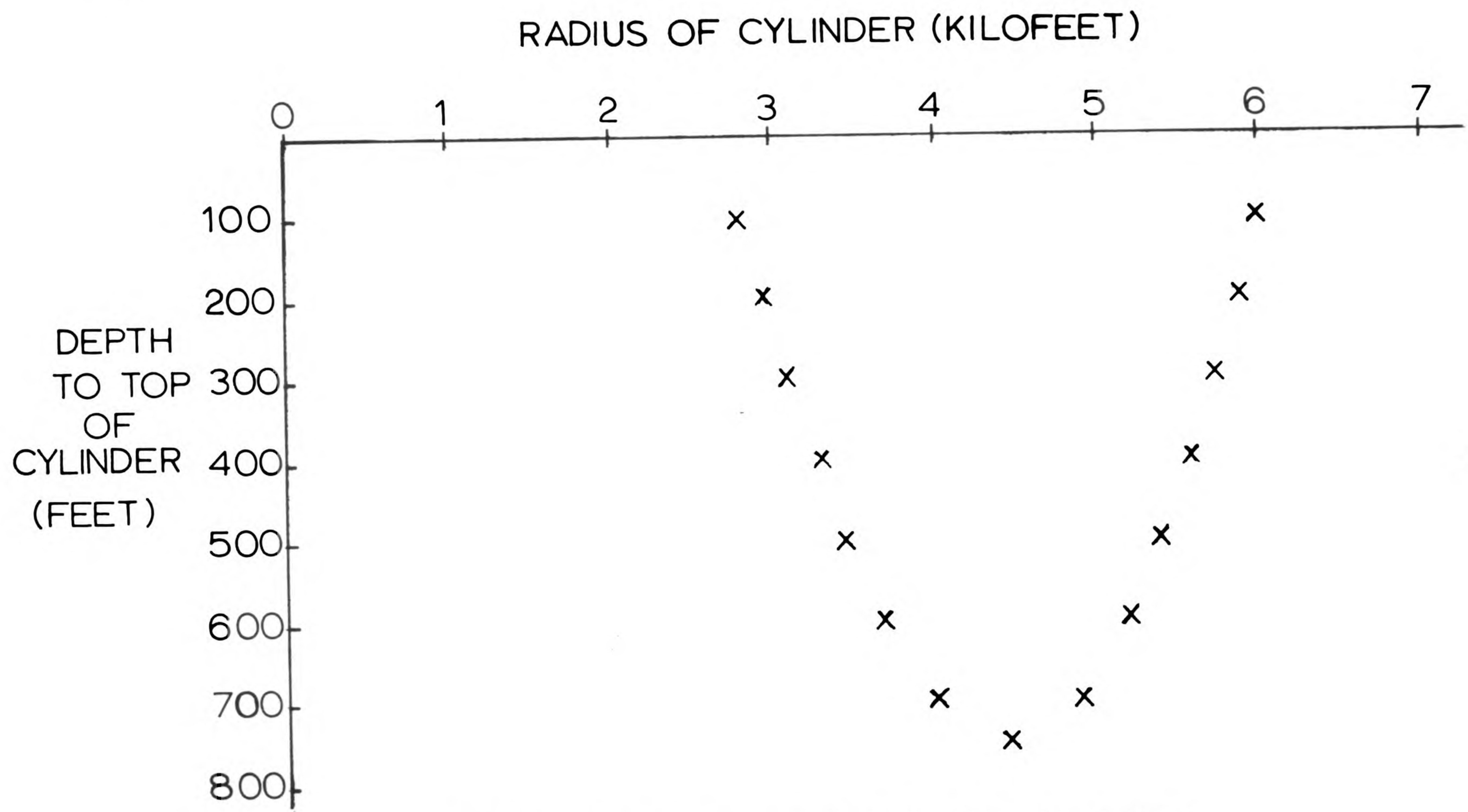


Figure 8. Vertical Gravity Profiles Over Cylindrical Models



CYLINDER PAIRS AT INCREASING DEPTH

FIGURE 9

Calculation of an Approximate Magnetic Susceptibility

Because a sphere is a good approximate model of the Round Lake anomaly and because calculation of the magnetic effects of a sphere is easily done, a sphere was chosen for the calculation of an approximate susceptibility. A number of assumptions were made during this calculation that should be kept in mind as they affect the accuracy of the calculated magnetic susceptibility in representing the actual model. The first assumption is that the body has no components of residual or permanent magnetization that would change the magnitude or direction or polarization. If the remanent polarization were parallel to the present field and had a magnitude comparable to the induced polarization, as often observed in igneous and metamorphic rocks, the calculations will lead to an apparent susceptibility which is twice as great as the true susceptibility. Another assumption is that the earth's magnetic field is vertically oriented in this area and therefore the sphere is vertically polarized. In fact the earth's magnetic field is inclined by 75 degrees in the study area. If these assumptions are allowed then the formula:

$$V = \left(\frac{4\pi R^3 I}{3z^3}\right)\left(\frac{2-(x/z)^2}{[1+(x/z)^2]^{5/2}}\right) \qquad [6.7]$$

can be used to calculate the magnetic susceptibility (Nettleton, 1942).

Rearranging the formula:

$$I = kH = \frac{(3Vz^3)\ (1+(x/z)^2)^{5/2}}{(4\pi R^3)\ (2-(x/z)^2)}$$

where I is the intensity of magnetization, k is the magnetic susceptibility, H is the magnetic field of the earth equal to 60,000 gammas, V is the maximum magnetic intensity of the observed anomaly equal to 9,704 gammas, R is the radius of the sphere equal to 4.515 kilofeet, z is the depth to the center of the sphere equal to 5.015 kilofeet and x is the radial distance, equal to zero. The calculated value for Δk the magnetic susceptibility is $26{,}450 \times 10^{-6}$ emu/cm^3 units.

This is a high value of magnetic susceptibility, corresponding to the maximum for basalt which is the highest listed for a rock type by (Dobrin, 1960). It should not be assumed that this value is accurate, but that it gives an approximate value for the magnetic susceptibility within an order of magnitude.

Relating Bulk Magnetic Susceptibility to the Volume of Magnetite

Formula 6.8 can be seen to consist of two variables, k and V. For a sphere of pure magnetite of the same radius and depth of that used for calculating approximate magnetic susceptibility, the relation

$$\frac{V_{obs}}{V_{mag}} = \frac{\Delta k}{\Delta k_{mag}} \qquad [6.9]$$

can be deduced. Where V_{obs} is the maximum magnetic intensity of the observed anomaly and V_{mag} is the maximum magnetic intensity of the sphere of pure magnetite. This relation V_{obs}/V_{mag} is indicative of the volume percentage magnetite of the anomalous body. The maximum vertical magnetic anomaly over the best fit vertical cylinder, determined from the gravity modeling, was also calculated assuming the susceptibility for pure magnetite. The maximum anomaly was similar to that for the sphere and thus the calculated susceptibility and percent magnetite for both magnetic models (sphere and cylinder) are similar. Using the approximate susceptibility of $26{,}450 \times 10^{-6}$ emu/cm^3 and $800{,}000 \times 10^{-6}$ emu/cm^3 the ratio $\Delta k/\Delta k_{mag}$ gives a percentage range of magnetite of 3.3% to 8.8%.

CHAPTER VII

CONCLUSION

Approximations Made

The first approximation made in the gravity model interpretation was that the observed gravity was closely approximated by that of a sphere in order that a constant volume could be assumed at a given density. Comparison of the two curves of actual and calculated gravity shows a close fit in both the radial and vertically continued directions. The volume and excess mass calculated from the best fit model are probably slightly higher than actual since the integral beneath the spherical best fit model is slightly greater than the integral beneath the observed anomaly (Figure 7).

The next approximation made was that the actual gravity anomaly could be represented by a cylinder. This is an accurate approximation in that it has radial symmetry, as does the gravity anomaly, and that a cylinder can assume the shape from a thin flat plate approaching a two dimensional bedding plane, to an almost equal dimensional mass such as a laccolith, and finally to a long length vertical cylinder approaching something that might be interpreted as a stock.

Another approximation made was that the density contrast of the anomalous body is 0.3 gm/cm^3. This is a reasonable value first because the anomalous body is denser than the surrounding rock and secondly because the high magnetics may be suggestive of a more basic and more dense rock type. The density contrast of 0.3 gm/cm^3 is meant to represent a basic rock such as peridotite, diabase or gabbro, all of which have density ranges including 2.97 gm/cm^3.

It is important to remember that a model solution to a gravity problem is not unique and that the anomalous body need not have vertical sides such as a cylinder nor must the density or the magnetic susceptibility be uniform throughout the body as was assumed. The purpose of a model study approach is to estimate, as accurately as possible, a geologic feature by a simple model that contains a minimum number of variables and still represents the feature to such a degree that the model is useful as an interpretive tool.

Simple Models Related to Geology

The gravity model study indicates that the body is an intra-basement structure, whose upper surface coincides roughly with the Precambrian basement and vertical extent is approximately 10,500 feet.

The depth and shape of the best fit cylindrical gravity model indicate the anomalous body may be an intrusive stock within the granitic Precambrian basement. The dipolar nature of the magnetic anomaly also indicates that the body has a reasonably large vertical extent. The magnetic anomaly itself is probably caused by disseminated magnetite within the body and possibly secondary alteration into magnetite.

In order to evaluate the geophysical model it would be interesting to study the results obtained from drilling the anomaly.

APPENDIX

DATA TABLE

APPENDIX

DATA TABLE

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Locations
E1	-77.34	805	-29.04	E1-E35, east from intersection F.H. 2235 and Camp 26 road to crossroads, Camp 26. Intervals, 500 to 800 feet.
E2	-77.61	808	-29.05	
E3	-77.40	815	-28.44	
E4	-76.45	799	-28.65	
E5	-75.55	789	-28.36	
E6	-76.53	805	-27.92	
E7	-75.45	801	-27.59	
E8	-75.37	793	-28.01	
E9	-73.69	793	-26.33	
E10	-73.41	790	-26.15	
E11	-72.46	782	-25.68	
E12	-71.49	786	-24.47	
E13	-71.90	789	-25.05	
E14	-70.96	790	-24.16	
E15	-70.23	797	-23.11	
E16	-69.99	798	-23.06	
E17	-69.68	795	-23.15	
E18	-67.43	795	-20.82	
E19	-66.33	796	-19.69	
E20	-65.02	800	-18.02	
E21	-63.84	798	-16.80	
E22	-62.98	811	-15.27	
E23	-64.57	817	-16.62	
E24	-65.33	817	-17.50	
E25	-65.21	814	-17.58	
E26	-65.95	818	-18.13	
E27	-66.72	834	-17.80	
E28	-66.21	838	-17.00	
E29	-64.89	831	-16.15	
E30	-67.07	845	-17.55	
E31	-67.30	848	-17.59	
E32	-67.90	860	-17.44	
E33	-67.53	853	-17.42	
E34	-67.03	844	-17.31	
E35	-66.46	835	-17.20	

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Locations
1	-66.06	826	-17.32	1-16 south on rail grade from crossroads, Camp 26, 500 foot intervals.
2	-64.78	804	-17.83	
3	-65.44	804	-17.75	
4	-66.14	804	-18.30	
5	-66.57	802	-18.71	
6	-66.77	800	-18.88	
7	-67.13	796	-19.34	
8	-66.98	792	-19.28	
9	-66.84	782	-19.58	
10	-67.17	781	-19.83	
11	-67.47	780	-20.05	
12	-67.83	774	-20.61	
13	-68.01	770	-20.88	
14	-68.08	764	-21.17	
15	-68.26	760	-21.43	
16	-68.57	759	-21.65	
18	-65.21	814	-17.58	From crossroads of Camp 26 road and hunting road, north on hunting road to intersection with F.H. 440, station 47. 500 foot intervals.
19	-66.59	814	-19.10	
20	-67.43	809	-20.38	
21	-68.34	807	-21.55	
22	-69.13	806	-22.54	
23	-69.78	807	-23.26	
24	-69.86	802	-23.77	
25	-70.01	797	-24.38	
26	-70.25	796	-24.83	
27	-70.47	795	-25.24	
28	-70.52	794	-25.48	
29	-70.17	795	-25.21	
30	-69.82	796	-24.95	
31	-69.52	794	-24.91	
32	-69.63	794	-24.17	
33	-69.17	792	-24.97	
34	-68.35	789	-24.47	
35	-67.64	787	-23.97	
36	-67.23	787	-23.75	
37	-66.72	786	-23.44	
38	-66.26	783	-23.31	
39	-66.15	781	-23.45	
40	-65.75	780	-23.25	
41	-65.53	781	-23.22	
42	-65.52	782	-23.28	
43	-65.41	780	-23.33	
44	-65.03	781	-23.05	
45	-65.25	780	-23.48	
46	-65.17	779	-23.58	
47	-65.03	781	-23.49	

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Location
S1	-66.15	836	-17.03	S1-S12, from Camp 26 and hunting camp road, SE on rail grade to intersection 1-16 line. 500 foot station spacing.
S2	-63.23	805	-15.91	
S3	-62.25	798	-15.18	
S4	-61.85	801	-14.47	
S5	-62.89	815	-14.52	
S6	-63.29	811	-15.02	
S7	-63.43	807	-15.27	
S8	-63.53	797	-15.84	
S9	-64.84	792	-17.34	
S10	-66.05	791	-18.55	
S11	-66.54	787	-19.23	
S12	-66.76	786	-19.34	
P1	-74.81	794	-27.36	P1-P21, from intersection Petosky rail grade and Camp 26 road, SE along grade to intersection 1-16 line, 500 foot intervals.
P2	-74.00	782	-27.10	
P3	-73.57	780	-26.69	
P4	-73.15	779	-26.26	
P5	-72.68	779	-25.70	
P6	-72.23	779	-25.17	
P7	-71.84	777	-24.81	
P8	-71.55	779	-24.31	
P9	-71.12	781	-23.68	
P10	-70.63	782	-23.10	
P11	-69.99	785	-22.28	
P12	-69.77	790	-21.70	
P13	-68.94	786	-21.06	
P14	-69.50	787	-20.51	
P15	-68.25	787	-20.20	
P16	-68.94	787	-19.83	
P17	-67.43	785	-19.37	
P18	-66.93	786	-18.81	
P19	-67.02	787	-18.86	
P20	-67.09	785	-19.04	
P21	-67.53	776	-20.00	
C3	-64.11	812	-16.43	C3-C15, south from intersection Camp 26 road and hunting camp road, along brushed sight line, 400 foot intervals.
C5	-63.25	807	-15.83	
C7	-62.26	805	-14.84	
C9	-62.05	806	-14.70	
C11	-61.81	796	-14.72	
C13	-61.43	795	-14.29	
C15	-61.14	796	-14.82	

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Locations
F1	-63.74	808	-16.14	F1-F21, D3-D21, on rail grades running E-W, 1,000 feet south of Camp 26 road and hunting camp road intersection, 400 foot intervals.
F3	-63.19	802	-15.94	
F5	-62.77	805	-15.32	
F7	-62.36	804	-14.94	
F11	-61.92	801	-14.62	
F13	-62.07	802	-14.71	
F15	-62.67	804	-15.22	
F17	-63.12	808	-15.47	
F19	-63.32	804	-15.95	
F21	-63.63	802	-16.42	
D3	-63.95	806	-16.69	
D5	-63.43	805	-16.16	
D11	-64.03	813	-16.09	
D13	-63.96	813	-15.98	
D15	-64.20	812	-16.24	
D17	-64.23	808	-16.46	
D19	-64.42	806	-16.69	
D21	-65.16	805	-17.41	
G1	-61.88	807	-13.92	G1-G35 north on road from Petosky hunting club, 400 foot intervals.
G3	-61.54	807	-13.49	
G5	-61.41	802	-13.55	
G7	-61.85	802	-13.90	
G9	-62.33	802	-14.28	
G11	-62.83	800	-14.84	
G13	-63.18	803	-14.98	
G15	-63.47	793	-15.77	
G17	-63.84	795	-15.92	
G19	-63.52	789	-15.89	
G21	-63.95	787	-16.35	
G23	-64.45	788	-16.69	
G25	-65.04	788	-17.28	
G27	-66.10	790	-18.04	
G29	-66.24	790	-18.10	
G31	-65.98	783	-18.18	
G34	-66.07	783	-18.20	
H19	-73.71	784	-27.05	H19-H1, NE on rail grade from station E9 on Camp 26 road to intersection with hunting camp road.
H18	-73.47	784	-26.92	
H17	-73.04	790	-26.26	
H16	-72.85	791	-26.14	
H15	-72.94	795	-26.12	
H14	-72.51	799	-25.55	
H13	-72.70	792	-25.40	
H12	-72.09	803	-25.15	
H11	-72.43	813	-25.01	

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Locations
H10	-70.52	801	-23.84	
H9	-69.28	799	-22.74	
H8	-68.13	800	-22.46	
H7	-67.12	801	-20.37	
H6	-67.10	804	-20.16	
H5	-66.91	804	-19.97	
H4	-66.84	802	-20.07	
H3	-67.63	807	-20.66	
H2	-68.29	820	-20.61	
H1	-66.72	814	-19.32	
J2	-69.21	869	-18.39	
J3	-69.38	858	-19.36	
J4	-70.98	855	-20.25	
J5	-70.29	850	-20.86	
J6	-69.53	842	-20.55	
I1	-68.05	806	-21.93	
I2	-69.69	831	-21.96	
I3	-69.65	836	-21.52	
I4	-70.69	848	-21.75	
I5	-71.00	854	-21.60	
I6	-70.27	844	-21.41	
I7	-70.15	849	-20.86	
M1	-75.21	786	-27.53	M17-M1, south on F.H. 2228 from intersection F.H. 400, 1/4 mile intervals.
M2	-76.02	791	-28.31	
M4	-77.37	811	-28.96	
M5	-76.27	800	-28.73	
M6	-76.09	800	-28.82	
M6	-76.42	806	-29.03	
M7	-76.42	806	-29.03	
M8	-77.63	822	-29.51	
M9	-77.14	818	-29.50	
M10	-76.08	805	-29.46	
M11	-74.87	803	-28.62	
M12	-74.42	797	-28.79	
M13	-74.28	798	-28.82	
M14	-73.97	799	-28.71	
M15	-73.89	802	-28.69	
M16	-73.55	803	-28.55	
M17	-73.11	800	-28.51	
N1	-73.31	773	-23.84	N1-N2, south on road from Petosky hunting club to intersection, F.H. 2440, 500 foot intervals.
N2	-72.70	770	-23.57	
N3	-72.53	772	-23.46	
N4	-71.89	770	-23.11	

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Locations
N5	-71.65	769	-23.02	
N6	-71.45	773	-22.70	
N7	-71.59	779	-22.62	
N8	-72.55	794	-22.80	
N9	-71.95	793	-22.53	
N10	-70.31	774	-22.16	
N11	-70.23	775	-22.04	
N12	-71.94	794	-22.67	
N13	-70.58	777	-22.49	
N14	-70.08	780	-21.89	
N15	-70.05	786	-21.64	
N16	-70.00	787	-21.83	
N17	-69.82	792	-21.43	
N18	-68.49	787	-20.49	
Q2	-73.48	773	-23.99	Q2-Q17, east from station N1 on F.H. 2440, 1/4 mile intervals.
Q2	-73.68	770	-24.26	
Q4	-73.66	769	-24.14	
Q5	-73.93	766	-24.43	
Q6	-72.75	745	-24.44	
Q7	-72.87	736	-24.91	
Q8	-74.58	860	---	
Q9	-74.80	864	---	
Q10	-74.85	861	---	
Q11	-73.82	742	-24.96	
Q12	-74.75	753	-25.12	
Q13	-74.21	744	-25.02	
O1	-73.31	773	-23.85	O1-O13, west from station N1 on F.H. 2440, 1/4 mile intervals.
O2	-83.41	767	-23.93	
O3	-74.77	778	-24.62	
O4	-73.71	761	-24.42	
O5	-73.08	748	-24.61	
O6	-73.87	768	-24.22	
O7	-75.23	789	-24.39	
O8	-74.95	786	-24.42	
O9	-74.72	784	-24.37	
O10	-74.43	786	-24.13	
O11	-73.70	782	-23.86	
O12	-72.89	776	-23.64	
O13	-72.95	777	-23.71	
O14	-73.11	780	-23.86	
O15	-72.17	772	-23.47	
O16	-70.37	755	-22.79	
O17	-70.48	758	-22.69	

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Locations
R1	-67.16	808	-18.81	R1-R8, east on sight
R2	-67.65	808	-19.36	line, from station 6.
R3	-68.02	814	-19.38	
R4	-68.13	814	-19.53	
R5	-67.83	803	-19.90	
R6	-67.84	804	-19.97	
R7	-67.94	803	-20.05	
R8	-67.97	804	-20.03	
R9	-68.23	808	-20.22	R16-R9, east on sight
R10	-68.32	810	-20.43	line, from station 4.
R11	-67.63	803	-20.13	
R12	-67.10	798	-19.83	
R13	-67.25	800	-19.84	
R14	-67.09	803	-19.42	
R15	-66.98	809	-18.90	
R16	-66.13	805	-18.27	
101	-66.97	817	-19.81	101 and 102, west of
102	-68.36	807	-19.76	station 8 at 500 foot
103	-68.43	764	-21.36	intervals.
104	-68.55	767	-21.30	103 and 104, west of
105	-68.77	795	-20.29	station 15 at 500 foot
106	-67.94	781	-20.30	intervals.
107	-67.52	775	-20.24	105-110 west of station
108	-66.93	778	-19.60	12 at 500 foot intervals.
109	-68.51	791	-20.40	
110	-67.43	780	-19.98	
111	-67.73	797	-19.51	
112	-69.03	822	-19.52	
113	-67.84	806	-19.51	
T1	-66.87	799	-18.94	T1-T8, on road west of
T2	-66.83	805	-18.59	station 6, 400 foot
T3	-66.03	803	-17.90	intervals.
T4	-65.34	804	-17.24	
T5	-63.73	808	-15.45	
T6	-62.77	810	-14.45	
T7	-63.05	816	-14.20	
T8	-63.23	803	-14.75	
U2	-63.17	803	-15.10	The Us, Vs, and Ws are
U3	-63.74	805	-15.60	on logging roads,
U4	-64.69	804	-16.49	approximately 1/4 mile
U5	-64.57	798	-16.66	east of the center of
V1	-64.64	810	-16.17	the anomaly.

Stn.	Drift Corrected Gravity (mgls)	Elev.	Bouguer Gravity (mgls)	Approximate Locations
V2	-64.53	800	-16.67	
W1	-64.63	797	-16.94	
V3	-64.59	792	-17.27	
V4	-64.25	797	-16.75	
V5	-64.40	802	-16.70	
W2	-65.22	797	-17.42	
W3	-65.83	793	-18.18	
X2	-68.49	848	-18.56	X2-X10, on road east of Camp 26, 600 foot spacings
X3	-67.53	830	-18.64	
X4	-67.63	822	-19.32	
X5	-67.17	808	-19.75	
X6	-67.28	805	-20.12	
X7	-67.73	803	-20.70	
X8	-69.53	828	-21.05	
X9	-67.73	804	-20.81	
X10	-66.19	798	-20.76	
Z21	-65.68	801	-27.86	Z21-Z23, on Petosky rail grade, north of Camp 26 road.
Z22	-65.05	795	-27.83	
Z23	-64.97	790	-28.19	
Z2	-71.36	802	-27.32	Z2-Z13, on F.H. 440, from intersection F.H. 2228 to F.H. 13.
Z2	-70.39	809	-26.60	
Z3	-70.39	809	-26.60	
Z4	-70.09	809	-26.70	
Z5	-69.47	810	-26.62	
Z6	-67.09	787	-25.50	
Z8	-65.13	779	-23.71	
Z9	-63.43	778	-21.63	
Z10	-63.27	787	-20.74	
Z12	-61.24	803	-17.85	
Z13	-61.27	807	-17.17	
S51	-63.27	824	-17.41	S51-S58, south on F.H. 13 from intersection F.H. 440.
S52	-62.73	813	-16.97	
S53	-63.40	806	-17.41	
S54	-65.19	809	-18.36	
S55	-65.34	796	-18.62	
S56	-69.77	838	-19.89	
S57	-72.06	849	-20.87	
S58	-68.66	778	-21.09	
59	-70.45	775	-22.09	
60	-78.10	854	-24.67	
61	-78.32	819	-25.69	

BIBLIOGRAPHY

BIBLIOGRAPHY

Bateman, Allan M. _Economic Mineral Deposits_. New York: John Wiley and Sons, Inc., 1955.

Bergquist, S. G. "The Pleistocene History of the Tahquahamon and Manistique Drainage Region of the Northern Peninsula of Michigan." Michigan Geological Survey Publication 40.

Dobrin, Milton B. _Introduction to Geophysical Prospecting_. New York: McGraw-Hill Book Co., 1960.

Frantti, Gordon E. "Geophysical Investigations in the Central Portion of Michigan's Upper Peninsula. _Mining Engineering_, Vol. 8 (1956).

Hamblin, W. K. "Cambrian Sandstones of Northern Michigan." Michigan Geological Survey Publication 51.

Nettleton, L. L. "Gravity and Magnetic Calculations." _Geophysics_, Vol. 7 (1942).

Paul, M. K. "Interpretation of the Gravity Anomaly Over a Causative Body with Circular Symmetry." _Geophysical Prospecting_, Vol. 20 (1972).

Zietz, Isidore, and Kirby, John R. "Aeromagnetic Map of the Western Part of the Northern Peninsula, Michigan and Part of Northern Wisconsin." Geophysical Investigations Map GP-750, U.S. Geological Survey, 1971.