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Relationship of Gravity Anomalies to a Drift Filled Bedrock Valley System in Calhoun County Michigan

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RELATIONSHIP OF GRAVITY ANOMALIES TO A
DRIFT FILLED BEDROCK VALLEY SYSTEM
IN CALHOUN COUNTY MICHIGAN

by

James W. Farnsworth

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
December 1980
Gravity geophysics along with well data were used to delineate and map the locations of buried river valleys in Calhoun County, Michigan. The valleys are filled with thick sequences of glacial-fluvial deposits which can serve as important aquifers.

One hundred and sixty-four gravimeter observations were made at approximately one-quarter mile intervals in a 35 square mile area. Four short-interval profiles were also established perpendicular to suspected valleys. A three-dimensional trend surface polynomial was fitted to the total Bouguer anomaly to approximate the regional effect of gravity. By comparing the observed residual gravity to theoretically derived anomalies, models were developed which approximated the shape of the bedrock topography.

Two main valleys were mapped with the use of gravity and well-log data. The topographic map of the bedrock surface indicates several tributaries and two possible saddles between the two valleys. Valley flow elevations indicate that locally, preglacial drainage was toward the southwest.
ACKNOWLEDGMENTS

The writer wishes to extend his sincere gratitude to Dr. Christopher J. Schmidt for his guidance, encouragement, and constructive criticism throughout the study. Thanks also go to Drs. William A. Sauck and W. Thomas Straw for their suggestions and review of the manuscript. Additionally, the writer would like to extend his appreciation to his fellow graduate students for their support and friendship. Particular gratitude is due William Johnston for his valuable assistance in the programming of the gravity data for the digital computer.

The field work in this study was done with considerable help from Paul Ciaramatero. Special appreciation is due him for his competent and valuable assistance.

This study was funded in part by a grant from The Graduate College, Western Michigan University. The writer is also grateful to Western Michigan University for the free use of the DECSYSTEM 10 computer.

Finally, the writer wishes to express his sincere thanks to Diane K. Farnsworth for her tireless encouragement and moral aid. To all these people, the writer extends his thanks.

James W. Farnsworth
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INTRODUCTION

Within glaciated regions, location of areas favorable for ground-water development often center around locating the trends of major buried bedrock valleys.

Prior to glaciation, what is now the sedimentary bedrock was exposed at the surface. Erosion by running water and mass wasting sculptured hills and valleys, some of these valleys serving as stream channels. The ice advance acted to at least partly fill the valleys with glacial drift. As the ice retreated, the glacial melt-waters were channeled into existing bedrock valleys. These bedrock valleys received large volumes of water derived from melting ice and precipitation, resulting in concentrations of coarse glacial materials within the valleys. Because of the porosity and permeability of the coarse materials they are generally excellent reservoirs for ground water. Many of these former valleys, after glaciation, are completely filled in, leaving little or no surface indication of their presence.

Although a bedrock map has been prepared for Calhoun County (Plate 6) (Wilmoth, Daniels, & Griest, 1977), because of the sporadic spacing of wells, it does not adequately define the bedrock surface. Where well information is insufficient, geophysical methods may be used to delineate bedrock features.

The primary objective of this thesis is to study the relationship between the dissected bedrock topography and the gravity field
in the west-central part of Calhoun County. To accomplish this objec-
tive, the effect of the regional gravity field must first be deter-
mined. The residual gravity which represents the influence of near
surface density changes, is found by removing this regional effect
from the total observed gravity. By using theoretical modeling tech-
niques, the source of the residual anomaly can be analyzed. Ulti-
mately a bedrock topographic and glacial till thickness map can be
constructed.

Previous studies of bedrock surfaces in Michigan (Klasner, 1964),
although in a different morainic system, have indicated that lateral
changes in density may be detected by the gravity method.
GEOGRAPHY OF THE AREA

The study area, shown in Figure 1, is located in Battle Creek and Leroy townships of Calhoun County. It lies between latitude 42° 11' N and 42° 17' N and longitude 85° 17' W and 85° 12' W. The area consists predominantly of privately owned farmland with some new residential area in Battle Creek township. The area is cut by U.S. Interstate 94 just north of the Leroy-Battle Creek township line. The majority of the area, however, is evenly divided by roads which follow section lines. Altitude of the land surface within the study area ranges from a high of 1,000 feet to a low of approximately 880 feet. Topographically the area is composed of gently rolling hills and swampy tracts with a maximum local relief of 40 to 50 feet.
Figure 1. Area of Investigation
GEOLOGY OF THE AREA

The area of investigation lies along the southern border of the Michigan Basin.

Information about the Precambrian geology is derived primarily from geophysics and a handful of deep oil wells. Throughout southwestern Michigan there is a broad positive gravity anomaly. This anomaly is extensive and reaches into northeastern Indiana where it is believed to be associated with magnetic anomalies originating from zones of basalt and mafic intrusions. These anomalies may represent the site of igneous activity along a Keweenawan age rift zone parallel to the mid-Michigan rift zone (Rudman & Blakely, 1965). Regional geophysical studies of Michigan (Hinze, Kellogg, & Merritt, 1971) indicate a strong negative magnetic anomaly (−600 gammas) and a positive gravity anomaly (+8 milligals) over the study area. The gravity anomaly is centered directly over the study area and localized within Calhoun County, but the magnetic anomaly can be traced for more than 75 miles along a northwest strike. Hinze, Kellogg, and O'Hara (1975) believed that this anomaly is caused by a dike-like feature or group of dikes which have reverse remanent magnetization and a pipe-like feeder centered under the gravity anomaly. They further concluded that the density contrast between the mafic and high-grade metamorphic rocks and the surrounding felsic and low- to medium-grade metamorphics is the probable cause of the regional gravity high.

Bedrock is composed predominately of Mississippian Coldwater shale. Toward the northeast corner of the area, Marshall sandstone
forms a thin veneer on top of the Coldwater. Both formations have been dissected by preglacial waters and dip gently northeast toward the center of the Michigan Basin.

The Tekonsha moraine and its associated outwash plains constitute the glacial covering. The Tekonsha moraine in Calhoun County was formed by the Saginaw lobe of the middle Wisconsin glacial stage (Leverett & Taylor, 1915). The topography of the Tekonsha moraine has been described as subdued, and is characterized by small knobs and kettles (Leverett & Taylor, 1915). The moraine appears to have been dissected in some areas by glacial drainage. It is composed of loose textured sand and gravels with isolated areas of finer clay-rich material (Shah, 1972). The high proportion of sand is derived from the Marshall sandstone, located to the northeast, as well as from the sorting of finer material during deposition. The Tekonsha moraine is bordered by outwash plains and lines of glacial drainage (Leverett & Taylor, 1915).
FIELD WORK

A Worden exploration type gravimeter, number 944, was used for this study. The calibration constant of the meter is .0970 milligals per scale division. The meter reads the relative acceleration of gravity to within .01 milligals. The acceleration of gravity at the earth's surface is normally about 980 gals. Thus .01 milligals is approximately one part in one hundred million of the normal gravity of the earth.

The Worden gravimeter is temperature and barometrically compensated and controlled. Even with these controls the instrument experiences drift variations. These drift effects are caused by fluctuating earth tides, temperature changes, spring fatigue, and rapid changes in barometric pressure. By reoccupying a base station or a series of base stations and rechecking the gravity readings, the drift variations may be accounted for. Base station readings were reoccupied at least once per hour during the course of the survey.

Base stations were located at convenient locations near the center of each subarea of the total survey. The primary base station was located near the center of the total survey area, longitude 85° 15' west, latitude 42° 15' north. The subbase stations were then tied to the primary base station by occupying both the subbase station and the primary base at the beginning of the survey and then assuming no relative changes in drift from one base station to another. A daily drift curve was plotted for the base stations and field station values were corrected from this curve.
Gravity stations were spaced at approximately one-quarter mile intervals. Four short-spaced profiles were located across the deepest known areas of the buried glacial valleys. The station interval on these profiles was approximately one-eighth mile. All gravity stations were tied to the base stations by regular base-check readings. The locations of the profiles and stations are shown on Figure 2.

Accurate gravity reduction requires accurate knowledge of station elevations. Station elevations were surveyed with the use of a Fuji-Path Instrument automatic level, AL-21. Two U.S. Geological Survey bench marks were used to establish elevation control. All survey traverses closed to a precision of .62 feet. Horizontal distances were determined by a combination of automobile odometer, topographic maps, measuring tapes, and stadia interval. Special consideration of horizontal distances were given to north-south locations and detail profiles. Distances were measured only from road intersection to road intersection to eliminate compounding of error.
Figure 2. Location of Gravity Profiles
REDUCTION OF DATA

Introduction

In order for the observed gravity data to be useful, several corrections must be made. These corrections are made to each gravity station with the end result being a Bouguer gravity anomaly. The object of all these corrections is to develop a picture or map of the relative gravity variations within the study area which depends only upon lateral changes in the densities of the subsurface rocks below a chosen datum plane.

A DECSYSTEM 10 digital computer was used to calculate the Bouguer gravity anomaly values. The Bouguer gravity anomaly is affected by surface and near surface features. Corrections were made according to the following equation:

\[
\text{Bouguer gravity anomaly} = g_o - g_l + g_f - g_s + g_t
\]

where:

- \( g_o \) = observed gravity
- \( g_l \) = latitude correction
- \( g_f \) = free-air correction
- \( g_s \) = Bouguer slab correction
- \( g_t \) = terrain correction
**Observed Gravity**

The observed gravity values were found by first correcting for drift. All gravity values observed during a day were plotted against time. The resulting curve which passes through the reoccupied points was used to determine the amount of systematic time variations in gravity or drift. These corrected values were then multiplied by the calibration constant of the gravity meter, .0970 milligals/division.

The base station was reoccupied on the average of once per hour. If the change in drift reading was found to be greater than one division, about .1 milligal, the stations that were occupied during the course of that hour were reoccupied and read again.

**Latitude Correction**

Latitude corrections are made to account for the systematic changes in gravity from the equator to the poles. Both the fact that the earth is not a perfect sphere and the differential centrifugal forces associated with its spin, cause an increase in gravity away from the equator toward the poles.

The International Formula for the variation of gravity, \( g \), with latitude, \( \phi \), was used:

\[
g = 978049. (1 + .0052884 \sin^2 \phi - .0000059 \sin^2 2\phi)
\]

By differentiating \( g \), with respect to \( \phi \), the rate of change of gravity, \( w \), with north-south movement, can be obtained. According to Dobrin (1976), \( w = 1.307 \sin 2\phi \) milligals/mile. In this study,
latitude corrections were made from latitude 42° 14.8' North. In the study area, \( w = 0.0002464 \) milligals per foot or 1.301 milligals per mile.

**Free-Air Correction**

The free-air correction takes into account the relative changes in elevation between stations. The gravitational attraction of the earth, as a whole, can be considered as if its mass were concentrated at its center. The change in gravitational attraction is proportional to the inverse-square of the distance to the center of the earth or some chosen datum. This correction for elevation differences was calculated by multiplying the difference in elevation between the gravity station and the datum, by the vertical gradient of gravity, \( 0.09406 \) milligals per foot. This correction is independent of the density of the material between station and datum.

**Bouguer Slab Correction**

The purpose of the Bouguer slab correction is to remove the gravitational effect of the material between gravity station and datum. If this horizontal layer has a density of \( \rho \) the gravitational attraction will be equal to \( 2\pi\gamma \rho h \) or \( 0.01277\rho h \) milligals per foot, where \( \rho = \) density, \( \gamma = \) universal gravitational constant, and \( h = \) the difference in elevation between gravity station and datum. This Bouguer correction is highly dependent upon the density and datum chosen for the slab.
In order to minimize the effect of changes in topography and thickness of slab, a datum of 888 feet above mean sea level, the elevation of the lowest gravity station, was used. The heterogeneous nature of the glacial material produces both lateral and vertical differences in density. The variation of height of water table also causes variations in densities. By minimizing the thickness of the Bouguer slab (using the lowest gravity station elevation), the effect of any error in choice of density was kept at a minimum.

The choice of 2.05 gm/cc as a density value was made by an indirect method proposed by Nettleton (1939). A traverse was established over an area of topographic relief with the elevations and distance between stations measured accurately. The topographic profile and the Bouguer anomaly were compared with several different densities being assumed for each set of computations. The density value which produced a gravity profile with least correlation with topography was chosen. One disadvantage of this method is that it only provides density information for near-surface material. By using the highest possible datum for the Bouguer slab, error in the density of the slab was minimized.

Terrain Correction

In order to test the necessity of terrain corrections, a station in a region of maximum relief was evaluated. The terrain correction which was done by using Hammer's (1939) graticule method, was found to be .03 milligals. This low value indicated that the local relief was too little to cause significant terrain effect, thus terrain
corrections were not incorporated into the Bouguer anomaly calculations.
PRECISION OF BOUGUER REDUCTIONS

Four primary factors may introduce errors in the calculation of the Bouguer anomaly:

1. Errors involved in obtaining observed gravity readings.
2. Errors involved in determining station latitude.
3. Errors involved in determining station elevation.
4. Errors involved in determining the density of Bouguer slab (glacial drift).

By reobserving selected stations several times on the same and different days it was possible to obtain an estimate of the precision of the instrument and the ability of the instrument reader to use the gravity meter properly. Seven stations were reoccupied on at least two different days and three were reoccupied at least twice on the same day, with proper correction for drift. A maximum difference of .4 meter divisions or approximately .04 milligals was recorded. The standard deviation for the gravity reobservation is ± .02 milligals, based upon these seven repeat observations.

Latitude measurements using a 7\textsuperscript{1/2} and 15 minute U.S.G.S. topographic quadrangles can be made to within an accuracy of 150 feet and 280 feet, respectively. The maximum error introduced in this manner is .04 milligals for 7\textsuperscript{1/2} minute and .06 milligals for 15 minute at .0002465 milligals per foot. On the density profile and the four detail profiles a measuring tape and/or stadia interval were used in determining the latitude of each station. This improved the accuracy
and precision.

Errors in elevation affect the free-air and Bouguer corrections. By the loop method the maximum misclosure was .62 feet. The maximum miss of survey lines run from two different geodetic bench marks was .35 feet over a distance of eight miles. If a maximum error in elevation of .62 feet were introduced it would cause an error of .06 milligals in free-air correction and a .04 milligal error in Bouguer gravity anomaly.

Since the density used in the Bouguer slab correction was determined by comparison of gravity profile and topographic profile, the degree of error involved is directly related to the degree of relief within the study area. The total range in elevation over the entire area is approximately 120 feet. Locally however, relief is rarely as much as 50 feet. Since topographic features sometimes are of anomalous lithology, the determined density may not be representative of the heterogeneous glacial drift as a whole. If, for example, the average density of the glacial material is off by .25 gm/cc, over a flat surface, this error would be constant. In areas of relief, however, this error would not be constant and deviations in Bouguer gravity would occur. Klasner (1964) estimated the error involved in this method of density determination by multiplying the magnitude of error per foot for each .1 gm/cc error in drift density. By this method, error in this study is:

\[ E = 0.001277 \cdot \Delta \rho \cdot \Delta h \]

where:
.001277 = the magnitude of error in milligals per foot for each .1 gm/cc error in density.

\( \Delta \rho \) = assumed error in drift density.

\( \Delta h \) = maximum local relief in feet.

This would result in an error of ± .16 milligals. This error would be detectable by its correlation with topography.

By combining all possible maximum errors a total error of ± .28 milligals is possible at any one station. A combination of all maximum degree of errors, all the same sign at the same time, however, is improbable.
The Bouguer gravity anomaly map (Plate 1) indicates the presence of a northwest-southeast oriented nose. The regional gravity decreases from .50 milligals in the southeast quarter of the map to -7.50 milligals in the north. This gravity high is in agreement with the Bouguer gravity map for the southern peninsula of Michigan (Hinze et al., 1971) in both shape and amplitude. The Michigan map which encompasses the entire anomaly, indicates that it is roughly oval in shape and oriented in a northwest-southeast direction.

Slight inflections in the form of the Bouguer gravity anomaly map may be seen in the north and northwest regions as shown in Plate 1. These inflections are probably caused by differences in bedrock topography.
SEPARATION OF RESIDUAL ANOMALIES
AND REGIONAL ANOMALIES

Introduction

The Bouguer gravity map (Plate 1) represents the total gravity of the area and the effect of the horizontal variations in the density of the subsurface material within the earth. This variation in density in turn affects the relative change in the acceleration of gravity. In order to delineate the shallow, near surface changes in density and acceleration of gravity, the larger deep-seated regional features and their effect on total Bouguer gravity must be removed. In order to approximate this deep regional gravitational feature, a three-dimensional trend surface was fitted to the Bouguer gravity anomaly data. A "best-fit" surface was defined by the least-square criterion. The residual gravity anomaly was then acquired by taking the difference between the total Bouguer anomaly and the regional anomaly, represented by the three-dimensional trend surface at each station.

Three-Dimensional Trend Surface Method

The trend surface algorithm used in separation of the residuals follows that of Davis (1973). The principle of the method is to pass a curve through a number of points so that the sum of the residuals is a minimum. To illustrate, by assuming a second degree polynomial of the form,

\[ G = a + bx + cy^2 \]

to n number of points of observations, \((x, y, z), (x_2, y_2, z_2)\).
where \( x^1, y^1, \) and \( z^1 \) represent longitude, latitude, and Bouguer gravity value, respectively, a close approximation of the observed gravity value, \( g \), may be determined. The sum of the squares of the residuals (\( \Sigma r^2 \)) is given as follows:

\[
\Sigma r^2 = \Sigma (g - G)^2 = \Sigma (g - a - bx - cy^2)^2
\]

where:

- \( g \) = the observed gravity value.
- \( G \) = the regional gravity value.
- \( r(x^1, y^1, z^1) \) = the residual gravity value at point \( i \).

To comply with the principle of least square, the summation of the squares of all the residuals should be a minimum. For the sum of the residuals to be a minimum, the total differential of \( \Sigma (g - a - bx - cy^2)^2 \) is equal to zero.

Thus:

\[
\begin{align*}
\frac{\partial (\Sigma r^2)}{\partial a} &= \frac{\delta (\Sigma r^2)}{\delta a} = 0 \\
\frac{\partial (\Sigma r^2)}{\partial b} &= \frac{\delta (\Sigma r^2)}{\delta b} = 0 \\
\frac{\partial (\Sigma r^2)}{\partial c} &= \frac{\delta (\Sigma r^2)}{\delta c} = 0
\end{align*}
\]

or:

\[
\begin{align*}
\frac{\delta (\Sigma r^2)}{\delta a} &= \Sigma 2(g - a - bx - cy^2) = 0 \\
\frac{\delta (\Sigma r^2)}{\delta b} &= \Sigma 2x(g - a - bx - cy^2) = 0 \\
\frac{\delta (\Sigma r^2)}{\delta c} &= \Sigma 2y^2(g - a - bx - cy^2) = 0
\end{align*}
\]

by rearranging in terms of \( a, b, \) and \( c \):
The three above equations may be simultaneously solved and the three coefficients (a, b, and c) determined by solving by matrices as follows:

\[
\begin{bmatrix}
 n & \Sigma x & \Sigma y^2 \\
 \Sigma x & \Sigma x^2 & \Sigma x y^2 \\
 \Sigma y^2 & \Sigma x y^2 & \Sigma y^4
\end{bmatrix}
\begin{bmatrix}
a \\
b \\
c
\end{bmatrix}
=
\begin{bmatrix}
 \Sigma g \\
 \Sigma x g \\
 \Sigma y^2 g
\end{bmatrix}
\]

The above fits a first degree equation for n points or stations. In a similar manner, higher degree equations can be computed to fit a set of gravity values. Solving this matrix can be quickly and easily done by the use of a digital computer.

The validity of the three-dimensional trend surface method depends upon two assumptions.

1. That a polynomial equation can adequately describe the regional Bouguer gravity.

2. That the proper polynomial order was chosen.

The second of these two assumptions is a subjective decision made with the need in mind that the polynomial order must be of a high
enough order to approximate the broad regional effect, but not sufficiently high to minimize or eliminate the residual entirely.

Unless a very closely-spaced grid of gravity stations is used, there is a loss of detail that may be geologically significant. If the area being considered is fairly large, one soon reaches a point where decreasing the size of the grid unit becomes prohibitively difficult and expensive, particularly if the stations are to be placed at the side of roads. In any gridding, it is necessary to interpolate a grid value between points of observed values, making an assumption that the value changes between points in some particular way. Errors may be introduced where this assumption is invalid.

Several three-dimensional trend surfaces were computed for the regional Bouguer anomaly. These included equations of the first, second, third, fourth, and sixth order. By comparing profiles of the observed Bouguer anomaly and the various polynomial curves (Figure 3), and examining their fit, the third degree surface was chosen as the best approximation (Plate 2).

Plate 3 illustrates the residual gravity anomalies from the fourth degree surface. In general, orientations of anomalies closely resemble the third-degree surface. There are, however, considerable differences in the magnitude and shape of the anomalies.

The residual gravity lows correspond to areas of bedrock valleys that have been filled with glacial deposits. The lateral variation from the less dense glacial material with its greater amount of pore space to the bedrock with its greater density, causes variations in gravitational attraction. These negative deviations in the
Figure 3. Profile of Bouguer Anomaly and Least Square Fits
acceleration of gravity from the regional gravity anomaly are indicated as lows on the residual gravity maps.

The central gravitational high in both the third and fourth order residual maps is probably due to either higher elevation on the bedrock surface or structures within the sedimentary column. Water-well data do indicate a rise in bedrock surface elevation over the central gravitational high. The lack of deeper wells further into the sedimentary column prevents a more thorough understanding of what effect, if any, the deeper stratigraphy may have on the gravitational acceleration.

The anomalously high gravity values at the edges of the area, particularly in the third order residual map, can be largely attributed to errors produced in using a low order polynomial equation.
Theoretical gravitational models can be used to aid in the interpretation of buried features. Since many of the features of interest are horizontally linear they can be approximated by a two-dimensional form of analysis. Talwani, Worzel, and Landisman (1959) have formulated a method by which the shape of a two-dimensional body is approximated with a vertical polygon, and an analytical expression is obtained for the gravitational attraction of that polygon. These modeled bodies are assumed to be infinite in directions parallel to their linear trend. Although models derived from such analysis may not make the calculated anomaly look exactly like the observed residuals, a comparison with the actual anomaly can be made. The closeness of fit between the theoretical and actual body depends upon the accuracy of the dimensions, depth of the polygon, and whether the chosen density contrast between the body and host rock is correct. The theoretical approximation can also be made more accurate by increasing the number of sides of the polygon which describes the body. By this method the vertical component of gravity due to the theoretical body may be obtained at any point. Neither the size nor the position is limited.

By establishing a coordinate system to locate the points at which the gravity is to be computed and the depth of the vertices of the polygon, the digital computer can solve for the complex integral expression of the vertical gravity component.
In accordance with the method described by Talwani et al. (1959), in Figure 4 let P be the point where the gravitational attraction will be calculated. P lies within the x-z plane, as does the polygon. The z direction or vertical is positive downward and $\theta$ is measured from the horizontal x-axis downward.

The vertical gravitational component at the origin (P) for a two-dimensional body or polygon is equal to:

$$2\gamma \rho \int zd\theta$$

where $\gamma$ is the universal gravitational constant, $\rho$ is the density contrast of the body, $z$ and $\theta$ are the respective distance and angle parameters which define the size and shape of the body, the line integral being taken around the periphery of the polygon.

To illustrate, the gravitational contribution of the area above side AG, can be computed by extending the side upward to meet the x-axis at Q creating angle $\phi_i$. Let PQ = $a_i$, then,

$$z = x \tan \theta$$

for any point R on side AG and

$$z = \frac{a_i \tan \theta \tan \phi_i}{\tan \phi_i - \tan \theta}$$

for AG,

$$\int z d\theta = \int \frac{a_i \tan \theta \tan \phi}{\tan \phi_i - \tan \theta} d\theta = z_i$$
Figure 4: Theoretical Model (Modified from Talwani et al., 1959)
The formula for the gravitational attraction due to the whole polygon at any point along the profile is equal to:

\[ V = 2\gamma p \sum_{i=1}^{n} Z_i, \]

where:

- \( \gamma \) and \( p \) are the same as above.
- \( Z_i \) = the result of the evaluation of the line integral over the \( i \)th side of the polygon.
- \( n \) = number of sides of the polygon.
- \( V \) = total gravitational effect of the polygon.

Four profiles were located across areas where well data had indicated the possibility of buried bedrock valleys. The locations of the profiles are indicated on Figure 2. The number of wells located near the profiles were inadequate to define the dimensions and extent of the apparent bedrock valley.

For each of the four profiles, the observed residual gravity profiles determined from the third order of the three-dimensional least-square interpretation were compared to the two-dimensional body anomaly computed by the Talwani et al. (1959) method.

A density of 2.65 gm/cc (Michigan State University unpublished data) was used for the Coldwater shale. The Coldwater shale constitutes a major portion of the bedrock in the area with a thin veneer of Marshall sandstone covering it in the northeast quarter of the area. The density of the material filling the bedrock valleys was found to vary from 2.23 gm/cc to 2.44 gm/cc. These densities
were determined by designing the models to comply with the shape of the residual profiles and depth at control wells and then adjusting the drift density in order that the theoretical anomaly for each point matched the observed anomaly.

Profile A-A' (Figure 5) was determined to have a density differential of .27 gm/cc. This gives 2.38 gm/cc as the density of the material filling the bedrock channel. Depth control was provided by a water well approximately .5 miles south of A, which indicated that the elevation of bedrock at that location was 880 feet. The total anomaly was determined to be nearly .92 milligals.

Profile B-B' (Figure 6) was located 1 mile east of profile A-A'. Depth as in A-A' was established by well data and a density contrast of .21 gm/cc was determined. This gives a density of 2.44 gm/cc for the material filling the bedrock channel. A total anomaly of .55 milligals was determined for this profile. The difference in total anomaly between this anomaly and the .92 milligals in A-A' can be attributed to the shorter length of profile B-B'. If B-B' had been extended to the flanks of the anomaly a greater anomaly implitude would have been indicated.

Profile C-C' (Figure 7) was located over a bedrock valley which trends north-south in the area just south of U.S. Interstate 94 in southern Battle Creek township. The shape of the valley and the density of glacial fill were determined in the same manner as in the two previous profiles. A density differential or contrast of .37 gm/cc was determined for this comparison profile.
Figure 5. Observed and Computed Residual Gravity Anomaly, Profile A-A'
Figure 6. Observed and Computed Residual Gravity Anomaly, Profile B-B'
Figure 7. Observed and Computed Residual Gravity Anomaly, Profile C-C'
There was a density differential of .42 gm/cc between bedrock and glacial valley fill along profile D-D'. This profile is .5 mile north of and parallel to C-C' and also trends across the same bedrock channel. Figure 8 illustrates the results that were obtained.

Without the depth control which was supplied by well logs, an accurate determination of the size, shape, and density differential would not have been possible. Knowledge of at least one of these variables is required in order to define the best solution from the infinite number of combinations of variables possible. This dependence upon well data for determination of shape and density differential makes the accuracy of well logs vitally important.

A theoretical test relating density of the glacial drift to its composition in terms of sand and gravel was made by McGinnis, Kempton, & Heigold (1963). In this study, the systematic packing of grains represented by large and small spheres, and their influence on porosity was considered. Their results as indicated in Figure 9, in terms of percent sand and gravel, show that the drift densities are highest for mixed-grain size material, such as sand or clay. The energy levels in this diagram refer to the type and degree of packing of the glacial material. The highest energy level indicates a situation in which the greatest amount of pore space is available. The lowest energy level indicates the greatest amount of packing and least amount of pore space. A density of 2.38 gm/cc, the value of drift for profile B-B', yields a value of either 36% or 90% sand and gravel. These values were taken from the lowest energy level (satisfaction) because the sediments filling the valley are buried by over
Figure 8. Observed and Computed Residual Gravity Anomaly, Profile D-D'
Figure 9. Theoretical Drift Densities Versus Percent Sand and Gravel (After McGinnis, et al., 1963)
200 feet of glacial drift. The lowest value of 2.23 gm/cc determined for profile D-D' is off scale for the lowest energy level (saturated) and for the highest energy level (dry). For the lowest energy level (dry), 2.23 gm/cc yields a sand and gravel percentage of either 38% or 90%. The highest energy level (saturated) value for 2.23 gm/cc is either 57% or 73% sand and gravel. Besides a possible difference in composition, the greater density of drift along profile B-B' than in profile D-D' might be explained by the greater degree of saturation due to a higher water table in the area of profile B-B'.

Lovan (1977), in a study of the glacial till in the area, found that sand size grains averaged 75% of total composition by weight percent. His sampling was done by trenching into outcrops of the till. This author, through qualitative analysis of several pits and outcrops, arrived at the same general high sand composition. Leverett (1915) described the drift in this area as having a high sand and gravel composition. He concluded that the sand is derived primarily from the Marshall sandstone.
COMBINED GRAVITY DATA AND WELL LOG INTERPRETATION

One must recognize that the residual gravity maps illustrate not the bedrock elevation but rather lateral changes in the acceleration of gravity caused by density differentials between bedrock and near surface glacial material. Both well data and data derived from the theoretical models were used in mapping the bedrock surface (Plate 4). The third-order residual gravity map was used in a subjective manner to complete the map in areas where well and model data were absent or lacked continuity. In most areas well control was inadequate, and gravity data aided in mapping the bedrock surface. In areas of sufficient well control, the gravity interpretation was further supported by the well log data.

Two major bedrock valleys are present within the study area. One valley trends east-west through the southern half of the area. The northern bedrock valley trends roughly north-south through profile C-C' and D-D' north of the Leroy-Battle Creek township line. Two saddles with about 100 feet of relief join the two valley systems in the central and east-central portion of the study. The orientation of tributaries indicates that the probable direction of flow was toward the southwest. The bedrock surface map of Calhoun County prepared from well record alone (Wilmoth et al., 1977), indicates the same direction of drainage.

The southern valley has a maximum relief of 245 feet in the vicinity of profile A-A'. This is the lowest bedrock elevation
within the study area (655 feet) and is a further indication that

drainage was toward the southwest. The valley which lies in the

northern section of the area obtains a maximum relief of 210 feet

with a minimum bedrock elevation of 680 feet along profile C-C'.

A map illustrating the thickness of glacial material was made

by subtracting the bedrock elevations from the corresponding surface

elevations (Plate 5).
SUMMARY

The bedrock topography has been successfully mapped by the gravity method in west central Calhoun County. Two primary valleys were delineated with numerous smaller tributaries also defined. By using both gravity and well log data a bedrock surface map has been prepared along with a glacial thickness map.

Five orders of least square polynomials were used in an attempt to prepare a regional gravity surface map. The higher degree equations approximated the total Bouguer anomaly to the extent that little residual anomaly remained, and lower orders tended to distort the gravity values along the edges of the study. The third order was determined to best fit this surface. The anomalies caused by the bedrock valleys were isolated by subtracting the regional surface from the total Bouguer anomaly.

Four gravity profiles established perpendicular to suspected bedrock channels were analyzed by the Talwani et al. (1959) method of two-dimensional theoretical modeling. All four profiles were established in areas of at least some well control. By using theoretical modeling and well control, the depth and the configuration of the bedrock surface and buried channels were determined.

The use of all available information, geophysical, well logs, and densities, were necessary to accurately delineate the buried river channels. This process was found to be a fast, accurate, economical, and ultimately successful method for defining buried river
valleys in Calhoun County, Michigan.

Buried river channels are extensive throughout the study region. The low density glacial drift which fills the valleys is composed predominantly of porous sands and gravels. This concentration of porous and permeable material could be an important source of ground water in the future for possible southward expansion of Battle Creek or farm irrigation.
REFERENCES


Wilmoth, S., Daniels, D., & Griest, S. D. *Bedrock topography and geologic map, Calhoun County, Michigan*. Unpublished map, Department of Public Works, Planning Department and Health Department, Calhoun County, Michigan, 1977.
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Wilmoth, S., Daniels, D., & Griest, S. D. Bedrock topography and geologic map, Calhoun County, Michigan. Unpublished map, Department of Public Works, Planning Department and Health Department, Calhoun County, Michigan, 1977.
RESIDUAL GRAVITY MAP

CONTOUR INTERVAL = Q1 mgals
THREE DIMENSIONAL TREND SURFACE METHOD
THIRD DEGREE FIT

PLATE NO. 2

MILES

0 1/4 1/2 3/4 1
RESIDUAL GRAVITY MAP
THREE DIMENSIONAL TREND SURFACE METHOD

CONTOUR INTERVAL = 0.1 mgals
FOURTH DEGREE FIT

PLATE NO. 3
TOPOGRAPHY OF THE BEDROCK SURFACE

CONTOUR INTERVAL = 25 FEET
ELEVATION IN FEET ABOVE SEA LEVEL
GRAVITY STATION •
WELL LOCATION •
TOPOGRAPHY OF THE BEDROCK SURFACE

based upon well data

ELEVATION IN FEET ABOVE SEALEVEL

CONTOUR INTERVAL  40 FEET

PLATE NO. 6