Mapping Buried Bedrock Topography with Gravity

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ABSTRACT

In the formerly glaciated Midwest, bedrock formations commonly are denser than overlying glacial sediments. Thus, gravity anomalies have a direct relationship to bedrock topography. Where the density contrast between the glacial sediments and the bedrock is known, the anomalies can be used to map the bedrock configuration if they can be isolated from gravity anomalies originating elsewhere in the geologic section. A method of isolating bedrock topography gravity anomalies is suggested based upon known bedrock elevations obtained from drillhole data. A regional gravity anomaly map is prepared by subtracting the excess gravitational effect of the known bedrock relief above a datum from the observed gravity anomalies at all drillhole sites. The regional gravity anomaly map is subtracted from the observed anomaly map to obtain a residual anomaly map reflecting the bedrock topography. The bedrock configuration can be calculated directly from this map. This method of isolating bedrock topography anomalies was found to be superior to the use of cross-profiling and least-squares polynomial approximation procedures in a study of Kalamazoo County, Michigan. The bedrock topography map of this County determined by the gravity-geologic method shows a complex bedrock topography and drainage system.

INTRODUCTION

In formerly glaciated areas, glacial sediments are often the only available source of potable ground water because bedrock formations are either poor aquifers or contain poor quality water. Glacial sediments in bedrock channels have proven to be favorable sites for locating ground-water aquifers in many areas because bedrock valleys have a greater probability of containing thicker sections of sand and gravel in view of the increased column of glacial drift and because they are often the loci of preserved or buried deposits of outwash.

Many local geological studies based on well records indicate a widespread occurrence of well developed valley systems in bedrock formations of the glaciated Midwest. Commonly these valleys have limited or no surface expression, and thus must be delineated by subsurface exploration, either through drilling or geophysical exploration. Geophysical exploration methods are particularly useful for detection of such valleys because drilling is slow and expensive. Electrical resistivity and seismic methods have been employed for this purpose for many years. Recently, however, gravity methods have been increasingly applied.

In most geologic situations, bedrock formations are denser than overlying glacial sediments. As a result, depressions in the bedrock surface filled with sediments cause a deficiency in gravity in comparison with bedrock topographic highs. The correlation between bedrock topography and gravity, therefore, renders the method suitable for mapping subsurface bedrock topography especially in cases where there is significant bedrock relief or where there is a well-developed hydromorphic pattern. Buried bedrock channels can be identified by the sinuous pattern of the correlative anomaly on gravity anomaly maps. In some cases, however, buried bedrock channels are difficult or impossible to delineate by the gravity method because the density of the glacial deposits is equal to or exceeds that of the adjacent bedrock (McGinnis et al., 1963; Lennox and Carlson, 1967).

The gravity method has been used not only to locate buried bedrock valleys, but also to define the configuration of the bedrock surface, particularly where some geological control is available (Klasner, 1964; Hall and Hajnal, 1962). A bedrock topography map is valuable, not only in groundwater studies, but also in engineering and geomorphic investigations.

In this paper the scope of the gravity method is expanded by developing a technique of computing bedrock topography from a combination of gravity observations and well data. The method is illustrated by its application to a drift covered area in Kalamazoo County, Michigan. This area was selected because of its economic dependence upon ground-water resources and the availability of ample well data for control.

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GRAVITY-GEOLOGIC METHOD OF MAPPING BURIED BEDROCK TOPOGRAPHY

The Problem

Mapping of buried bedrock topography by the gravity method is subject to several limitations imposed by inherent characteristics of the method and by the nature of the source of the gravity anomalies. A primary difficulty results from the range of density contrasts between the bedrock and the glacial sediments. Published densities indicate that bedrock formations exhibit a wide range of densities even within formational units. However, the principal uncertainty in density contrasts in the Midwest which is underlain by low-dip Paleozoic sedimentary rocks is derived from the wide spectrum of densities in the glacial sediments. This, of course, relates to glacial sediments being extremely heterogeneous, with sharp lateral and vertical variations of their physical properties. As a result, though negative gravity anomalies are anticipated, bedrock channels may be characterized by unmeasurable or even positive gravity anomalies (Lennox and Carlson, 1967). Also, the relative amplitudes of gravity anomalies may not be indicative of the bedrock relief. This problem is compounded by generally limited data on glacial sediment densities. Furthermore, the precision of the bedrock configuration interpretation from gravity anomalies is directly dependent upon the validity of the assumed density contrast between bedrock and the glacial sediments and upon the availability of auxiliary geologic information on depth of the bedrock surface.

Assuming that a known density contrast exists between the bedrock and glacial sediments, the major problem in application of the gravity method to mapping buried bedrock topography is the isolation of anomalies due only to this source. Gravity anomalies from density variations within the glacial drift and underlying formations are superimposed on the anomalies derived from bedrock topography. Therefore, it is necessary to isolate the residual anomalies caused only by bedrock topography. In the simplest of cases, this can be approached through graphical methods such as smooth contouring and profiling. In more complex situations, it is necessary to utilize an analytical technique such as least-squares polynomial approximation (Agocs, 1951). In all cases, the isolation of anomalies is a somewhat subjective process which can distort the areal configuration and amplitude of the bedrock topography anomalies, thus leading to interpretational errors. The problem, therefore, is to develop a procedure for isolating gravity anomalies due to buried bedrock topography which will minimize errors in determining the bedrock configuration from gravity anomalies.

Explanation of Method

The gravity-geologic method of mapping buried bedrock topography is based on isolating the gravity anomalies attributed to bedrock topography by utilizing available information on bedrock configuration obtained from drillholes or supplemental geophysical data. The lowest known elevation on bedrock surface is selected as datum. A regional gravity anomaly map is prepared by subtracting the excess gravitational effect, resulting from the presence of bedrock instead of glacial sediments above the datum, from the gravity anomaly at all drillhole sites. The regional gravity anomaly map is subtracted from the gravity anomaly map to obtain a residual anomaly map reflecting the deviation of the bedrock from the assumed datum. The bedrock configuration can be calculated directly from the residual gravity anomaly values and the assumed density contrast.

The method is illustrated in Figure 1. For purposes of illustration a gravity and geologic profile is shown, but the method obviously can be applied to maps as well as profiles. The gravity anomaly profile (A) is obtained by reduction of gravity observations in the normal manner. Observations are made at drillholes and regularly distributed sites between the drillholes. The excess gravitational effect of the bedrock above the datum relative to the glacial sediments is calculated at each drillhole assuming the bedrock above the datum can be represented by a horizontal slab using the equation:

$$g_n = 2 \pi \gamma H_n (\sigma_b - \sigma_d) \qquad (1)$$

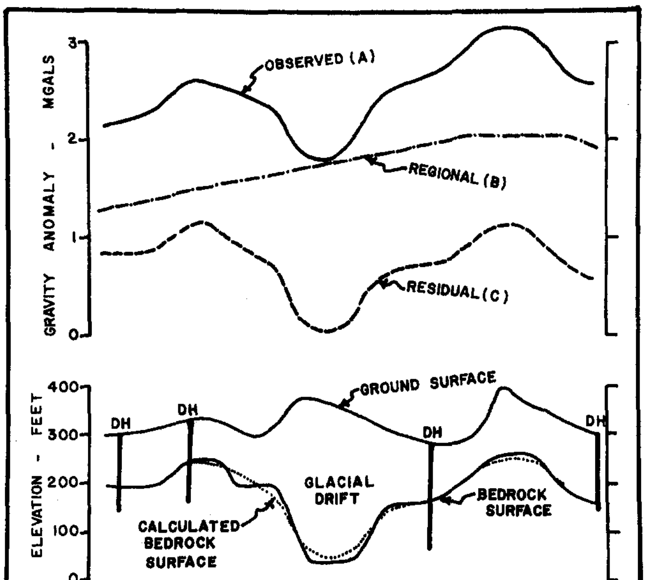

Fig. 1. Gravity-geologic residual gravity anomaly method.

where g_n = the excess gravitational effect at the n^{th} drillhole,

γ = gravitational constant,

H_n = height of the bedrock surface above the datum at the n^{th} drillhole, and

$(\sigma_b - \sigma_d)$ = difference in density between the bedrock and the glacial sediments.

The excess gravitational effect at each drillhole is subtracted from the gravity anomaly to obtain the regional anomaly profile (B). The regional anomaly (B) is then subtracted from the anomaly (A) at all observation sites resulting in the residual gravity anomaly profile (C) which represents the gravitational effect of the bedrock above the datum in excess of the glacial sediment effect.

The elevation of the bedrock above the datum can be computed from the residual values assuming the bedrock is in the form of an infinite horizontal slab by rearranging equation (1):

$$H_m = [g_{r_m} / 2 \pi \gamma (\sigma_b - \sigma_d)] + D \qquad (2)$$

where

H_m = height of the bedrock surface above the datum at the m^{th} observation site,

g_{r_m} = residual gravity anomaly at the m^{th} observation site,

D = elevation of assumed datum above sea level,

and the other terms are as described in equation (1). The results of this calculation are compared to the theoretical bedrock profile in Figure 1.

A number of assumptions are made in calculating the residual gravity anomaly and the bedrock configuration from the residual anomaly which may impose serious limitations on precision of the results. The following assumptions are made:

1. The number and distribution of bedrock drillholes are assumed to be sufficient to define the regional gravity anomaly pattern, whose anomalies are broad and smooth with respect to those derived from the bedrock topography.

2. The known density contrast which exists between the bedrock and the glacial sediments is of sufficient magnitude to produce measurable anomalies. In areas of limited density information it may be necessary to assume a constant density contrast; thus, variability of density contrasts between the bedrock and glacial sediments and within the glacial sediments should be minimal.

3. The bedrock topography is generally assumed as a gently undulating surface to justify the approximation of bedrock by infinite horizontal slabs. Where drillhole data are sufficiently concentrated, however, corrections can be made for deviations from the horizontal slab in the calculation of the regional anomaly. Bedrock elevations computed from the residual gravity will also be affected by this assumption. The effect will be to subdue the slopes of the bedrock topography.

APPLICATION OF METHOD TO KALAMAZOO COUNTY, MICHIGAN

Geologic Character of Area

In order to illustrate the gravity-geologic method of mapping buried bedrock topography a gravity survey was conducted of Kalamazoo County, Michigan, during 1964-1967. This area was selected because of the availability of ample well data for processing and evaluating the gravity-geologic method and the strong dependence of the area upon glacial drift aquifers for water resources. Preliminary studies suggested a direct relation between observed gravity anomalies and bedrock topography.

Kalamazoo County which is located in the southwestern portion of the Southern Peninsula of Michigan is covered with glacial drift ranging in thickness from less than 50 to 650 feet. The glacial sediments vary from well sorted lenticular outwash deposits to unsorted, mostly compact till. The major topographical features of the County are moraines of the Lake Michigan and Saginaw lobes of the Wisconsinan glaciation (Deutsch, et al., 1960).

The Coldwater shale of Mississippian age is the bedrock formation in most of the County. The Marshall sandstone overlies the Coldwater shale in the extreme northeastern corner of the County though it has not been well delineated. The shale is relatively impermeable and is not known to supply useable water in Kalamazoo County; however, the Marshall sandstone supplies water in the County and elsewhere in Michigan.

Data Acquisition and Reduction

Approximately 4,000 gravity stations were established in the 16 township County. The majority of the stations are located at approximately 500-foot intervals along roads in areas of primary ground-water interest. These areas were determined on the basis of proximity to users and available ground water and geologic data. Station elevations were determined by leveling and horizontal distances were measured from stadia intervals. To complete the gravity coverage of the County an additional 400 gravity stations were established at bench marks and road intersections where surface

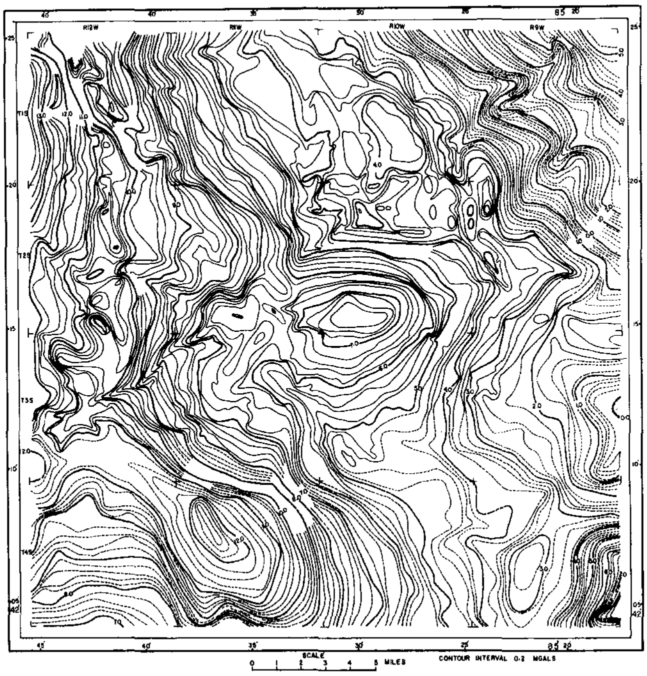

Fig. 2. Gravity anomaly map of Kalamazoo County.

elevations are known from U. S. Geological Survey topographic maps. The leveled stations have a precision of better than ±0.1 feet and station elevations obtained from topographic maps are accurate to ±2 feet. Gravity observations have a precision of approximately ±0.02 mgals.

The observed gravity readings were corrected for latitude, elevation, and mass above a horizontal datum using a density of 2.15 gm/cc in the normal manner. The resulting gravity anomaly map of Kalamazoo County is shown in Figure 2.

Comparison of Methods of Isolating Buried Bedrock Gravity Anomalies

An attempt to isolate residual gravity anomalies associated with bedrock topography in Kalamazoo County was made using the cross-profiling method, the method of polynomial fitting by the least-squares technique, and the gravity-geologic method previously described. To evaluate these methods of eliminating regional trends and isolating gravity residuals reflecting bedrock topography, the residual gravity anomalies at 39 randomly chosen drillholes were compared with the elevation of bedrock in the drillhole logs. The selection of the 39 drillholes was performed by drawing at random 10 percent of the test holes of each township, with a minimum of 2 holes from each township. Even if the residual isolation procedures are totally effective, a perfect correlation is not expected because of variation in density contrast between the bedrock and the glacial drift across the County. However, the relative correlation between the residuals and bedrock topography should be indicative of the effectiveness of the procedure.

The cross-profiling method was performed by drawing smooth regionals through 2 sets of gravity anomaly profiles normal to each other with a separation of about 3 miles between parallel profiles. Regional gravity profiles were adjusted until values at the intersections of the 2 sets of profiles were equal. The resulting regional gravity anomaly map was subtracted from the gravity anomaly map to obtain the residual values. The comparison of these residual values at the 39 drillholes with the bedrock elevation is shown in Figure 3. The scatter of points from the least squares line is appreciable. This is evidenced by a correlation coefficient of 0.21. The extremely divergent data points on this plot are associated with drillholes located over prominent, broad gravity anomalies caused by deep-seated masses. Obviously, the cross-profile method did not completely eliminate these regional anomalies.

The extraction of gravity residuals by approximating the regional gravity trends by a polynomial applying the method of least squares also was performed on the gravity map of Kalamazoo County. Residual maps were calculated using the fifth and seventh degree polynomial representation of the regional. The residual values corresponding to the fifth and seventh degree polynomial regionals are plotted against bedrock elevations in Figures 4

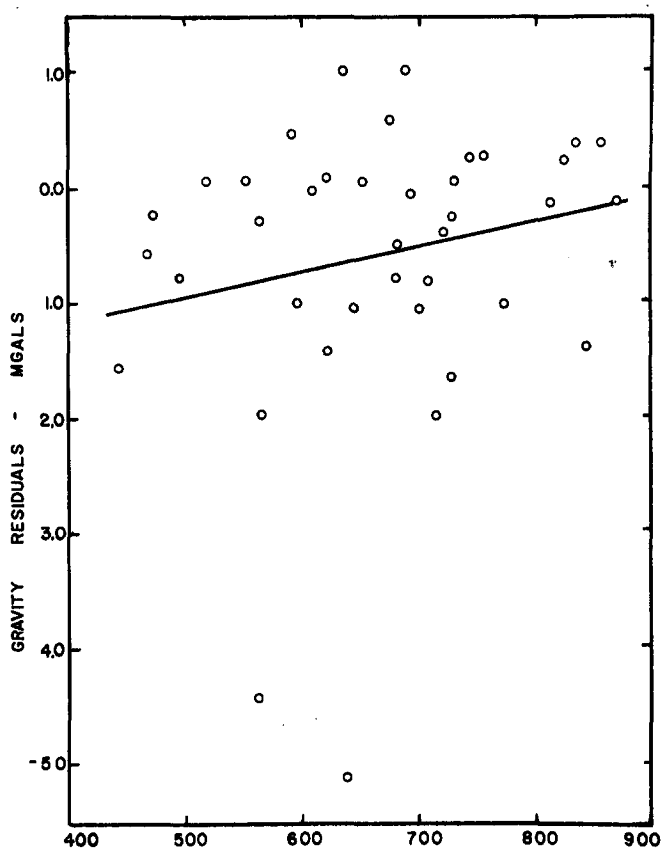

Fig. 3. Relation between cross-profile residual gravity anomalies and bedrock elevation.

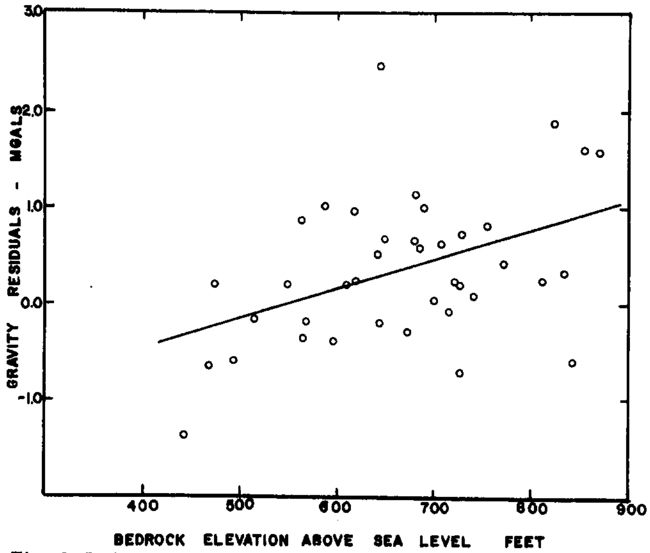

Fig. 4. Relation between fifth degree polynomial residual gravity anomalies and bedrock elevation.

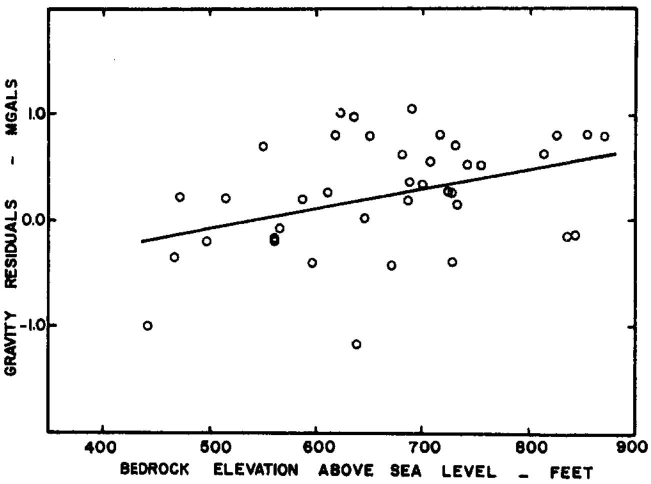

Fig. 5. Relation between seventh degree polynomial residual gravity anomalies and bedrock elevation.

and 5 respectively. Figure 4 displays less scatter of points than Figure 5 which is apparent from correlation coefficients of 0.44 for the fifth and 0.34 for the seventh degree polynomial representation of the regional. These correlation coefficients are superior to the results obtained from cross-profiling, but indicate that the method of representing the regional trend by polynomial analysis results in distorted residuals.

A gravity-geologic residual gravity anomaly map of Kalamazoo County (Figure 6) was constructed using the procedure previously described. In this area, bedrock has been reached by approximately 250 drillholes and an additional 50 deep drillholes were available as further guides in the computations. The horizontal datum used in the calculations was chosen to be the lowest known elevation of the bedrock surface in Kalamazoo County, i.e., 300 feet above mean sea level. A density contrast of 0.4 gm/cc was used in equation

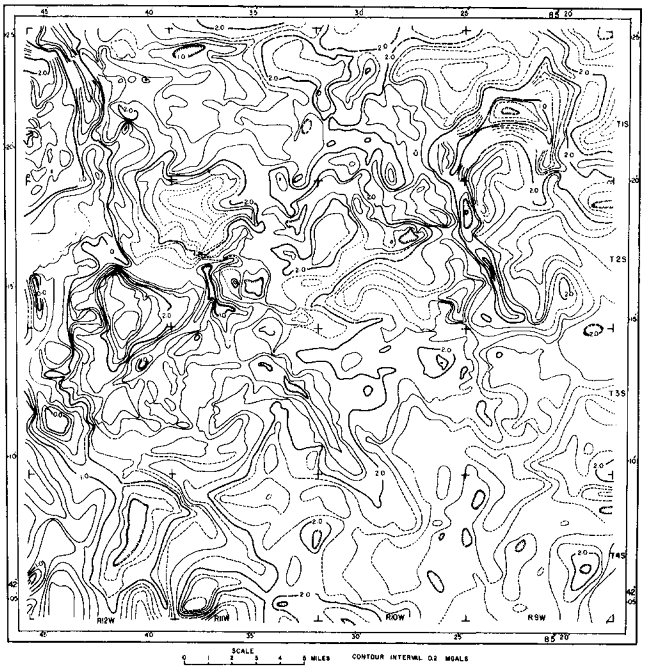

Fig. 6. Gravity-geologic residual gravity anomaly map of Kalamazoo County.

(1), based upon an assumed density of 2.15 gm/cc for the saturated glacial sediments, and 2.55 gm/cc for the bedrock. In view of the lack of density control, this density contrast was used across the entire County. No attempt was made to correct the horizontal slab equation [equation (1)] for a sloping bedrock surface. The gravity values at drillholes were computed from direct gravimetric readings or interpolated from the gravity contour map. The gravity-geologic regional map was employed to estimate the gravity regional at each gravity station. These values were subtracted from the gravity anomaly map to obtain the gravity-geologic residual gravity anomaly map.

To evaluate the effectiveness of this method of isolating gravity residuals reflecting bedrock topography, the 39 drillholes previously used to test the residual gravity maps were assumed nonexistent. The regional gravity values at each drillhole were estimated by interpolating from the regional values obtained by the gravity-geologic method at the nearby drillholes. These values were subtracted from the gravity anomaly values to obtain the gravity-geologic residual anomaly values which are plotted against bedrock elevation in Figure 7. The data points in this graph exhibit appreciably less scatter around the least squares line than those shown in Figures 3, 4, and 5. The correlation coefficient of the data points in Figure 7 is 0.91, and the correlation between bedrock elevations and gravity-geologic residual gravity anomalies is highly significant at the one percent level. This shows the superiority of this method for

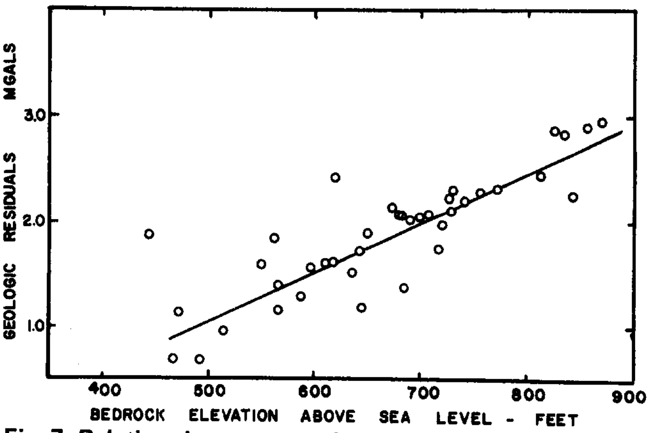

Fig. 7. Relation between gravity-geologic residual gravity anomalies and bedrock elevation.

isolating gravity anomalies which reflect bedrock topography. Most of the data points in Figure 7 which show appreciable deviation from the least squares line are associated with drillholes located in areas where bedrock control is sparse. The regional gravity values at these sites were therefore obtained by interpolating from regional gravity values located at large distances.

Bedrock Topographic Map

The bedrock elevation at each gravity station was computed utilizing equation (2) and assuming a bedrock-glacial drift density contrast of 0.4 gm/cc. The results were plotted and contoured to produce a bedrock topographic map of Kalamazoo County (Figure 8). The contour lines are dashed in areas where bedrock control and gravity coverage are insufficient to permit accurate determination of bedrock topography. The accuracy is further limited by the assumptions stated in the previous discussion of the gravity-geologic method of mapping buried bedrock topography. The primary source of error may be considered to be the constant density contrast assumed in the calculations.

The bedrock topography map shows in general a westward slope of the bedrock surface. Bedrock elevations of 850 feet are found in the eastern part of the County, while elevations in the western part seldom reach 800 feet and are less than 350 feet in the valleys. Superimposed on this general bedrock surface are several prominent topographic highs. Low elevations of the bedrock surface exist locally along the axes of bedrock channels. The complex bedrock topographic pattern is a result of glacial modification of the pre-existing drainage system.

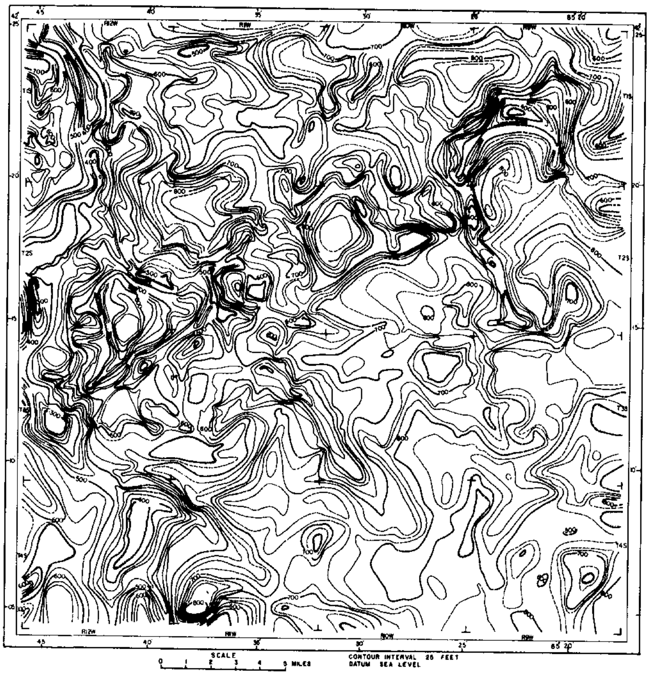

Fig. 8. Bedrock topography of Kalamazoo County.

The bedrock topographic map will be integrated with the glacial geology of Kalamazoo County in a forthcoming paper which will discuss the glacial history of the County.

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