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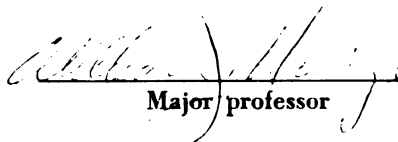
A Gravitational Investigation of
Niagaran Reefs in Southeastern Michigan

presented by

Gary Gordon Servos

has been accepted towards fulfillment
of the requirements for

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ABSTRACT

A GRAVITATIONAL INVESTIGATION OF NIAGARAN REEFS IN SOUTHEASTERN MICHIGAN

by Gary Gordon Servos

Precision detailed gravity surveys can detect Niagaran reefs buried at depths up to at least 3500 feet in the Michigan Basin.

Three southeastern Michigan reefs, Marine City, Belle River Mills, and Berlin, are studied by the gravity method using graphical statistical and analytical techniques of interpretation. The characteristics and sources of the anomalies are studied and optimum methods of reef anomaly enhancement are suggested.

The gravity anomalies associated with reefs in the Michigan Basin are positive with a magnitude of about 0.2 milligals. The ratio of the width of the anomalies to the width of the reef varies from 2:1 to 1.3:1 depending on the technique used.

There are negative anomalies parallel and adjacent to the reef anomalies. In areas where bedrock topography is known, these negative anomalies coincide with bedrock channels. Theoretical calculations using the configuration of the bedrock channels show that the channels can produce a gravity effect with the magnitude of the observed negative anomalies.

The sources of the reef anomalies are lateral variations in the density of the dolomite formations overlying and surrounding the reef. The reef mass alone cannot cause the anomaly.

The graphical and statistical techniques isolate the anomalies, but many of the undesirable effects of shallow source anomalies are retained by these techniques. The analytical technique of downward continuation of an upward continued surface has a high resolution and eliminates the shallow source anomalies. The maximum resolution occurs when the upward continued surface is calculated at a height equal to the depth of the reef and then downward continued to a depth not greater than the reef. The second derivative of an upward continued surface has the highest resolution using Henderson's 1960 formula. The optimum enhancement occurs when the mesh interval used in these techniques is equal to one-half the reef depth.

A GRAVITATIONAL INVESTIGATION OF NIAGARAN
REEFS IN SOUTHEASTERN MICHIGAN

By

Gary Gordon Servos

A THESIS

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in partial fulfillment of the requirements
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By

GARY GORDON SERVOS

1965

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CHAPTER I

INTRODUCTION

General Statement

Exploration for oil and gas bearing Niagaran reefs has been emphasized in the Michigan Basin since 1960. This has resulted in the discovery of several reefs in southeastern Michigan in St. Clair and Macomb Counties. In addition, isolated reefs have been found at several locations around the basin and, thus, the prospect of locating additional reefs is excellent.

Exploration for the reefs has included both geological and geophysical techniques. Seismic investigations have had limited application, but the gravity method has been widely employed and is credited with making several major discoveries. Despite the wide use of gravity no detailed reports of case histories have been presented for reefs in the Michigan Basin.

The purpose of this investigation is to study the gravity anomalies of known reefs in the Michigan Basin and to establish the optimum methods of interpretation and isolation of the anomalies.

Although the results of gravity prospecting in the Michigan Basin have not been reported, several investigators

have discussed gravity prospecting for reefs. Yungul (1961) has produced the most comprehensive report on reef anomalies in several areas including the case histories of a reef in Ontario (Pohly, 1954). Geyer (1962), using theoretical approximations, concluded that reefs in the Michigan Basin could be found by gravity.

Three well defined reefs of different relief, areal extent, and depth of burial were selected for study. A precision detailed gravity survey was conducted over the three reefs during the summers of 1962 and 1963. A high station density was used to obtain all the details of the gravity anomalies. The three reefs chosen are Belle River Mills, Marine City, and Berlin.

The Belle River Mills reef is one of the larger reefs discovered. It is approximately 3000 feet wide and two miles in length. It is buried at a depth of 2300 feet below the surface and has a relief of 300 feet.

The Marine City reef is three miles south of the Belle River Mills reef and is buried at the same depth. It consists of two circular cone shaped pinnacles on a broad base. The pinnacles are one mile apart and have a relief of 250 and 300 feet. The Marine City reef contains less reef mass than the Belle River Mills reef.

The Berlin reef is located thirty miles west of the Marine City and Belle River Mills reefs and is buried at a

depth of 3500 feet. It has a width of 2500 feet and a length of one mile. The relief is about 200 feet.

Several graphical, statistical, and analytical techniques were used in the interpretation and isolation of the reefs. The techniques used include cross-profiles, least squares polynomial analysis, upward continuation, downward continuation and second derivatives. Two-dimensional and three-dimensional gravity formulas were used to calculate the theoretical gravity of the reefs. All computations were performed on a digital computer.

Location and Physiography of Areas

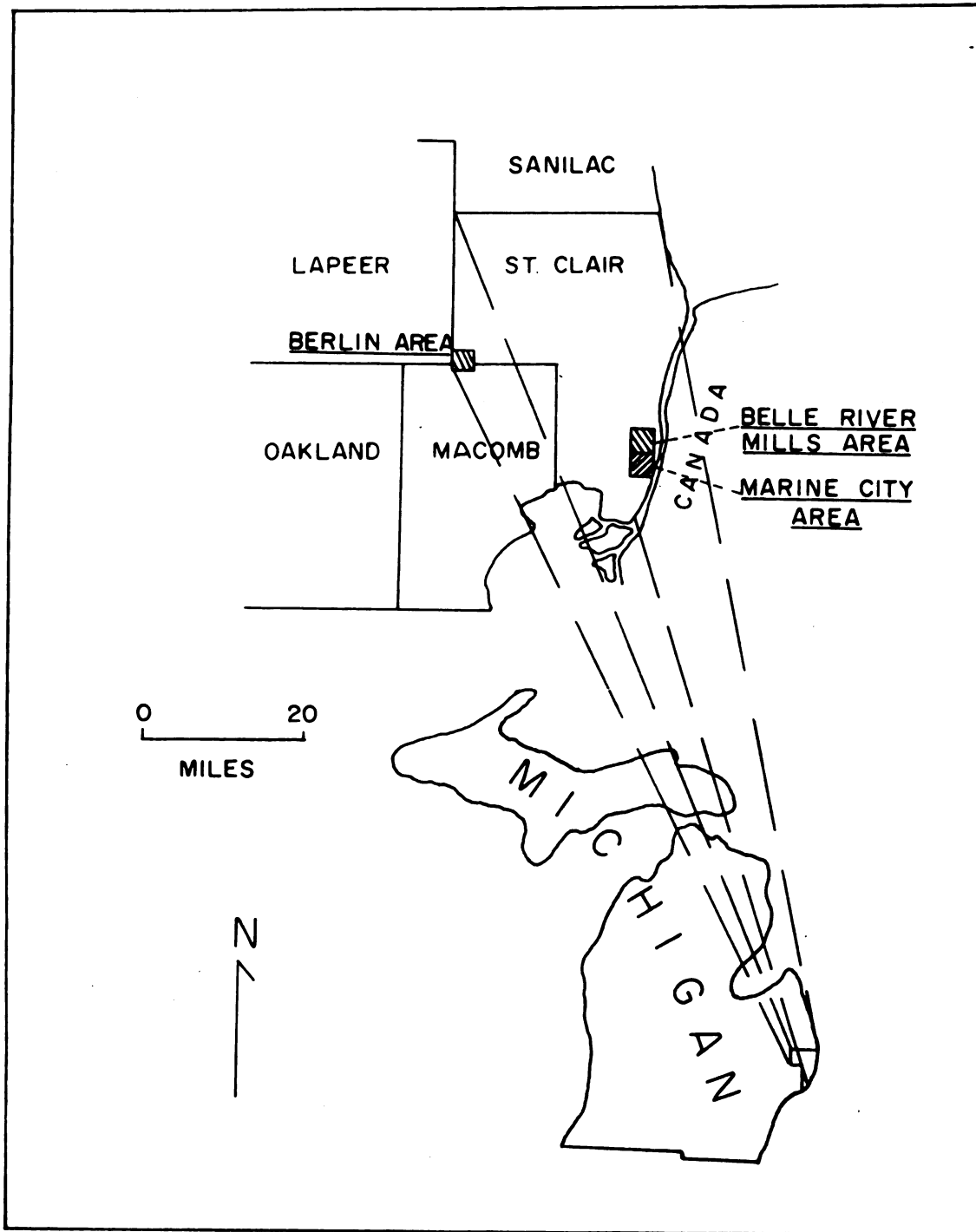
The areas of study, shown in Figure 1, are located in St. Clair and Macomb Counties, Michigan. The Marine City and Belle River Mills areas are in the extreme eastern part of St. Clair County along the St. Clair River. This area lies between latitude $42^{\circ}40'00''$ N and $42^{\circ}48'30''$ N and longitudes $82^{\circ}30'00''$ W and $82^{\circ}35'00''$ W. The Berlin area is located along the northern Macomb and southern St. Clair County line. This area lies between latitudes $42^{\circ}52'00''$ N and $42^{\circ}56'30''$ N and longitudes $82^{\circ}53'45''$ W and $82^{\circ}58'45''$ W.

Both the Marine City and Belle River Mills areas are situated in the Erie-Huron Lowland, a topographic sub-province in the Southern Peninsula of Michigan, (Newcombe, 1933). This sub-province is characterized by surficial glacial lake clays and lake bed sands. This area was

covered by several glacial lake substages of the Wisconsin glacial stage (Leverett, 1939). This area is generally flat with a maximum relief of fifty-five feet and the elevation gradients of five to ten feet per mile. The only exceptions are the several stream channels in the area which have a maximum relief of thirty feet.

The Berlin area is situated in the Thumb Upland, a topographic sub-province characterized by several moraines (Newcomb, 1933). The immediate area of the Berlin survey is flat with a maximum elevation difference of about forty-five feet. The elevation gradients also are five to ten feet per mile. Both areas are divided by a network of section line and intermediate roads. Generally the area consists of privately owned farms.

Primary drainage in the Marine City-Belle River Mills area is to the south and east. The major tributary is the Belle River. The Berlin area exhibits little or no drainage pattern and there are no major streams in the area.



LOCATION OF AREAS

FIGURE 1

CHAPTER II

GRAVITY STUDY

Field Methods

The areal extent of the gravity surveys was selected to cover the reefs adequately and include the regional gravity of each area. The existing road network allowed good coverage, but in addition to the road traverses, cross-country traverses were placed in the immediate vicinity of the reefs at one-half mile intervals. These cross-country traverses were made in the areas whenever possible and in all cases at least one cross-country traverse was placed in the sections associated with the reefs.

A station spacing of five hundred feet was selected for the survey. The station elevations were established with a Zeiss self-leveling level and elevation control was obtained from three U. S. Geological Survey and several Michigan State Highway Department bench marks. All traverses were closed and cross-country lines were tied into established elevations. Horizontal distances were determined by stadia intervals and control was carried from road intersection to road intersection to eliminate cumulative error.

Two exploration type gravity meters were used in the survey. These were World Wide meter number 45 and Worden number 99. These meters had calibration constants of 0.10093 and 0.0995(1) mg. per scale division respectively. These constants were checked prior to the beginning of the survey each summer and midway through the summer. Both meters measure the relative acceleration of gravity to an accuracy of 0.01 mg.

The meters are subject to time variations or drift even though they are temperature compensated and barometrically controlled. These time variations are a result of temperature changes, tidal variations, spring fatigue, and handling of the meter. To determine these variations a check reading was made at a number of pre-established base stations at least once every hour during the course of the survey.

A primary base was established near the center of each area and sub-bases were established at strategic points by the base-looping method. The Belle River Mills and the Marine City areas are adjacent and the primary bases of each area were tied to allow correlation. The Berlin area was not tied to the other two surveys because it is thirty miles away.

Gravity readings were made every five hundred feet at the pre-established elevation. These readings were tied to the base station by the hourly drift check. In addition, a number of stations were reread at various times during

the course of the survey to establish the accuracy of the readings. At each gravity station the meter was read until two values were obtained which did not differ by more than 0.2 scale divisions or 0.02 mg.

Reduction of Data

Introduction

Observed gravity, to be useful in geological studies must be corrected for station elevation, latitude, and terrain. These corrections are applied to each station. The resulting values are called the Bouguer gravity anomaly.

The complete Bouguer gravity anomaly was calculated on a digital computer according to the following formula:

$$G_{cbg} = g_o - g_l + g_{e\&m} + g_t \quad (1)$$

where

G_{cbg} = complete Bouguer gravity anomaly

g_o = observed gravity

g_l = latitude correction

$g_{e\&m}$ = combined elevation and mass correction

g_t = terrain correction.

Observed Gravity

The observed gravity values are obtained by correcting the meter readings in scale divisions for drift, and then multiplying the values by the calibration constant of the meter. The drift is determined from graphs of hourly

base-readings. When the drift exceeded one scale division per hour, the drift check readings were decreased to three-quarters of an hour.

Latitude Correction

The Earth's gravity increases from the equator to the poles. The latitude correction takes into account this change in gravity. Latitude corrections are made from a base latitude by multiplying the latitude distance of each station by a constant, K. Nettleton (1940) determined K to be $1.307 \sin 2\theta$ mg. per mile, where θ is the mean latitude of the survey area. In the survey areas of this study a base latitude of $42^{\circ}40'00''$ N was used for the Marine City-Belle River Mills area, and a base latitude of $42^{\circ}52'00''$ N for the Berlin area. The value of K is 0.0002474 mg. per foot for these areas.

The stations of the three surveys were placed on the Michigan Coordinate System, east zone, a plane-coordinate system established by the U. S. Coast and Geodetic Survey. This allows each station to have x (ordinate) and y (abscissa) coordinates which are on a rectangular grid system. In the process of reducing the data by the digital computer, the Michigan Coordinate System was rotated to correspond with latitude and the latitude correction was made in the normal manner.

Elevation and Mass Correction

The elevation or free-air correction and the mass or Bouguer correction are often combined and called the elevation and mass correction. The combined correction takes into account the vertical decrease of gravity with an increase in elevation and the increase in gravity due to the attraction of the material between the datum and individual stations. This correction is calculated from the combined formula:

$$g_{e\&m} = (0.09406 - 0.01276\rho)h \quad (2)$$

where

h = elevation difference between the datum and
the gravity station in feet

ρ = density of surface material in g/cc.

The datum to which the gravity was reduced was chosen near the lowest elevation of the surveys.

Density Determination

The determination of the correct density for the near surface material in the survey areas is extremely important. A density value for glacial drift is often given in the literature as 1.8 g/cc. This value does not appear to be correct for near surface glacial drift in eastern Michigan. A density value of 2.1 g/cc was determined by the Nettleton density profile method at several locations in the vicinity of the survey areas. Klasner (1964)

determined a density of 2.15 g/cc for the near surface drift in western Michigan.

An incorrect density of 0.3 g/cc and relief of thirty feet will cause the gravity values to be in error by about 0.12 mg. In the search for reefs this value alone is close to three times the desired accuracy. In areas with no topography, a larger error in density can be tolerated. However, in areas with relief it is very important to determine the density with the highest precision possible.

Terrain Correction

The relief in the survey areas was low enough that no terrain corrections were needed. Where the local variations of the several stream valleys in the areas were encountered, stations were placed far enough away from the feature that the effect was negligible or the stations were not used. The placing of stations in these areas was determined from correction curves calculated by Hubbert (1948).

Summary of Accuracy

In making gravity reductions, there are several factors which cause errors in the Bouguer gravity anomaly. These are:

1. Errors in observed gravity
2. Errors in elevation
3. Errors in latitude
4. Errors in assumed density of the glacial drift.

To check the accuracy of the gravity readings for the Belle River Mills survey, 16 stations were reread during the survey. The standard deviation for the repeated stations is ± 0.01 mg.

The errors in elevation affect the elevation and mass correction. Thirty-six closures were made during the survey. The standard deviation of the closures is ± 0.09 feet. The maximum possible error in the elevation and mass correction caused by 0.09 foot error, using a density of 2.1 g/cc, is 0.006 mg.

The latitude measurements were made to an accuracy of fifty feet. They were measured on a base map with a scale of 1:12000. The maximum error from the latitude correction is 0.012 mg.

An incorrect density value of 0.1 g/cc with a maximum change in elevation between any two stations of 10 feet will cause an error of 0.01 mg. The formula for calculating this error is:

$$\text{Error} = 0.00128 \sigma h$$

where

0.00128 = magnitude of error in milligals per foot
for each 0.1 g/cc error in density

σ = error in density in units of 0.1 g/cc

h = maximum relief in feet.

The maximum error possible considering these sources is ± 0.038 mg.

Table 1 shows a comparison of the maximum errors for the Belle River Mills, Marine City, and Berlin surveys. The errors for the Marine City and Berlin surveys were calculated in the same manner as those of the Belle River Mills survey.

TABLE 1
ACCURACY OF GRAVITY DATA

Number of Gravity Stations Reread	Standard Deviation of Reread Stations in mg.	Number of Elevation Closures	Standard Deviation of Closures in Feet	Maximum e&m Error Us- ing Standard Devia- tion of Closures and Density of 2.1 g/cc.	Maximum Latitude Error in mg. Stations Accu- rate to 50 feet.	Maximum Error for 0.1 g/cc Density Error and Elevations Differ- ence of 10 ft. between two stations.	Maximum Error Possible in mg.
16	0.1	36	0.09	0.006	0.012	0.01	±0.038
27	0.13	30	0.06	0.004	0.012	0.01	±0.041
30	0.14	8	0.11	0.007	0.012	0.01	±0.043

CHAPTER III

GEOLOGY

Regional Structure and Stratigraphy of Michigan Basin

The Michigan Basin is an oval intracratonic sedimentary basin enclosed by the Findlay, Algonquin, Kankakee and Wisconsin Arches, and the Canadian Shield. The development of the basin probably began in middle Silurian time (Ehlers and Kesling, 1962). During the middle Silurian (Niagaran Series) a system of reefs was formed on shelf areas surrounding the Michigan Basin. Slight rises in the areas bordering the Michigan Basin, accompanied by a barrier of Niagaran reefs, caused a restriction of the basin late in Silurian time. The Michigan Basin continued to receive sediments throughout the Paleozoic period.

The general stratigraphy of the basin is shown in Figure 2 (after the Michigan Geological Survey). The Niagaran and lower Cayugan Series of the Silurian, which are of major interest in this study, consists of the Niagaran Group (or Guelph) and the Salina Group respectively.

Lowenstam (1950) suggested that Niagaran reefs possibly surround the entire Michigan Basin. Isolated reefs which have been found around the margins of the basin

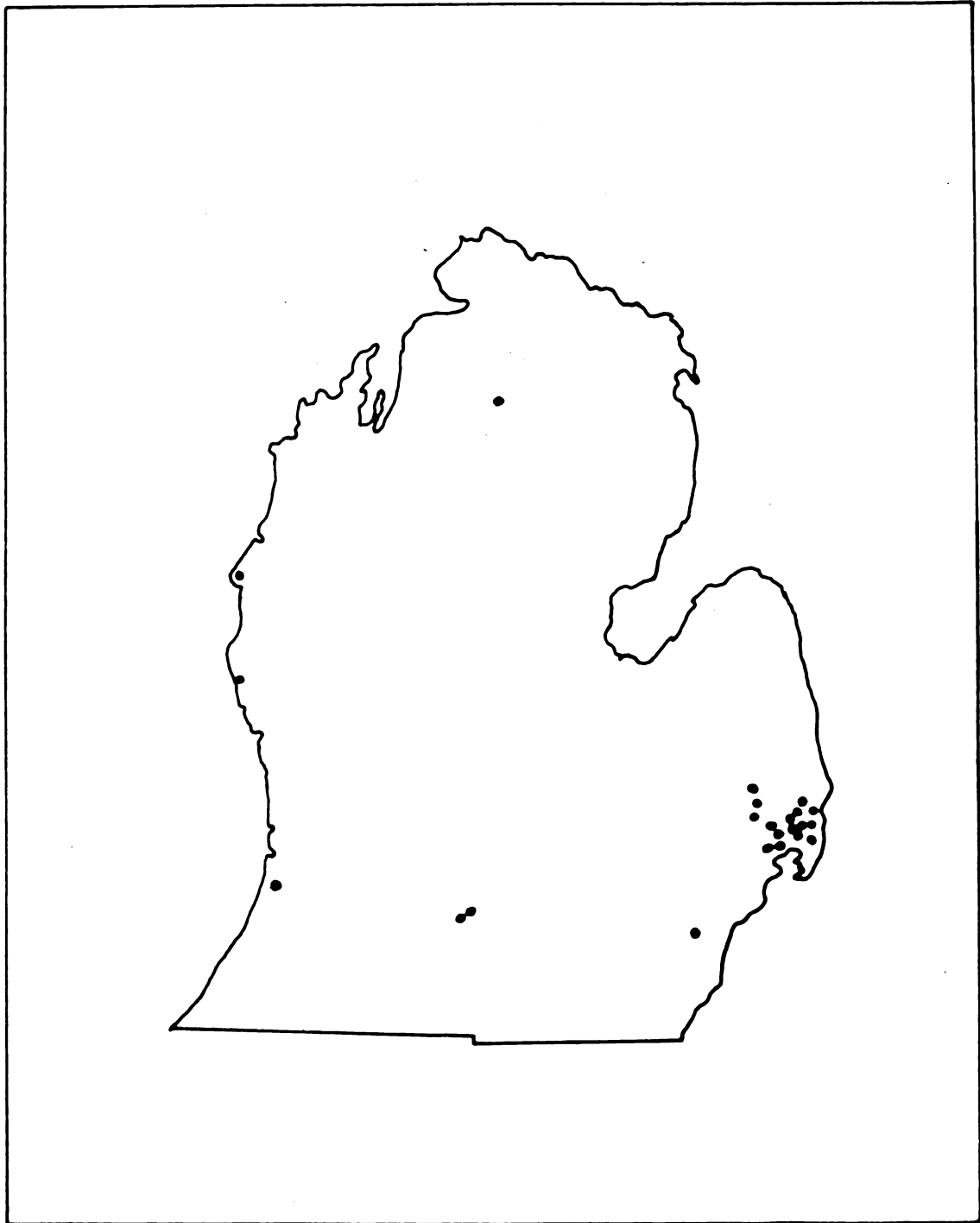
substantiate this (Figure 3). Reefs also are present in the Silurian outcrops on Drummond Island, Michigan (Manley, 1964). Generally the reefs developed around the basin are of the pinnacle type.

Niagaran Structure and Stratigraphy of St. Clair County

The regional dip of the geological formations in this area is in the order of 30-40 feet per mile. This becomes an important factor in searching for reefs in the Michigan Basin as the gravity method is useless if the reef is below a limiting depth.

The general stratigraphy of the Niagaran and Salina groups in the St. Clair area is shown in Figure 4 (Alguire, 1962). There is a possibility that the carbonate sequences of the Niagaran and Salina Groups are regionally limestone and only locally dolomitized about the reefs (Jodry, 1965).

Typical reefs in the St. Clair County area have relief up to 300 feet with an areal extent usually less than one half mile in width and one mile in length. Basinward the reefs are more pinnacle in nature and have a smaller areal extent. The structure of a typical reef is shown by a cross-section through the Marine City reef (Figure 5, Alguire, 1962). This cross-section includes the stratigraphic units from the Clinton shale (Niagaran) through the B-Salt member of the Salina group. The entire geologic column from the reef facies upward show some degree of doming over the reef



LOCATION OF REEFS IN MICHIGAN

FIGURE 3

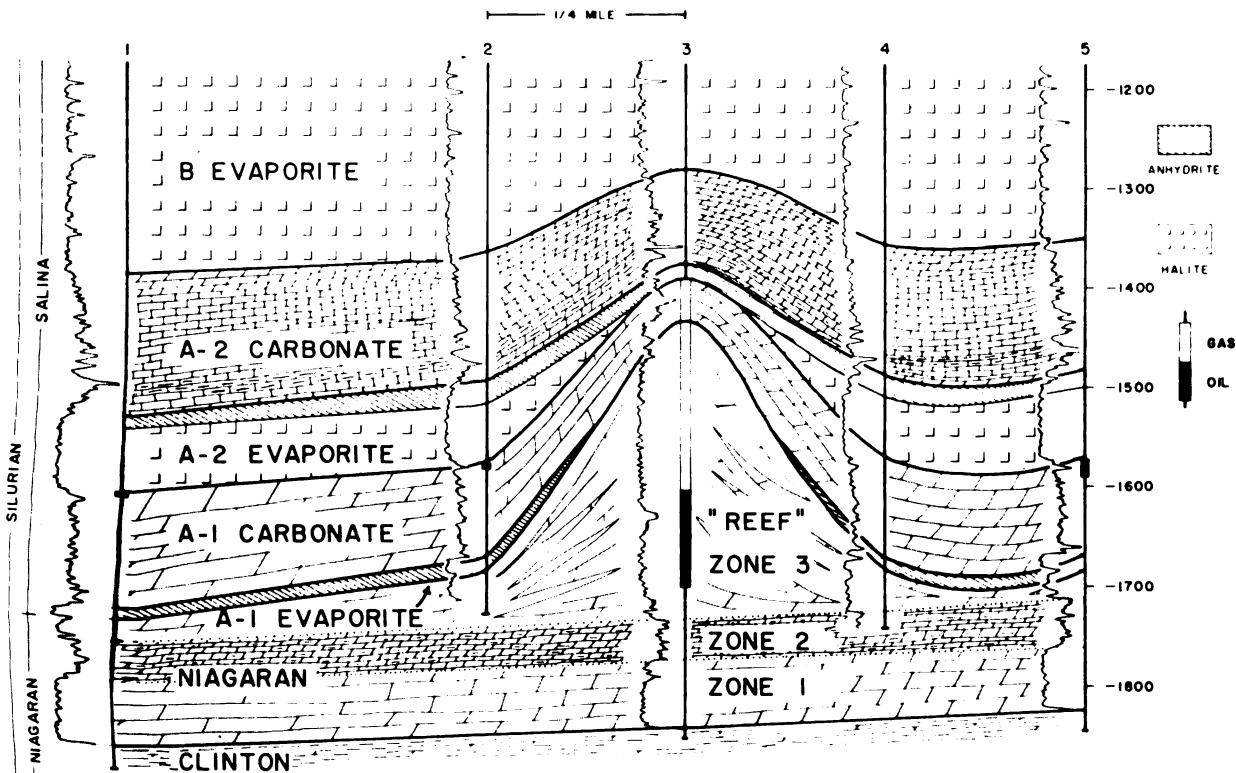
NIAGARAN AND SALINA STRATIGRAPHY

Formation	Unit	Description
SALINA	G	DOLOMITE: brown, finely crystalline; shaly dolomite; some anhydrite.
	F	SALT: in thick beds separated by beds of shale, shaly dolomite, gray and buff, and brown, crystalline dolomite; anhydrite nearly always present.
	E	SHALE: with argillaceous, gray and buff dolomite.
	D	SALT: nearly pure; thin partings of buff dolomite.
	C	SHALE: gray, dolomitic.
	B	SALT: thick salt beds with thin dolomite layers.
	A-2	DOLOMITE: brown, brown gray, gray and dark gray, finely crystalline; some dark bituminous shale. SALT: where salt is absent the base of A-2 is marked by anhydrite.
	A-1	DOLOMITE: buff, brown, brown gray and dark gray, dense to medium crystalline; some dark bituminous shale. ANHYDRITE: at base.
NIAGARAN GROUP	Guelph-Lockport or Niagaran	DOLOMITE: tan, gray brown and brown, very finely to coarsely crystalline and vugular; often finely laminated near top. DOLOMITE: light and dark gray mottled, finely crystalline. DOLOMITE: light to blue gray, finely to coarsely crystalline.

FIGURE 4

AFTER ALGUIRE

STRUCTURE AND STRATIGRAPHY OF MIDDLE SILURIAN NIAGARAN AND UPPER SILURIAN SALINA STRATA ACROSS A PART OF THE MARINE CITY REEF FIELD, ST. CLAIR COUNTY, MICHIGAN. VERTICAL SCALE 6.6x HORIZONTAL SCALE



AFTER ALGUIRE

FIGURE 5

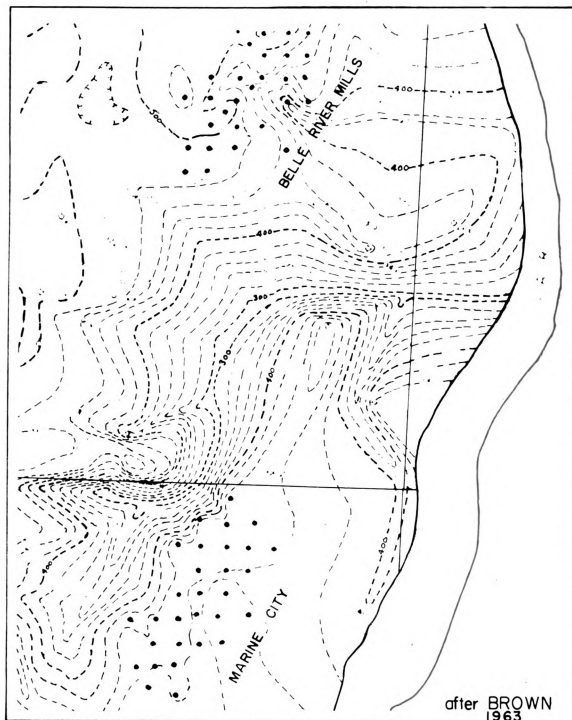
(Ells, 1964). In most cases this doming of the sediments can be accounted for by compaction.

Details of the structural and stratigraphic development of reefs have been reported by many authors (Cummings and Shrock, 1928), (Lowenstam, 1950, 1957), (Textoris and Carozzi, 1964).

Bedrock Geology

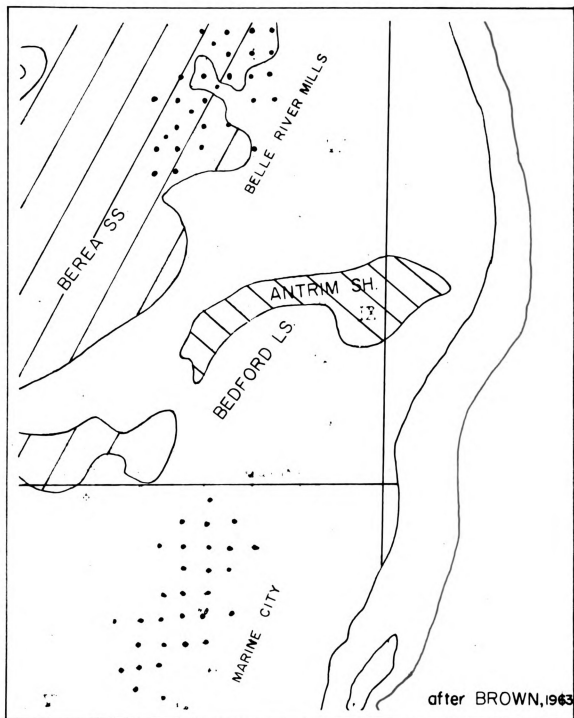
The glacial drift deposits covering the St. Clair County area consist primarily of lake bed clays and sands. Isopach maps of the glacial drift (Brown, 1963) show variations in the drift thickness in the order of 200 feet. Structure contours of the bedrock surface beneath the drift show numerous bedrock channels (Figure 6, Brown, 1963). Klasner (1964) showed that gravity can be used successfully to determine the location of these bedrock channels. Bedrock channels with depths of 200 feet can cause negative gravity anomalies which will tend to mask the anomalies of the reefs.

According to Brown (1963) the bedrock lithology varies from older to younger beds to the west as illustrated in Figure 7. These changes in bedrock lithology are important in the theoretical gravity to determine the bedrock topographic effects, as variations in lithology change the density contrasts between the bedrock and glacial drift.



BEDROCK TOPOGRAPHY OF MARINE CITY
AND BELLE RIVER MILLS AREAS
C.I.=20'

FIGURE 6



BEDROCK LITHOLOGY OF MARINE CITY
AND BELLE RIVER MILLS AREAS

FIGURE 7

CHAPTER IV

INTERPRETATIONAL METHODS

General Statement

Gravity measurements have been used for a number of years as an exploration tool, but the confidence placed in the method has been limited. However, in the last decade confidence in the gravity method has increased markedly for several reasons. First, a better knowledge of geology by geophysicists and a better understanding of the application of geophysics by the geologist has contributed much to the change in attitude. Second, previous studies have defined the usefulness and validity of the gravity method for various geologic situations. Third, a better knowledge of the assumptions and variables used in gravity interpretation has been gained and applied in evaluating gravity data.

New and useful techniques such as density logging are and will be a great help in future gravity interpretations. The determination of the correct density contrast between geological formations is often difficult, but is extremely important in gravity interpretation. The gravity method depends on horizontal changes in density and, fortunately, geological conditions produce these density contrasts.

An inherent problem in gravity interpretation is the ambiguity of results. Skeels (1950) has shown that any gravity anomaly produced by a mass (x) can be reproduced by another mass (y) at a different depth. Studies in the last decade have helped to overcome the ambiguity by defining the types of anomalies produced by various geological features in different geological situations.

Regional gravity surveys are widely used, but detailed surveys have not been fully utilized in the search for small geologic features. Noise levels are constantly being lowered as detailed gravity surveys are used more frequently. When the data is collected in the most accurate form and proper assumptions made in the interpretation, the detailed survey can be used with confidence.

Digital computers now allow many new and older interpretational techniques to be used which have been impractical due to involved and time consuming arithmetic. There has been much discussion and disagreement on graphical versus analytical and statistical techniques in interpretation. The graphical techniques are simple, but are subject to personal bias of the interpreter while the analytical techniques have a higher resolving power and are readily performed on the digital computer. The statistical methods also are easily adapted to the computer and are subject to less bias than the graphical methods. Each method has its use in gravity interpretation given the proper set of geological and geophysical conditions.

Theory of Techniques Used for Interpretation

General Statement

Graphical, statistical, and analytical techniques were used in the interpretation of the reef anomalies as one of the purposes of this study is to determine optimum methods of interpretation for a particular geologic situation. A flow diagram, shown in Figure 7a, illustrates the step by step procedure followed in the interpretation and the results of each particular method. The theory of these techniques is presented in the following sections.

Cross-Profiles Graphical Technique.

The cross-profile method was used to determine the relationship of the residual anomaly obtained using a graphical technique to those obtained using analytical and statistical techniques. This method consists of drawing a smooth curve of the estimated regional gravity gradient along a profile as shown in Figure 8.

CROSS PROFILE METHOD

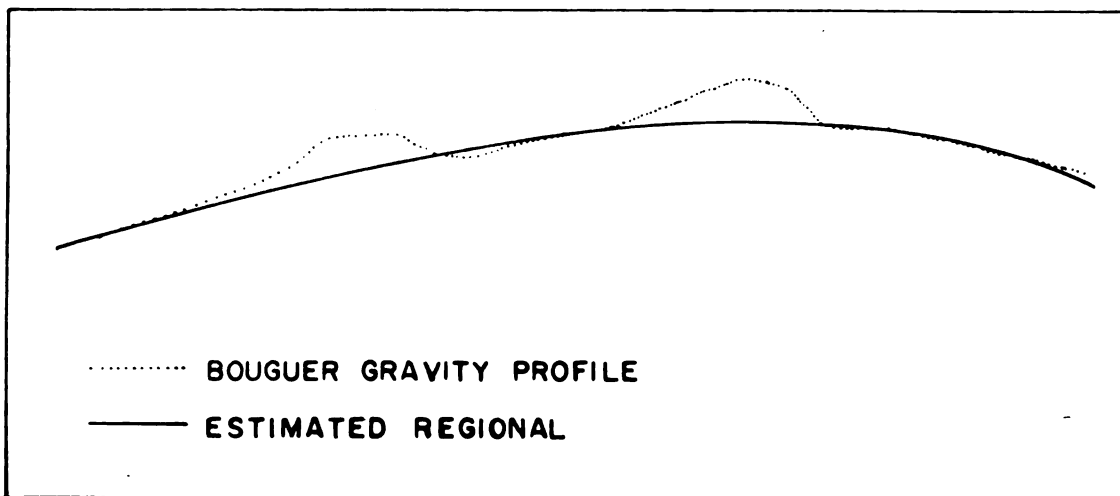
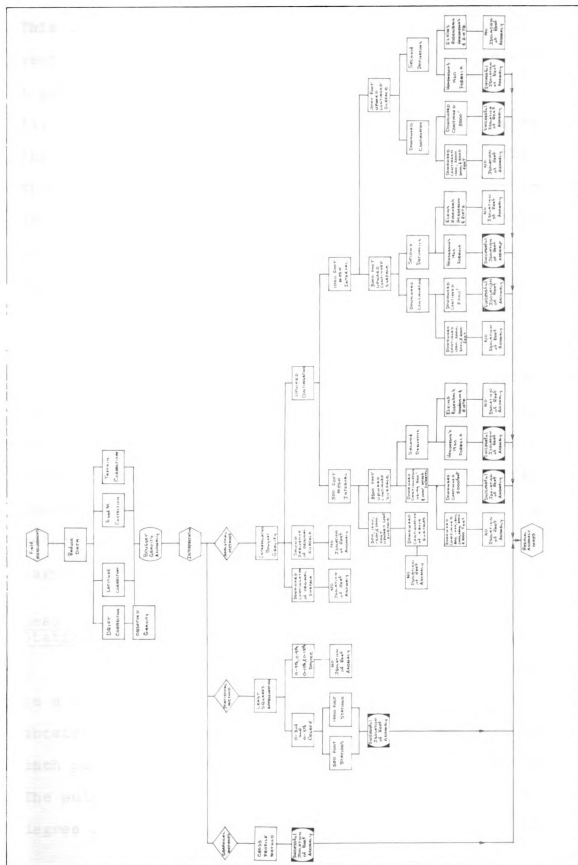


FIGURE 8



FLOW CHART OF INTERPRETATION PROCEDURES

This is done for all profiles of gravity values which intersect another profile. If the regional gradient selected is a good approximation, the point of intersection on two profiles will agree in value. If the values do not agree, then the approximated regional gradient is adjusted until the values at the intersection points agree and are geologically reasonable. When all values of intersection agree, it is assumed the regional gradient has been correctly determined. The approximated regional gravity is then removed from the Bouguer gravity values leaving the residual gravity.

This method has the advantage of being a simple method to obtain the residual and permits the knowledge of an area to be used. The results from this method are, however, subject to the personal bias of the interpreter which can be both an advantage and a disadvantage. The method is limited if the residual anomalies are low in magnitude or the regional gradients are complex.

Least Squares Polynomial Statistical Analysis

This method consists of fitting a polynomial equation to a three-dimensional surface. In this case the surface consists of x, y coordinate points and a gravity value at each point giving the third dimension in the z direction. The polynomial equation is fitted to the surface to a degree where the regional gravity is adequately defined.

The portion of the surface which is not fitted exactly by the equation is considered the residual. The success of this approach depends on the validity of the assumption that the regional can be described accurately by a polynomial equation.

The least squares principle states that the coefficients of the polynomial equation must be such to make $\sum_1 (\epsilon_1)^2$ a minimum, where ϵ is the residual or the portion of the surface not fitted exactly by the polynomial equation.

The basic polynomial equation used is

$$\Delta\phi_{\text{Regional}} = \alpha_{00} + \alpha_{10}x + \alpha_{01}y + \dots + \alpha_{pq}x^p y^q \quad (4)$$

where the α 's are the coefficients of the equation and (p, q) is the degree of the equation. The equation can be solved easily by matrices on a digital computer and the resulting gravity value expression is subtracted from the Bouguer gravity to give the residual.

Analytical Techniques

Upward and Downward Continuation

Often in the interpretation of gravity data it is desired to study the gravitational field on a plane above or below the original plane of observation. The upward continuation method results in moving the plane of observation further away from the source of anomalies. The effect of this method is to eliminate small sharp gradient anomalies from sources close to the plane of observation

further away from the source of anomalies. The effect of this method is to eliminate small sharp gradient anomalies from sources close to the plane of observation and to retain the broad lower gradient anomalies caused by masses at a greater depth. The downward continuation method allows the plane of observation to be moved to levels near the masses producing the anomalies. This results in an enhancement and increased resolution of the anomaly. Both upward and downward continuation have proven highly useful in gravity interpretation.

The following mathematical evaluation based on Henderson's (1960) development results in a practical approximation for both the upward continuation and downward continuation equations.

Basically, the problem is to compute the gravity value $\Delta\phi(x, y, z,)$ above and below the plane of observation.

The origin of the right-handed coordinate system is taken at the point where the field is to be computed, with the z-axis positive downward.

The integral solving the Dirichlet problem for a plane (the upward continuation integral) in polar coordinates is

$$\Delta\phi(-ma) = \int_0^{\infty} \frac{ma \Delta\phi(r) r dr}{(r^2 + m^2 q^2)^{3/2}} \quad (5)$$

$$m = 1, 2, 3, \dots, n$$

where a is the mesh interval of the gravity values, m is the number of mesh units above the original plane, and

$$\Delta \bar{\phi}(r) = \frac{1}{2\pi} \int_0^{2\pi} \Delta \phi(r, \theta) d\theta. \quad (6)$$

The physical meaning of $\Delta \bar{\phi}$ on (r) is the average value of $\Delta \phi$ circles of radius r about a point. Experimentally it has been found that radii of $r = 0, a, a\sqrt{2}, a\sqrt{5}, a\sqrt{8}, a\sqrt{13}, a\sqrt{25}, a\sqrt{50}, a\sqrt{136}, a\sqrt{274}$ and $a\sqrt{625}$ adequately sample the field. The number of mesh points falling on the circles having these radii are respectively 1, 4, 4, 8, 4, 8, 12, 12, 8, 8, and 12 as shown in Figure 9.

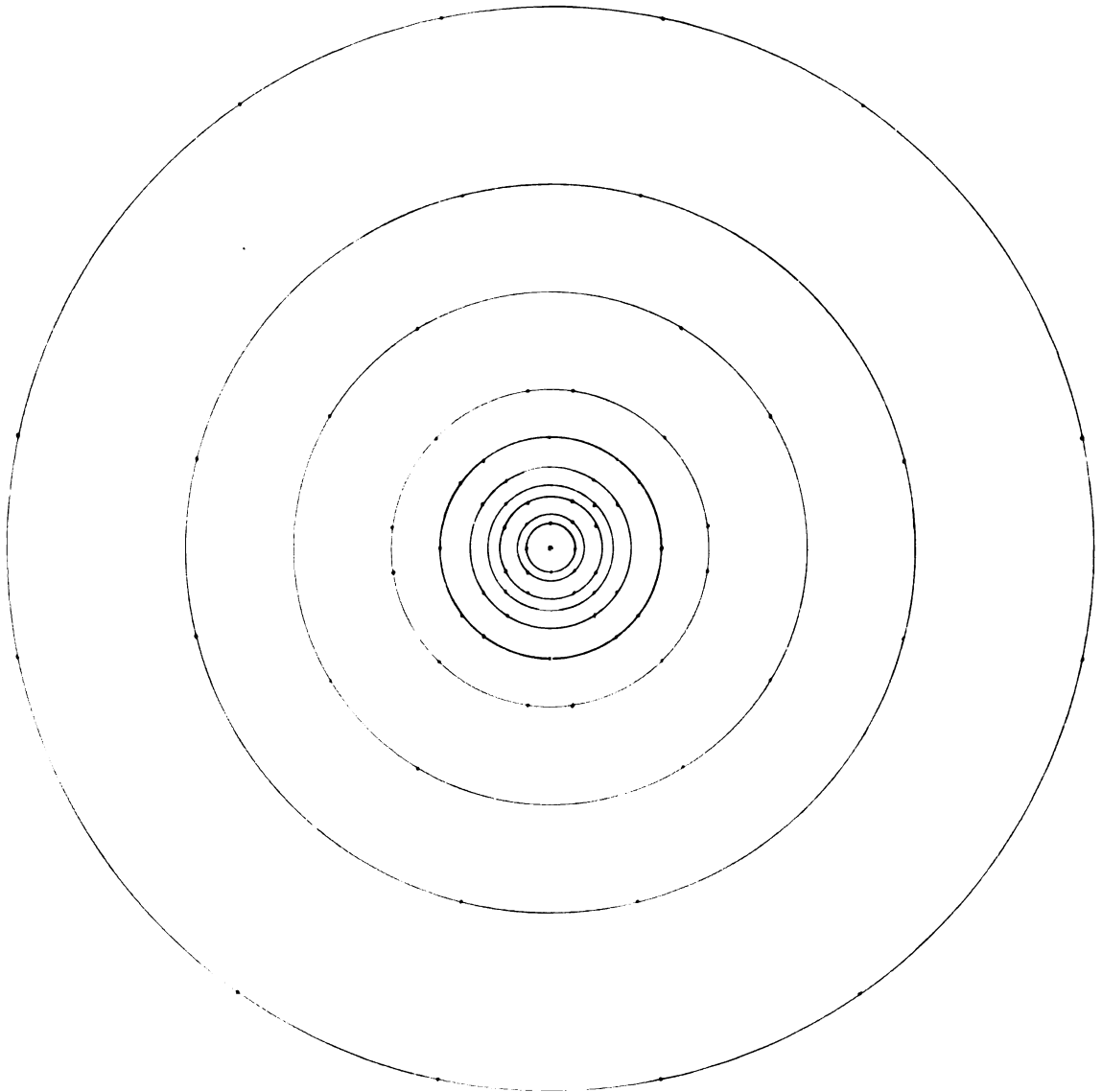
Next a Lagrange interpolation polynomial is fitted to $\Delta \phi(0)$ and the n values $\Delta \phi(-ma)$ computed from equation 5 to obtain the approximation formula,

$$\Delta \phi(z) \approx \sum_{m=0}^n \frac{(-1)^n z (z+a)(z+2a) \cdots (z+na)}{a^n (z+ma) (n-m)! m!} \Delta \phi(-ma). \quad (7)$$

From experimental work it has been found that the approximations are good for $n < 5$.

The accuracy of equation 7 depends on the accuracy of $\Delta \phi(-ma)$ as computed from the upward continuation integral, equation 5. A numerical integration employing a mean value theorem over each integral $r_1 \leq r \leq r_{i+1}$ is carried out. The integral in equation 5 is replaced by the sum

$$\Delta \phi(-ma) \approx \sum_{i=0}^{n-1} \left[(r_{i+1} - r_i)^{-1} \int_{r_i}^{r_{i+1}} \Delta \phi(r) dr \right] ma \left\{ \left[r_i^2 + (ma)^2 \right]^{-\frac{1}{2}} - \left[r_{i+1}^2 + (ma)^2 \right]^{-\frac{1}{2}} \right\} + O\left(\frac{1}{r_n}\right) \quad (8)$$



TEMPLATE FOR ANALYTICAL METHODS

FIGURE 9

By setting α equal to unity and successively evaluating equation 8 for $m = 1, 2, 3, 4, 5$, the five sets of coefficients adopted for upward continuation are obtained. The working equation is given as

$$\Delta\phi(-ma) \approx \sum_{i=0}^{10} \Delta\bar{\phi}(r_i) K(r_i, m) \quad (9)$$

where $K(r_i, m)$ is the set of coefficients which operate on the center value and the ten ring-averages values, $\Delta\bar{\phi}(r_i)$, to give $\Delta\phi$ at ma mesh units above the original plane.

For downward continuation, z is set equal to $a, 2a, 3a, 4a, 5a$, in equation 7. This results in the calculation of the gravity on these levels below $z = 0$, using the same ten ring averages, $\Delta\bar{\phi}(r_i)$. The working equation is given as

$$\Delta\phi(k) \approx \sum_{i=0}^{10} \Delta\phi(r_i) D(r_i, k) \quad (10)$$

where $D(r_i, k)$ is the set of coefficients for computing $\Delta\phi$ k mesh units below the original plane.

Second Derivative

The second derivative method has proved useful for gravity interpretation. Its importance arises from the fact that the second derivative analysis tends to emphasize the smaller, shallower geologic features at the expense of larger, regional features. The subject of second derivatives

is treated by many authors, including Peters, (1949); Elkins (1951); Henderson and Zietz (1949); Rosenbach (1953), and Henderson (1960). Henderson's method was used in this study.

The comprehensive character of equation 5 for upward continuation is demonstrated in that it can be differentiated to give the first and second derivatives of the gravity field. The second derivative equation uses the same ten ring averages, $\Delta\bar{\phi}(r_i)$.

Equation 7 can be written in the following equivalent determinantal form:

$$\Delta\phi(z) \approx - |V|^{-1} \begin{vmatrix} 0 & 1 & -z/a & (z/a)^2 & \dots & (-z/a)^n \\ \Delta\phi(0) & 1 & 0 & 0 & \dots & 0 \\ \Delta\phi(-a) & 1 & 1 & 1 & \dots & 1 \\ \Delta\phi(-2a) & 1 & 2 & 2 & \dots & 2^n \\ . & . & . & . & \dots & . \\ . & . & . & . & \dots & . \\ . & . & . & . & \dots & . \\ \Delta\phi(-na) & 1 & n & n^2 & \dots & n^n \end{vmatrix} \quad (11)$$

where (V) is the Vandermode determinant obtained by deleting the first two rows and columns of equation 11.

If n equals 5 in equation 11 and differentiating with respect to z the first derivative equation is obtained.

$$\frac{\partial(\Delta\phi)}{\partial z} = -(a|V|)^{-1} \begin{vmatrix} 0 & 0 & -1 & -2(z/a) & -3(z/a)^2 & -4(z/a)^3 & -5(z/a)^4 \\ \Delta\phi(0) & 1 & 0 & 0 & 0 & 0 & 0 \\ \Delta\phi(-a) & 1 & 1 & 1 & 1 & 1 & 1 \\ \Delta\phi(-2a) & 1 & 2 & 2^2 & 2^3 & 2^4 & 2^5 \\ \Delta\phi(-3a) & 1 & 3 & 3^2 & 3^3 & 3^4 & 3^5 \\ \Delta\phi(-4a) & 1 & 4 & 4^2 & 4^3 & 4^4 & 4^5 \\ \Delta\phi(-5a) & 1 & 5 & 5^2 & 5^3 & 5^4 & 5^5 \end{vmatrix} \quad (12)$$

If $Z=0$ in equation 12, first vertical derivatives can be calculated on the plane of observation by the equation

$$\frac{\partial \Delta \phi}{\partial z} \Big|_{z=0} \approx \frac{1}{a} \left[1 + + + + \Delta \phi(0) + \frac{1}{a} \sum_{m=1}^5 \frac{(-1)^m 5!}{m^2 (m-1)! (5-m)!} \Delta \phi(-ma) \right] \quad (13)$$

To obtain the sets of coefficients for computing $[\partial(\Delta \phi)/\partial z]_{z=k}$ using the ten ring averages, $\Delta \bar{\phi}(r_i)$, setting a equal to unity, and putting the working upward continuation equation into equation 12, the first derivative working equation is obtained,

$$\frac{\partial(\Delta \phi)}{\partial z} \Big|_{z=k} \approx \sum_{i=0}^{10} \Delta \bar{\phi}(r_i) D'(r_i, k), \quad (14)$$

where $D'(r_i, k)$ are the first vertical derivative coefficients for the appropriate K mesh units below the plane of observation.

Similarly the second vertical derivative formula can be obtained by differentiating equation 12 with respect to Z .

$$\frac{\partial^2(\Delta \phi)}{\partial z^2} = - (a^2 |V|)^{-1} \begin{vmatrix} 0 & 0 & 0 & 0 & -6(z/a) & 12(z/a)^2 & -20(z/a)^3 \\ \Delta \phi(0) & 1 & 0 & 0 & 0 & 0 & 0 \\ \Delta \phi(-a) & 1 & 1 & 1 & 1 & 1 & 1 \\ \Delta \phi(-2a) & 1 & 2 & 2^2 & 2^3 & 2^4 & 2^5 \\ \Delta \phi(-3a) & 1 & 3 & 3^2 & 3^3 & 3^4 & 3^5 \\ \Delta \phi(-4a) & 1 & 4 & 4^2 & 4^3 & 4^4 & 4^5 \\ \Delta \phi(-5a) & 1 & 5 & 5^2 & 5^3 & 5^4 & 5^5 \end{vmatrix} \quad (15)$$

The resulting working equation for the second vertical derivative is

$$\left[\frac{\partial^2 (\Delta \phi)}{\partial z^2} \right]_{z=k} \approx \sum_{i=0}^{10} \Delta \bar{\phi} (r_i) D'' (r_i, k) \quad (16)$$

where $D'' (r_i, k)$ are the coefficients of the second derivative.

Theoretical Gravity Formulas

Talwani's Gravity Computations for Two-Dimensional Bodies

In geological and geophysical studies, many of the structures of interest are horizontally linear and can be approximated by two-dimensional forms of analysis. The outer boundary of any two dimensional body can be approximated by a polygon. This approximation can be made as accurate as one wishes by making the number of sides of the polygon sufficiently large.

The vertical component of gravity due to the polygon can be obtained at any given point and there are no limits on the size or position of the body. The digital computer allows the complex expression for the vertical component of gravity to be solved easily and rapidly.

Given an n sided polygon ABCDE, Figure 10.

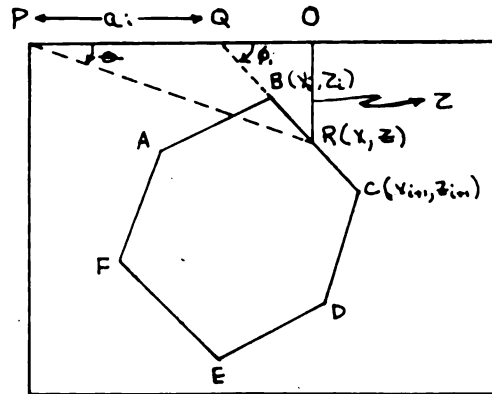


FIGURE 10

Geometrical elements for Talwani's 2-D calculations.

Let P be the point at which the gravitational attraction will be calculated. The point P lies in the xz plane as does the polygon. Let z be defined as positive downwards and θ is measured from the positive x -axis downward.

The vertical component of gravity at the origin (P) from the two-dimensional polygon is

$$2G\rho\oint z d\theta \quad (17)$$

where G is the universal gravitational constant and P the volume density differential, with the line integral being taken around the outer boundary of the polygon (Hubbert, 1948). The above integral is then evaluated for the given polygon. The contribution of a side of the polygon, say, side BC can

be computed. The side CB is extended to meet the x-axis at q at an angle ϕ_1 . Let PQ = a_1 , then

$$z = x \tan \theta \quad (18)$$

for any point R on side BC and

$$z = (x - a_1) \tan \phi_1. \quad (19)$$

From equations 18 and 19

$$z = \frac{a_1 \tan \theta \tan \phi_1}{\tan \phi_1 - \tan \theta} \quad (20)$$

now

$$\int_{BC} z d\theta = \int_B^C \frac{a_1 \tan \theta \tan \phi_1}{\tan \phi_1 - \tan \theta} d\theta = z_1. \quad (21)$$

The vertical component of gravity V can now be given as

$$V = 2Gp \sum_{i=1}^m z_i \quad (22)$$

with the summations being made over the n sides of the polygon. The integral for Z_1 must now be solved.

For the general case it can be shown that

$$z_1 = a_1 \sin \phi_1 \cos \phi_1 \left[\theta_1 - \theta_{1+1} + \tan \phi_1 \log_e \frac{\cos \theta_1 (\tan \theta_1 - \tan(\phi_1))}{\cos \theta_{1+1} (\tan \theta_{1+1} - \tan \phi_1)} \right] \quad (23)$$

where

$$\theta_1 = \tan^{-1} \frac{z_1}{x_1}$$

$$\phi_1 = \tan^{-1} \frac{z_{1+1} - z_1}{x_{1+1} - x_1}$$

and

$$a_1 = x_{1+1} + z_{1+1} \frac{x_{1+1} - x_1}{z_1 - z_{1+1}}$$

It should be noted that θ_i , θ_{i+1} , ϕ_i , and a_i can all be explicitly expressed in terms of the x_i 's and z_i 's. This is advantageous as the easiest way to define the outer edges of a body is to specify the coordinates of adjacent points or the vertices of the body.

Talwani's Gravity Computations for Three Dimensional Bodies of Arbitrary Shape

A three-dimensional body can be represented by contours on the body. By making the number of sides of a polygon sufficiently large, any irregular outline can be closely approximated. If each contour of the three-dimensional body is replaced by polygonal lamina, the gravitational attraction caused by the lamina can be calculated at any point external of the body. Thus, by interpolating between contour lines and numerical integration, the gravitational attraction of a three dimensional body can be computed.

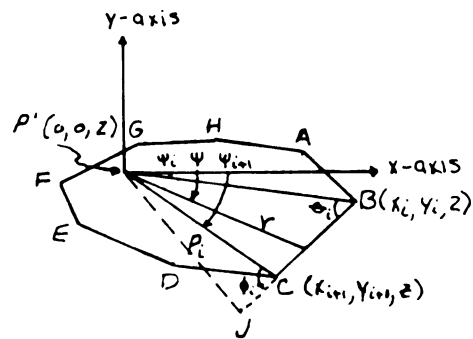
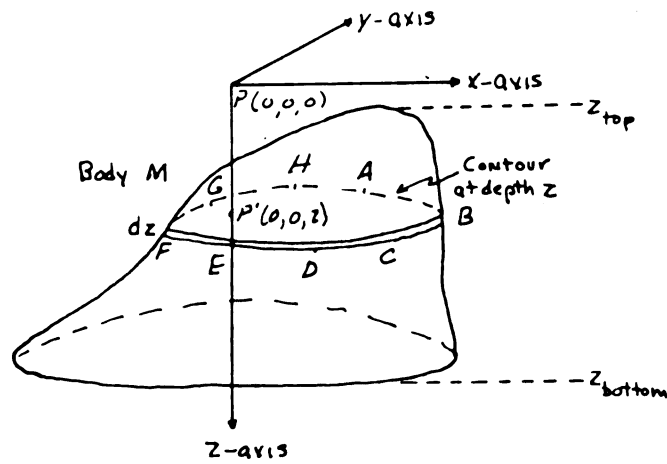


FIGURE II

Geometrical Elements for Talwani's 3-D Calculation

Figure 11 shows geometrically the elements involved in the gravity computations for a three-dimensional body. Point P represents the point at which the gravitational attraction of the three-dimensional mass will be calculated. Point P also is the origin of a left handed cartesian coordinate system with the z-axis positive downward. A contour on the surface of the body is represented by the polygonal lamina ABCDEF'...' of infinitesimal thickness dz. Let Δg be the gravitational attraction at P from ABCDEF'....

Then

$$\Delta g = Vdz \quad (24)$$

where V is the attraction caused by ABCDEF'... per unit thickness. V can be expressed by a surface integral, and this can be reduced to two line integrals along the boundary of ABCDEF'....

Now

$$V = G\rho \left[\oint \frac{z}{(r^2 + z^2)^{3/2}} d\psi \right], \quad (25)$$

where G is the universal gravitational constant, ρ is the volume density differential of the lamina and z, ψ and r are the cylindrical coordinates used to define the boundary of ABCDEF'....

If P' is the projection of P on the plane ABCDEF'.... then PP' equals z. The line r is the radius vector in the plane ABCDEF'..., and ψ is the angle which it makes with an arbitrary x-axis in this plane, where ψ is positive in a clockwise sense from the positive x-axis.

If we evaluate the contribution of the two line integrals from side BC, the first integral gives

$$s d\psi = \psi_{i+1} - \psi_i \quad (26)$$

for $\overrightarrow{P'C}$ and $\overrightarrow{P'B}$. The second integral can be evaluated by drawing $P'J$ perpendicular from P' to BC . Let $P'J$ equal P_1 and θ_1 and ϕ_1 be respectively the angles which $\overrightarrow{BP'}$ and $\overrightarrow{CP'}$ make with BC . It can be seen from Figure 11 that

$$r = \frac{P_1}{\sin(\phi_1 - \psi_{i+1} + \psi)} \quad (27)$$

Making this substitution, and noting that P_1 , θ_1 , and ψ_{i+1} are all constants, so that ψ is the only variable left, the integral can then be solved to give the value,

$$\text{arc sin } \frac{z \cos \theta_1}{(P_1^2 + z^2)^{1/2}} - \text{arc sin } \frac{z \cos \phi_1}{(P_1^2 + z^2)^{1/2}} \quad (28)$$

Thus

$$V = G\rho \left[\psi_{i+1} - \psi_i - \text{arc sin } \frac{z \cos \phi_1}{(P_1^2 + z^2)^{1/2}} + \text{arc sin } \frac{z \cos \theta_1}{(P_1^2 + z^2)^{1/2}} \right] \quad (29)$$

The above expression is the attraction caused by the triangular lamina $P'BC$ per unit thickness at point P . The total attraction is then obtained by summing V over the n sides of the polygon to obtain

$$V = G\rho \left[\sum_{i=1}^n \left\{ \psi_{i+1} - \psi_i - \text{arc sin } \frac{z \cos \phi_1}{(P_1^2 + z^2)^{1/2}} + \text{arc sin } \frac{z \cos \theta_1}{(P_1^2 + z^2)^{1/2}} \right\} \right] \quad (30)$$

The terms P_1 , ψ_1 , ψ_{i+1} , $\cos\theta_1$ and $\cos\phi_1$ can be expressed in terms of x_1 , y_1 , the coordinates of B, and x_{i+1} , y_{i+1} , the coordinates of C. Thus V can be expressed in terms of coordinates of the vertices of the polygon ABCDEF....

The attraction caused by equation 30 is only for one lamina. The total attraction Δg from the mass can be evaluated by integrating equation 24 between z -top and z -bottom.

Thus

$$\Delta g \text{ total} = \int_{z \text{ bottom}}^{z \text{ top}} V \, dz. \quad (31)$$

CHAPTER V

GRAVITY ANOMALIES FROM REEFS

Yungul (1961) reviewed the problem of gravity exploration for reefs and answered some of the classical questions concerning reefs and gravity. Those questions which Yungul sought answers to are: "Do reefs create recognizable gravity anomalies?" and "If they do, what causes these anomalies?" At the time of his review, Yungul found literature concerning reefs and gravity for three geologic provinces.

His summary of the case histories prior to 1961 is shown in Table II which is shown on the following page.

A summary of the literature prior to 1961 as assembled by Yungul is as follows:

1. "Reefs frequently show recognizable gravity anomalies which may be (a) a simple high, (b) a high with a negative rim around it, (c) a low with a positive tendency in the center, or (d) a simple low. Most frequently it is a high with a negative rim around it, like a 'sombrero.'"
2. When the anomaly is of the sombrero type or a simple high, its intensity is of the order of +0.5 mg. This is greater than an allowable density contrast between the reef mass and the enclosing sediments could produce. What is more, a gravity high may be present even when the reef density is less than that of the enclosing sediments. Clayton (1951) reports that at North Snyder the cores show the reef is less dense than the surrounding shales. Yet the anomaly is +0.6 mg.

TABLE II
REEF GRAVITY, AVERAGE CONDITIONS AND RESULTS IN THE THREE REGIONS (after Yungul, 1961)

Geography	Geology						Gravity		
	Depth to Reef Bottom (feet)	Height of Reef (feet)	Width of Reef (miles)	Reef Rock	Envelope Formation	Draping	Basal Structure	Regional	Residual
West Texas (Midland Basin)	7000	600	2.5	CaCO ₃	Sandy Shale	Yes	Local high over a regional high	Flank, near apex of a high 3mg/mile	mg mg +0.6 2.5
The Great Lakes Region	2000	300	1.2	?	Dolomitic beds and salt beds thinning or wedging over reef	With salt layer: no Without salt layer: yes	?	?	+0.4 1.2
Alberta	6000	500	1.0	Dolomite	Calcareous Shale	Yes	?	Flank	+0.25 1.5

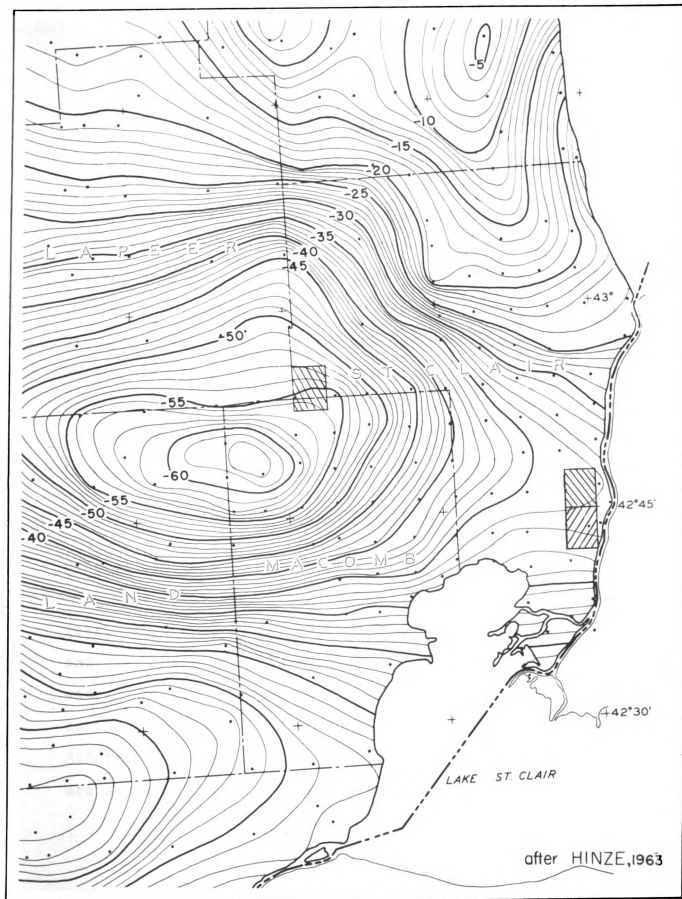
3. "The existence of a negative rim has so far not been satisfactorily explained.
4. The gravity highs are too narrow to be generated by masses at specified reef depths.
5. When the anomaly is of the sombrero type, the width of the positive is of the order of the width of the reef, irrespective of the reef depth.
6. The local (residual) anomalies are frequently located near the apexes of regional gravity highs.
7. As far as west Texas is concerned, the reef bottoms are local positive reliefs. We have no such data for the other regions.
8. Thinning and draping in the shales over and around the reefs are more than that indicated by conventional calculations of differential compaction.
9. Either because of certain underlying causes, or merely because of world-wide abundance of shales, the surrounding regional formations are shales in most cases.
10. The equivalent porosities in the reefs are estimated to be of the order of 12 per cent. The main constituent of most reefs is calcium carbonate. Consequently, the density is about 2.5.
11. The reef heights are from about one hundred to about eight hundred feet, widths 1/2 to 3 miles, and the known depths 2,000 to 7,000 ft. The slopes on the flanks may be up to 40 degrees.
12. In view of the wide ranges of the observed reef geometries and anomaly types, it seems, at present, that there is no direct, evident relation between the reef mass specifications (depth, height, extent, density) and the gravity anomaly specifications (type, intensity, extent). Consequently, certain factors other than the reef mass play the major role."

Yunguls conclusions, after his study of sedimentation and compaction around the reefs, were:

1. Isolated reefs show gravity anomalies on the order of +0.5 mg, with a true negative ring around it.
2. No direct relation between reef specifications and gravity anomaly specification can be expected.
3. The importance of the reef is not the reef itself but the conditions it created following its development.
4. The gravity anomaly depends on what happened after the reef was covered and to some extent pre-reef formations.
5. The major cause of the anomaly is probably the lateral variations of sand content in the shales around and above the reef.

He also mentions that while regional surveys could be used to locate reef belts, the potential of the gravity survey at present, is to locate the isolated reefs in a known reef belt.

As stated earlier, one purpose of this study is to define the anomalies from reefs in the Michigan Basin Province. The geological conditions for the Michigan Basin are understandably different from the reef areas discussed by Yungul, thus reef anomalies in the basin also can be expected to show differences from the anomalies of other areas.



PORTION OF REGIONAL GRAVITY MAP
OF MICHIGAN C.I.= 1 mg

FIGURE 12

CHAPTER VI

INTERPRETATION METHOD

Regional Gravity of Study Area

The Belle River Mills and Marine City survey areas are situated on the rim of a closed regional gravity minimum. This minimum, shown in Figure 12 (Hinze, 1963), is centered along the northern Macomb and Oakland County border. The Berlin area is situated closer to the center of the minimum than the other areas. The regional gravity of each of the survey areas agrees with the regional gravity pattern shown in Figure 12.

Marine City Reef Study

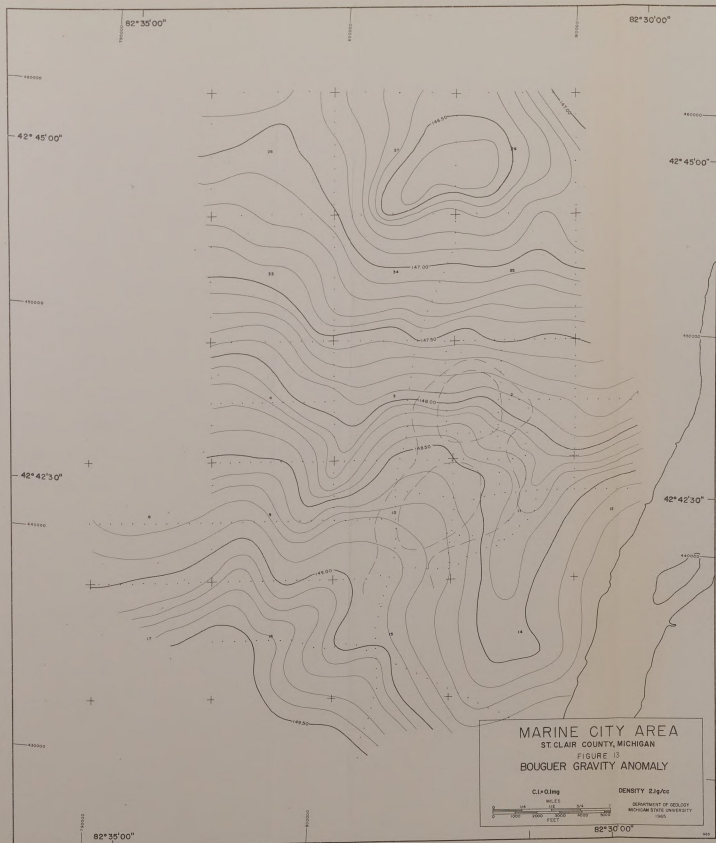
General Statement

The first reef selected for study is the Marine City reef. This reef is buried at a depth of about 2300 feet and has a base which is about one mile long and 3000 feet wide. Two pinnacles about one half mile apart are located on the broad base. These pinnacles have relief of 250 and 300 feet. The step by step procedures used in this study are shown by the flow chart (Figure 7a).

Observed Bouguer Gravity Anomaly Map

As shown on the regional gravity map, Figure 12, the Marine City survey is located in an area where the regional gravity gradient changes from a north-northwest trend to a western trend. The Bouguer gravity map (Figure 13) shows the regional gradient increasing 3.2 mg from north to south.

There are several anomalous areas which are readily observed. The closed low in the north-central portion of the area is quite noticeable. At first this was believed to be a result of a deep bedrock channel. However, the size and low gravity gradients indicate a much deeper source. The other recognizable anomaly is a north-northeast trending gravity high associated with the Marine City reef bordered on both sides by linear gravity lows. The magnitude of this high determined by the cross profile method is about 0.3 mg. It has a width of about 1.2 miles. The gravity lows have a magnitude of -0.3 mg. The linear nature of the two lows immediately brings to mind the possible presence of bedrock channels. A check of the bedrock topography map (Figure 6), confirms the presence of the channels. The sharpness and narrowness of the lows is a good indication that they are caused by features buried at a shallow depth. The outline of the reef mass is shown by dashed lines on all maps.



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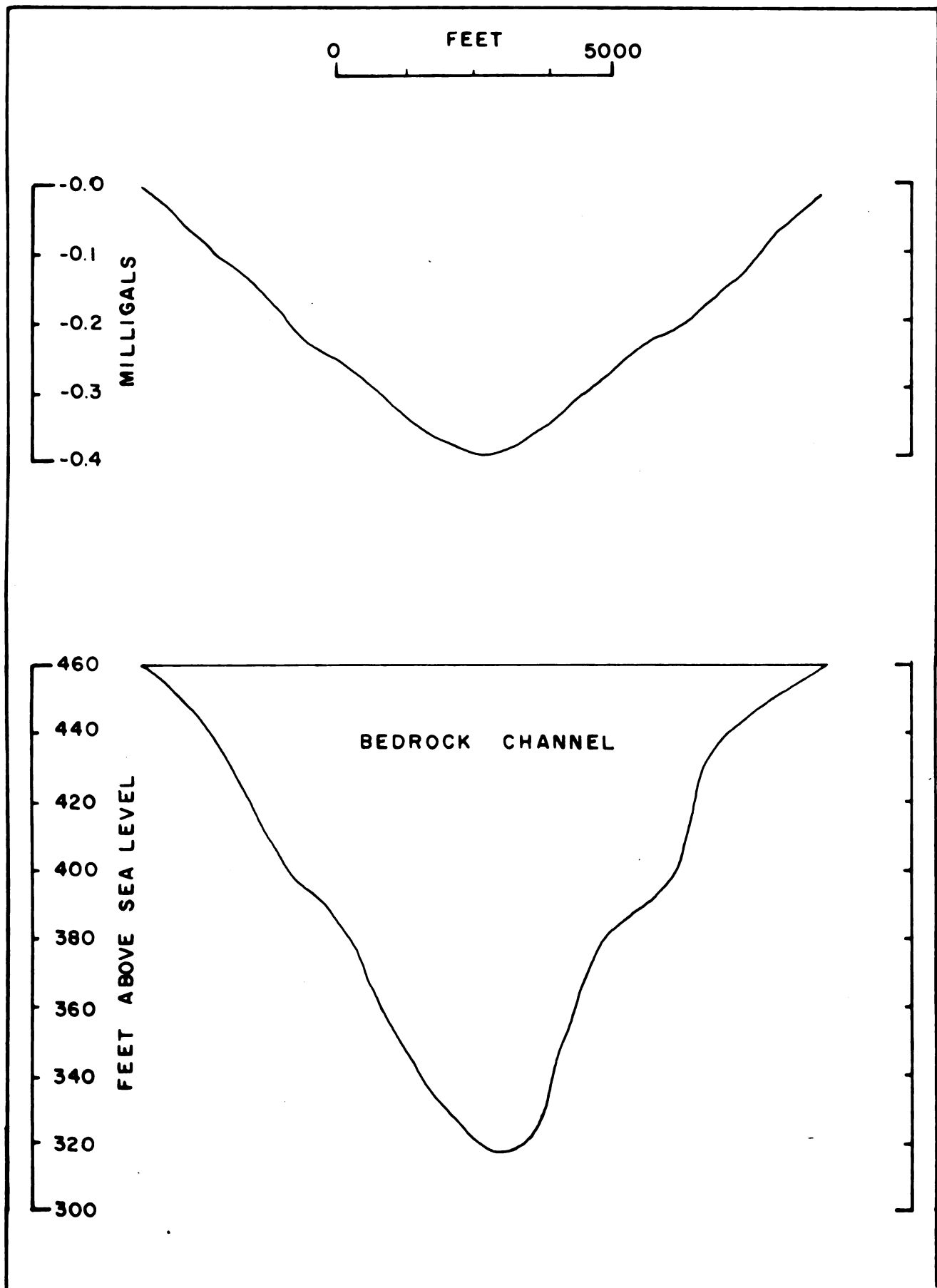
Effects of Bedrock Geology

The bedrock topography in this study area is quite irregular as seen on Figure 6. There is no doubt that the linear gravity lows flanking the Marine City reef anomaly are coincident with the bedrock channels shown by Brown (1963).

Profiles were constructed perpendicular to the strike of the channels at several locations. The gravity effects from the channels were calculated using Talwani's gravity computation method for two-dimensional bodies. The results indicate that the gravity effect of the channels in the area can produce the -0.3 mg anomaly observed on the Bouguer gravity map. Figure 14 shows the profile of a typical bedrock channel in the area and the resulting gravity effect. A density contrast of -0.2 g/cc was assumed for the calculation. The width of the anomaly is about two miles.

From this portion of the study it was concluded that bedrock topographic effects cause significant anomalies which can mask the reef anomaly. When the bedrock topography is known these gravity effects can be calculated using the two-dimensional method and removed from the Bouguer gravity. Another method of eliminating the bedrock effects will be discussed later.

TYPICAL BEDROCK⁵¹ CHANNEL AND GRAVITY ANOMALY



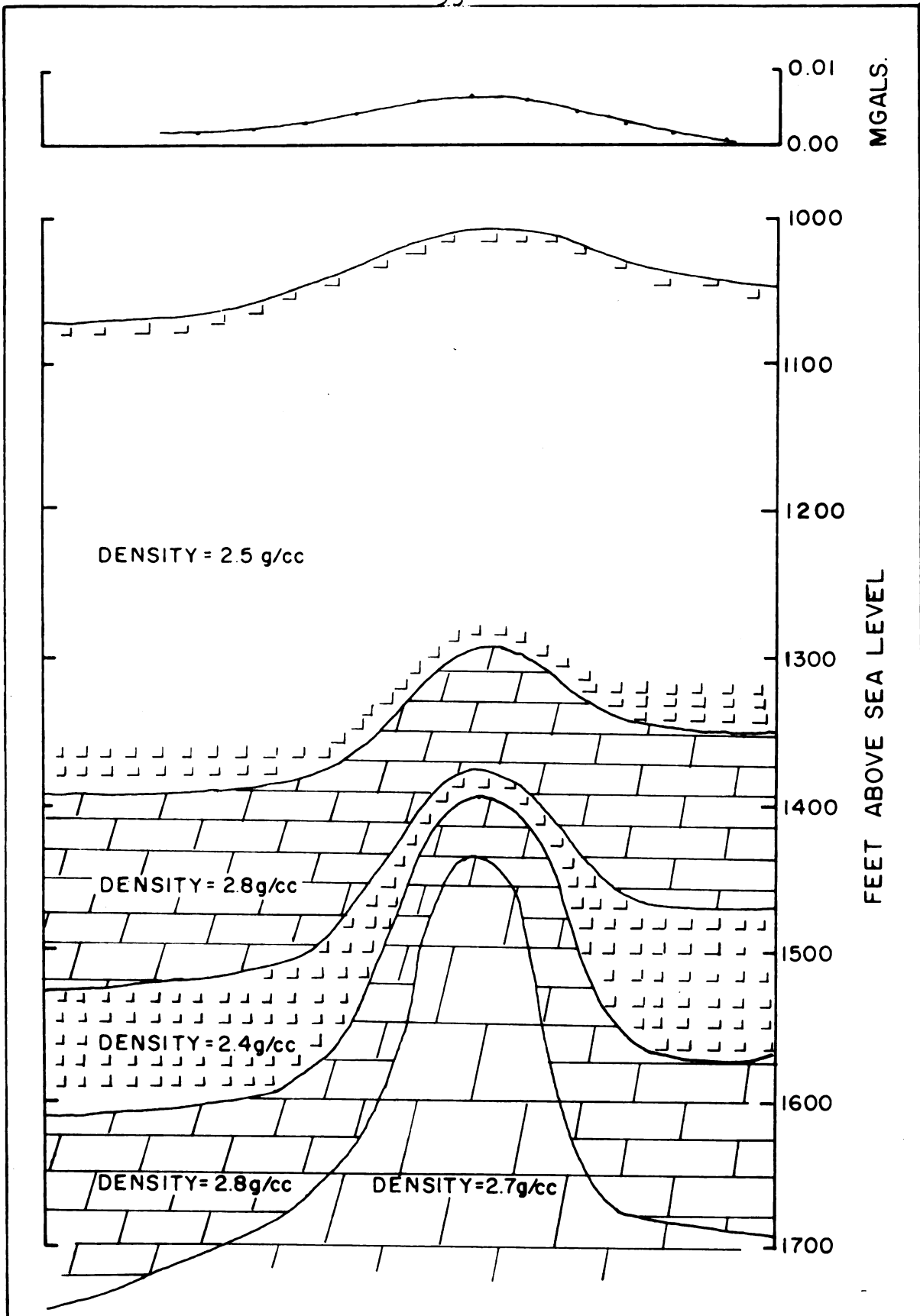
Expected Gravity Effects from Reefs

The structure of the Marine City reef is well defined from a large number of wells drilled both on and off reef. Structural contour maps of units which exhibit definite lithologic changes were obtained from the Michigan State Geological Survey (Ells, 1964) for the Marine City reef. Using the known geological conditions around the reef, the gravity effects of the reef were calculated using Talwani's three-dimensional technique.

The density contrasts used in the approximation were obtained from two density logs in St. Clair County and from an unpublished density study of the department of Geology, Michigan State University, using well cuttings from the St. Clair County area.

The formational units which exhibited a density contrast were divided into sections which could be approximated by a three-dimensional body. The density contrasts of the bodies used for the approximation were both positive and negative. The resulting gravity effect, calculated on the plane of observation, is on the order of $+0.006$ mg or essentially zero. A geologic cross-section of the reef with the associated gravity anomaly profile is illustrated in Figure 15.

The gravity effects produced only by the thinning of salt over the reef also were calculated. A small positive anomaly of 0.08 mg was obtained. This indicates that the



CROSS-SECTION OF REEF USED IN THREE-DIMENSIONAL GRAVITY CALCULATIONS AND THEORETICAL ANOMALY

FIGURE 15

salt thinning adds to the anomaly, but is not the primary factor causing the anomaly.

Several conclusions can be made from this part of the study. First, the anomaly is not caused by the geologic structure overlying the reef using average density values for the sediments. Second, the densities used are not representative or not enough information is available concerning the lateral variation of densities surrounding the reef.

A calculation of the theoretical gravity was made based upon a Mg/Ca ratio division of the stratigraphic units around and overlying the reef (Jodry, 1965). A theoretical anomaly of +0.23 mg was obtained using representative density values for the different lithologies as shown in Figure 16. The width of the anomaly is about two miles. These results confirm the earlier conclusion that there is insufficient knowledge of lateral density variations around the reefs.

A brief study was made to determine the depth at which the Marine City reef could be detected if all other factors were kept constant. A depth of burial of 4000 feet will cause an anomaly of about +0.1 mg. A detailed precision survey could detect an anomaly of this size.

The conclusions arrived at from the theoretical study are:

DENSITY VARIATIONS OVER MARINE CITY REEF AND THEORETICAL GRAVITY ANOMALY

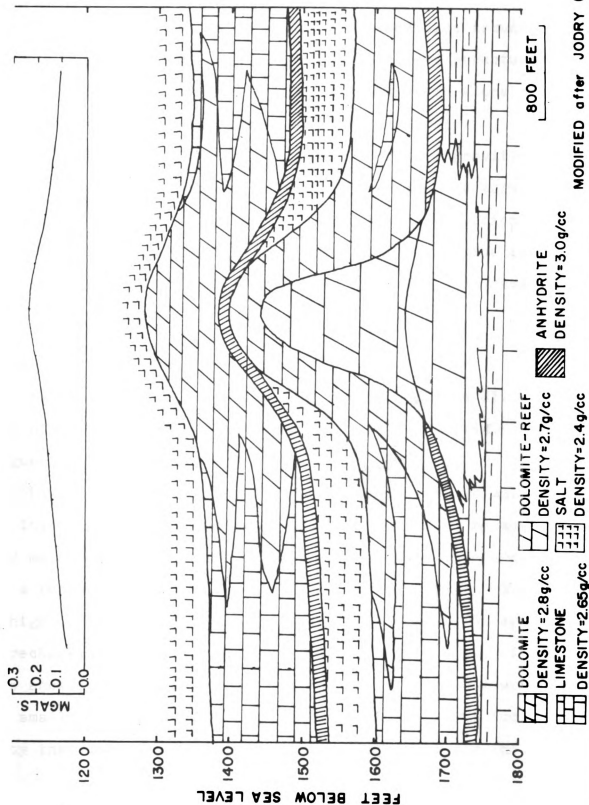


FIGURE 16

1. The principal cause of the anomaly is not from the reef itself or the post-reef structure alone, but from lateral variations in densities around the reef associated with the post-reef structure.
2. The thinning of the salt over the reefs alone cannot produce the observed gravity anomaly.
3. Theoretically, the reefs can produce a gravity anomaly which can be detected by detailed surveys.
4. A reef with the same set of geologic conditions as the Marine City reef, but buried at twice the depth still can be detected by a detailed gravity survey.

Cross-Profile Method

The cross-profile residual is shown in Figure 17. Each of the anomalous areas discussed on the observed Bouguer map (Figure 13) are readily isolated by this technique. The highest magnitude attained is +0.22 mg. The lows flanking the high have magnitudes of -0.3 mg and -0.2 mg and the low in the upper-central part of the area has a residual magnitude of -0.3 mg. In addition, a +0.2 mg high is observed in the left center portion of the area. In rechecking the observed Bouguer map, an indication of this anomaly is apparent. This anomaly is associated with the small China East reef. It was not known by the survey party that the area included the China East reef and the

fact was not checked until the residual anomaly was isolated by the cross-profile method.

The width of the zero contour of the Marine City reef is 6500 feet. This is less than the value obtained from the theoretical calculations.

There is no question that the cross-profile technique isolates the reef, but the undesirable effects of the bedrock topography are still present.

Least Square Polynomial Analysis

A least squares approximation of the original data was made using a 3rd, 5th, 7th, 9th, and 11th degree polynomial equations. The 3rd and 5th degree approximations isolate the reef anomaly with approximately the same amplitude as the theoretical anomaly. The 7th through 11th degree equations approximate the original data too closely and no recognizable residual is left. The 3rd and 5th degree residuals are shown in Figures 18 and 19. The extreme edges of the maps were not contoured as anomalous effects are created in areas where station density is limited.

The anomalous areas previously discussed are apparent on both the 3rd and 5th degree residual. The 3rd degree residual does not show a completely closed zero contour around the reef anomaly. This is an indication that the 3rd degree polynomial may not have adequately approximated the regional surface. The 5th degree residual map indicates

a north-northeast trend to the positive anomaly which conforms with the trend of the reef. The magnitude attains a value of 0.19 mg, but the contours only show 0.10 mg due to the 0.10 mg contour interval. The width of the positive anomaly is 6000 feet. This agrees closely with the cross-profile residual, but is less than the theoretical anomaly. The anomaly from the China East reef also is isolated by this technique. The anomalies over the Marine City and China East reefs are the only areas on the map which attain a magnitude of about +0.20 mg.

The data used in the previous discussion were the original data at a 500 foot station spacing. The data were then divided into two groups based on alternate stations, resulting in two maps with a 1000 foot station spacing. The 3rd and 5th degree polynomial approximations were calculated for both groups of 100 foot stations. The results show no appreciable difference from the results of the 500 foot stations. The 3rd and 5th degree residuals for the even number stations are shown in Figures 20 and 21.

It was concluded from the least squares polynomial analysis that:

1. The least squares analysis using random spaced data, will isolate the reef anomalies, but like the cross-profile method leaves the undesirable effects.

2. A 1000 foot station spacing is sufficient for detailed gravity surveys searching for reefs, however, there must be coverage in the immediate vicinity of the reef other than along the road network.

Interpolation of Bouguer Gravity

In order to apply the upward continuation, downward continuation, and second derivative techniques, gravity values must be interpolated from the original random spaced data onto a rectangular grid or square mesh system. This can be done manually by overlaying a grid system on the Bouguer map and interpolating gravity values at the desired points or the process can be accomplished with the aid of a computer in a relatively short time. Figure 22 shows the results of interpolating the gravity values on a 500 foot grid system for the Marine City area. There is a slight lateral shift in some gravity values on this map due to the interpolation process, but it is small enough to be unimportant.

Downward Continuation and Second Derivative on Original Surface

As described in the section on upward and downward continuation theory, the term $\Delta\bar{\phi}(r_1)$ is the average of the values computed on ten rings surrounding a center point. If all ten rings were used with a mesh interval of 500

feet, the diameter of the largest ring would be greater than the distance across the survey area. Therefore, a test was made using only seven rings. The results were compatible with the known reef anomaly and it was assumed that seven rings give the approximation desired. Using seven rings the radius of the largest ring is $\sqrt{50}$ times the mesh interval.

By calculating the gravity values on a plane below the original observation plane the perceptibility of gravity values is increased. The Bouguer gravity values were calculated on planes m mesh intervals below the original plane where $m=1, 2, 3, 4, 5$ and the mesh interval equals 500 feet.

The size of the interpolated grid system is an important factor in the results as the mesh interval chosen depends on the lateral extent of the anomalies and the sharpness of the gradients. If the mesh interval is too small, oscillation will develop and if it is too large only regional anomalies will remain (Henderson, 1960). A mesh interval of about one-fourth the depth to the top of the mass causing the anomaly is usually satisfactory (Henderson, 1960; Vacquier, 1951; and Nettleton, 1940).

There was no correlation between any of the anomalies on the downward continued planes and the anomalies on the original plane. The anomalies on the downward continued planes showed an oscillation character indicating the mesh interval was too small.

Upward Continuation

Gravity effects caused by features buried at a shallow depth are minimized by calculating the Bouguer gravity values on a plane above the original plane of observation. The gravity values were calculated on surfaces m mesh intervals above the original plane where $m = 1, 2, 3, 4, 5$ and the mesh interval equals 500 feet. The Bouguer gravity values on the plane five mesh intervals or 2500 feet above the original plane are shown in Figure 23. This method eliminates most of the small sharp anomalies and leaves the broad anomalies as desired. The anomaly over the Marine City reef is present but the anomaly from the China East reef is almost eliminated. The large low in the northern portion of the area is still present indicating a source other than a bedrock channel.

Downward Continuation of Upward Continued Surfaces

The size of the rings used in calculating $\Delta\bar{\phi}(r_1)$ cause an area to be lost around the periphery of the original area. When using a 500 feet mesh interval, the center point of the rings must be moved toward the center of the map a factor of seven mesh intervals before a complete set of values will be obtained as shown in Figure 24. This means a distance of seven mesh intervals is lost around the edge of the map when the upward continuation surface is calculated and an equal distance is lost from the upward continued surface when the downward continuation and second derivative values are calculated.

If the downward continuation and second derivatives techniques are performed on the upward continued surface, which is void of undesirable effects, the reef anomaly may be isolated. The upward continuation surface 2500 feet above the original surface was downward continued one through five mesh intervals maintaining the 500 foot mesh interval. The reef anomaly was not isolated by the downward continuation method, however, it was apparent that isolation of the reef was increasing for each successively lower plane. The reef anomaly is successfully isolated on the plane 5000 feet below the 2500 foot upward continued surface as shown in Figure 25, however, the anomaly is narrower than obtained by previous methods. The maximum width is approximately 5000 feet. This is not unrealistic as the plane on which the Bouguer gravity is calculated is about equal to the depth of the reef. The magnitude of the Bouguer gravity values are relative to one another and are in milligals. No other anomalies attain a magnitude equal to the reef anomaly.

Nettleton (1954) compared the results of several derivative techniques using a mesh interval of one-fourth, one-half, and equal to the depth of the source. The results indicate that while a mesh interval of one-fourth the depth of the source in most cases is optimum, a mesh interval of one-half the depth also is satisfactory. Because the 500 foot mesh interval appears to be too small for this study area, the mesh interval was changed to 1000 feet. When the

mesh interval equals 1000 feet, only five rings of the template are used. This was tested and the results indicated the approximation using five rings was adequate for this type of survey.

By changing the mesh interval on the upward continued surface from 500 feet to 1000 feet the downward continued planes can be calculated at intervals of 1000 feet. This effectively places the highest upward continued plane at 5000 feet above the original plane. By placing the planes of observation higher, the Bouguer gravity values show little change, except for a smoothing effect.

The downward continuation technique, using the 1000 foot mesh interval, applied to the 3000 and 5000 foot upward continuation surfaces successfully isolates the reef anomaly on the plane 5000 feet below each upward continued surface as shown in Figures 26 and 27.

The anomaly on the plane 5000 feet below the 3000 foot upward continued plane is narrow with a maximum width of 4000 feet. This is consistent with the previous downward continuation results. The magnitude of the closed anomaly is +0.8 mg.

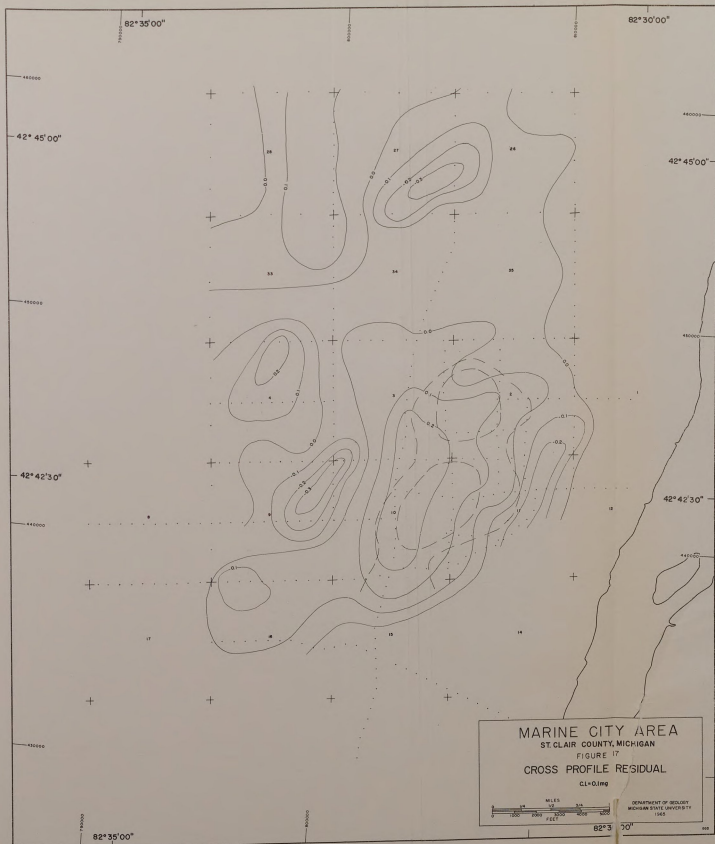
The anomaly on the plane 5000 feet below the 5000 foot upward continued surface is unique in that it isolates not one but two anomalies which almost coincide with the two pinnacles of the Marine City reef. The plane on which the two anomalies are isolated is essentially the same as

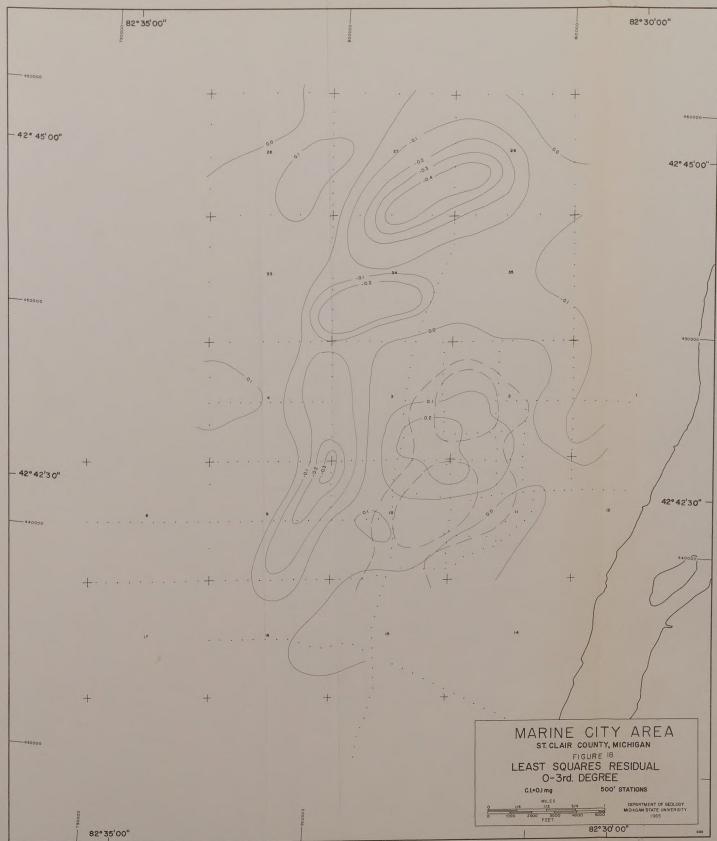
the original plane. The magnitude of the closed anomalies is $+0.3$ mg which is near the value of the original observed anomaly. The widths of the anomalies are approximately 5000 feet.

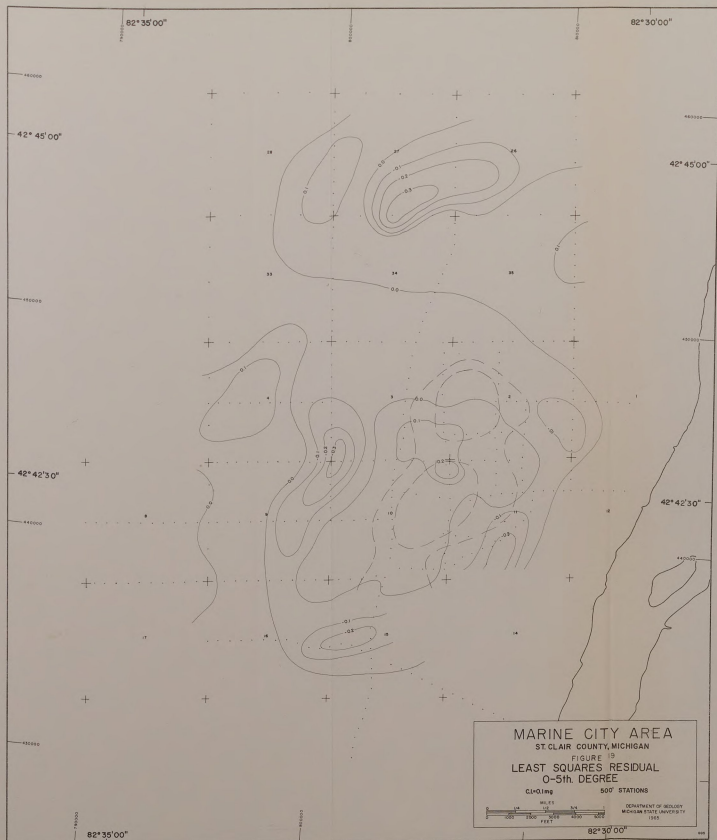
The Marine City reef anomaly is thus isolated on planes 5000 feet below the upward continued surfaces of 2500, 3000, and 5000 feet. It is concluded that by using a mesh interval of one-half the depth of the reef, the downward continuation method will isolate the reef anomalies from a surface upward continued a distance equal to the depth of the reef.

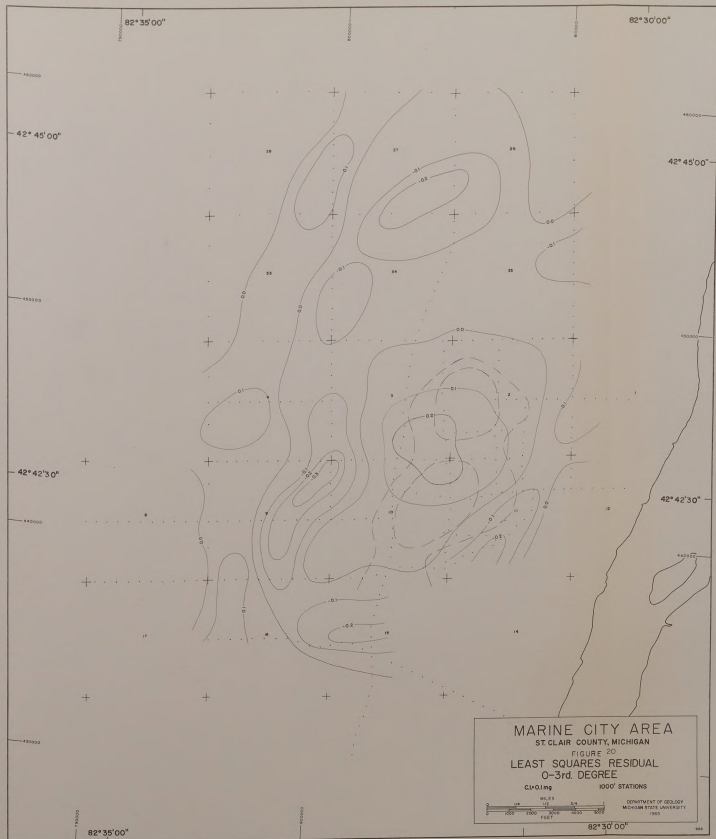
Second Derivatives

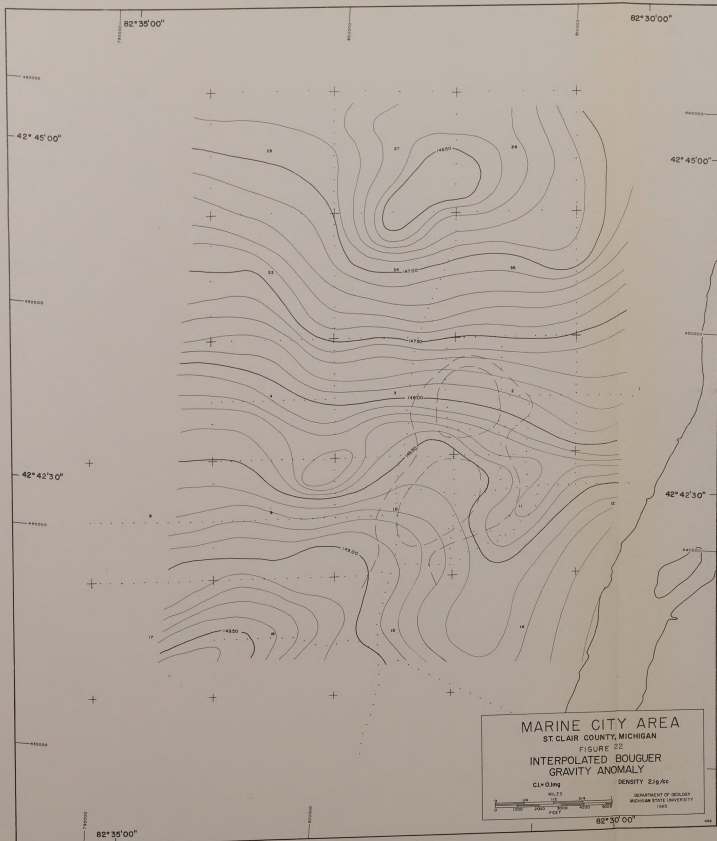
The second derivative technique of Henderson (1960) was applied to each upward continuation surface calculated. When the second derivative is calculated using seven rings and a 500 foot mesh interval, an oscillation effect results and no isolation of the reef anomaly occurs. When the derivatives are calculated using five rings and a 1000 foot mesh interval, the reef anomaly is isolated from the 2500, 3000, and 5000 foot upward continued surfaces (Figures 28, 29, and 30). The magnitudes of the reef anomaly produced by the second derivative techniques are not duplicated elsewhere on the map, however, the magnitude of the second derivative values were not evaluated quantitatively. The width of the anomalies is generally greater than those produced by the

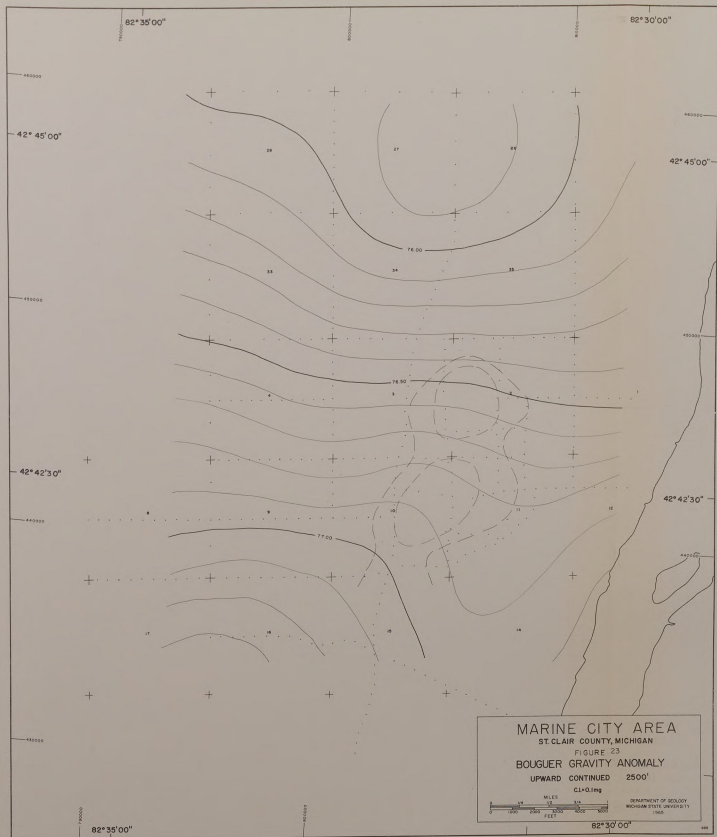












BOUNDARIES OF ANALYTICAL METHODS

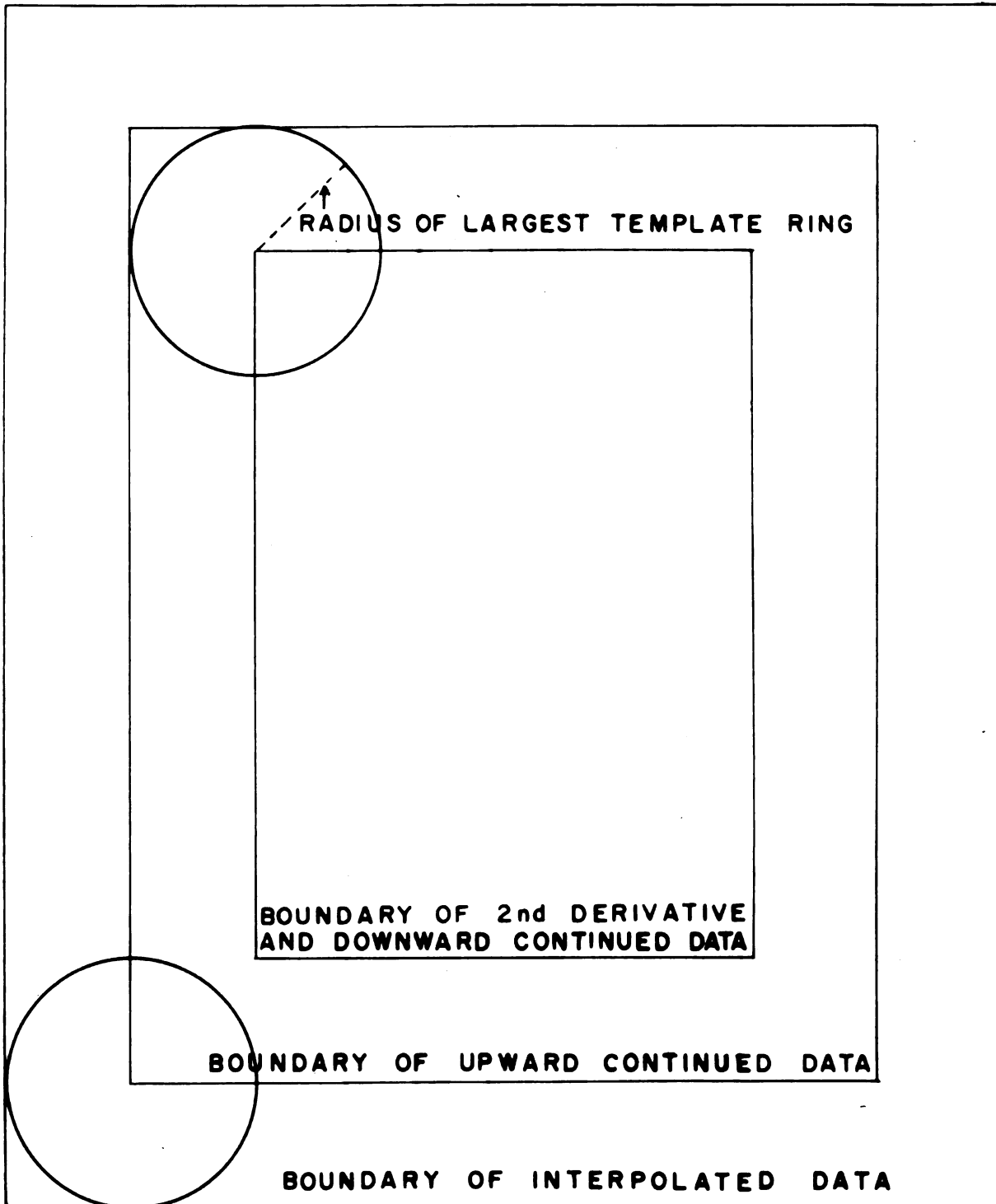
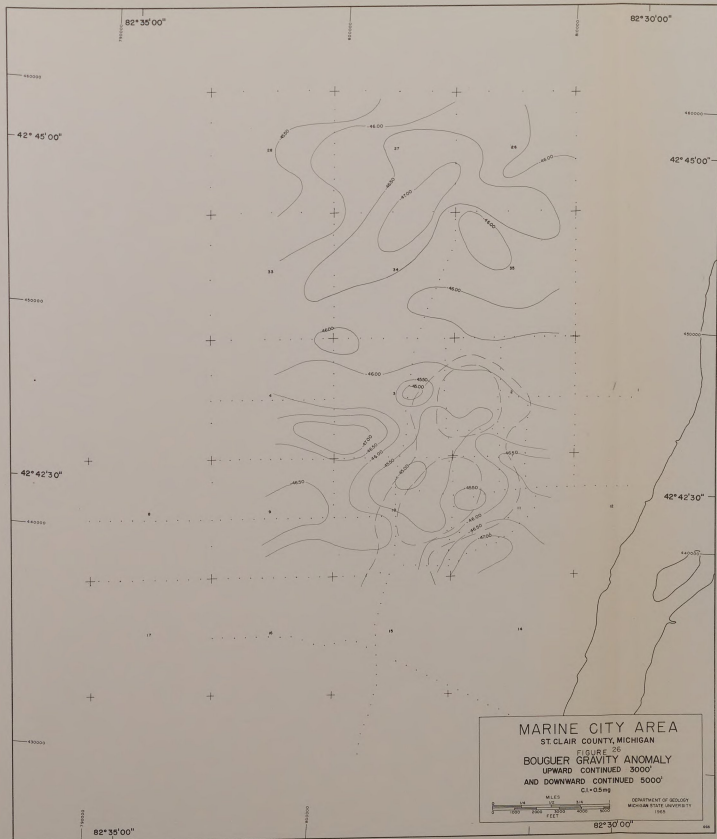
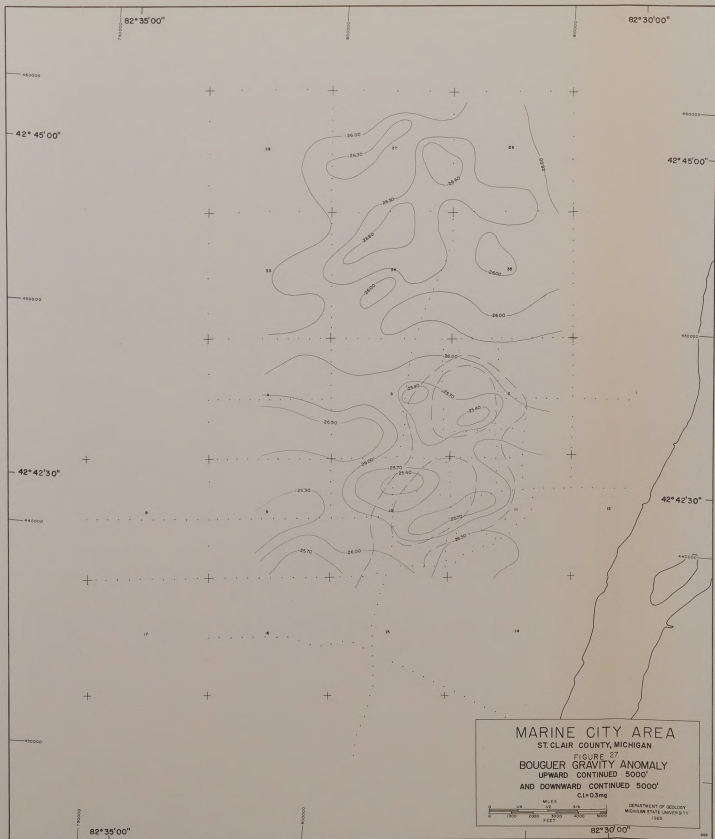
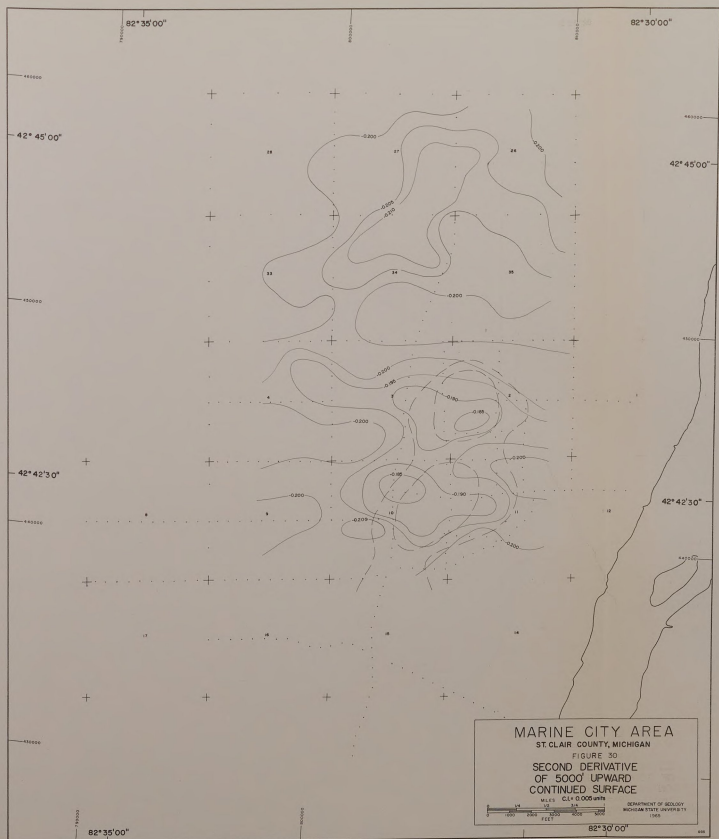


FIGURE 24







downward continuation technique below the surface, but less than the original observed and theoretical anomaly. They are on the order of 5000 feet wide. The anomaly isolated by the second derivative method from the 5000 foot upward continued surface (Figure 30) is actually two anomalies coinciding with the two pinnacles of the Marine City reef. This is consistent with the results of the downward continuation techniques.

It is concluded that the second derivative technique has a high resolving power and will successfully isolate the reef anomaly using a mesh interval of one-half the depth of the reef on upward continued surfaces calculated on planes approximately equal to the depth of the reef.

Belle River Mills Reef Study

General Statement

The second reef studied is the Belle River Mills reef. This reef is about three miles north of the Marine City reef and possesses several characteristics which are different from the Marine City reef. The two reefs are buried at approximately the same depth, but the Belle River Mills reef has a greater areal extent and is not a pinnacle type reef. The reef maintains a relief of 300 feet along its length of two miles. Its overall width is about 3000 feet. Compared to the Marine City reef, the Belle River Mills reef is greater in both areal extent and reef mass.

Observed Bouguer Gravity Anomaly Map

The Belle River Mills area is situated in an area where the regional gravity gradient flattens out and changes from a northwest direction to a western direction as shown in Figure 12. The resulting pattern for the area is a saucer shaped depression with a maximum change in magnitude of only 0.9 mg (Figure 31). Three anomalous areas are readily apparent on the Bouguer gravity map. A gravity high with a magnitude of 0.3 mg trends northeast across the center of the area. Two closed gravity lows with magnitudes of -0.15 mg and -0.35 mg flank the gravity high. The northernmost part of the high is associated with the Belle River Mills reef. The southern portion of the high will be discussed later.

Comparing the Bouguer gravity map with the bedrock topography map (Figure 6), it can be seen that several bedrock features coincide with the gravity anomalies in the area. The linear low on the southeast side of the high does not correlate with any bedrock channels, but well control in this area is sparse and there is a good possibility that a bedrock channel exists. The trend of the low can be followed into the Marine City area to the south. A major bedrock channel does exist in the area bordering the southern edge of the Belle River Mills area and the northern edge of the Marine City area. The channel predicted for the Belle River Mills area could possible be a tributary of this bedrock

channel. For comparison purposes, the gravity stations on the southern border of the Belle River Mills area are coincident with those on the northern border of the Marine City area.

Theoretical Study

Effects of Bedrock Topography

The gravity low to the northwest of the reef anomaly coincides with a broad bedrock depression. The gravity effect from this depression was calculated using Talwani's two-dimensional method. The resulting theoretical anomaly of -0.15 mg indicates the depression can cause the observed anomaly.

Expected Gravity Effects from Reef

The theoretical gravity effect of the Belle River Mills reef was calculated using Talwani's three-dimensional method. The average density contrasts were used because information on lateral density variations around the reef are not available. The calculated gravity anomaly is on the order of 0.006 mg. This is consistent with the anomaly calculated from the Marine City reef.

Results of Isolation Techniques

General Statement

The isolation techniques used in the Belle River Mills study were essentially the same as employed in the Marine

City study. These are the cross-profile, upward continuation, downward continuation, and second derivative methods.

Cross-Profile Method

The cross-profile residual is shown in Figure 32. An anomaly is associated with the reef, but it does not isolate the reef satisfactorily. The width of the zero contour is nearly two miles and the magnitude is +0.2 mg.

Least Squares Polynomial Analysis

The same degree polynomial approximations calculated for the Marine City area were used for this area. Again the 3rd and 5th degree polynomial equations for both the 500 and 1000 foot station spacing isolate the reef anomaly. The residual maps are shown in Figures 33, 34, 35, and 36. For this area, however, the 3rd degree fit was better than the 5th degree fit. This may be explained by the fact that the regional gradient is very small. The 5th degree polynomials for both the 500 foot and 1000 foot station spacing tend to approximate the original surface too closely.

The magnitude of the reef anomaly from the least square polynomial analysis is +0.18 mg. This is almost identical with the value obtained for the Marine City reef. It had been expected that the Belle River Mills reef would cause an anomaly larger than the Marine City reef. The similarity of the magnitudes substantiate the previous conclusion that the anomalies are not caused by the reef, but

by post reef conditions. The southern high is also indicated with a magnitude of about $+0.13$ mg.

It is concluded from the comparison of the Belle River Mills and Marine City least squares analysis that the degree of approximation depends on the nature of the regional gravity pattern and not the nature of the anomalies.

Interpolation of Bouguer Gravity

Several spurious effects are created in the interpolation of the Bouguer gravity for the Belle River Mills area (Figure 37). This is an inherent problem in interpolating the Bouguer gravity by the method adopted for the computer. These spurious effects are generally created in an east-west direction. The spurious effects on the Belle River Mills interpolated gravity map are near the edge of the reef anomaly but are not directly associated with the anomaly.

Downward Continuation and Second Derivative on Original Surface

The results were identical with the Marine City study and confirmed the previous conclusions that a mesh interval of one-fourth the depth to the anomaly causing mass is too small.

Upward Continuation

The upward continued surface 2500 feet above the original plane of observation is shown in Figure 39. The reef anomaly remains with two minimum areas on either side. The anomaly on the northwest side is the anomaly discussed

previously which coincides with a bedrock depression. It was not removed in the upward continuation method indicating the anomaly is too broad.

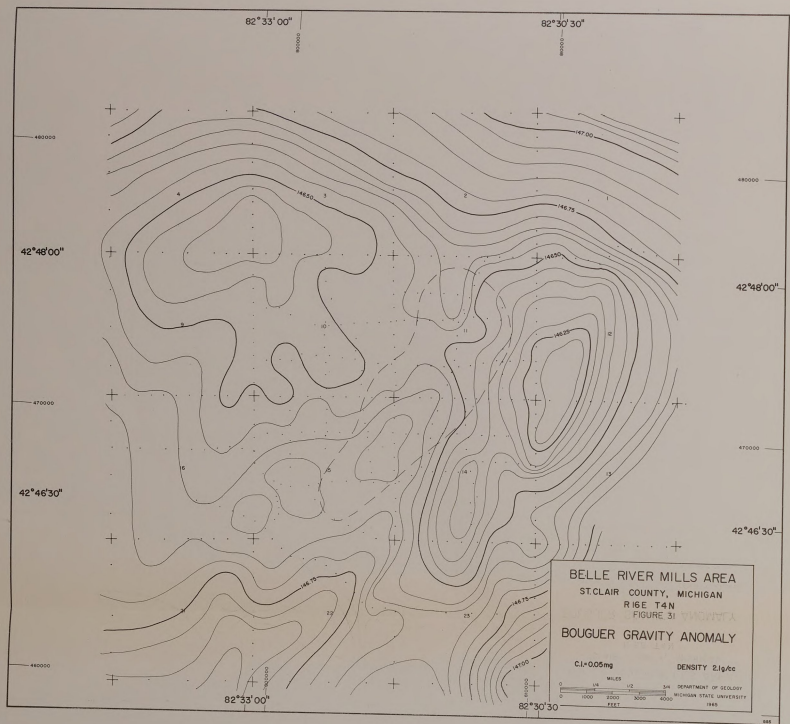
Downward Continuation of Upward Continued Surfaces

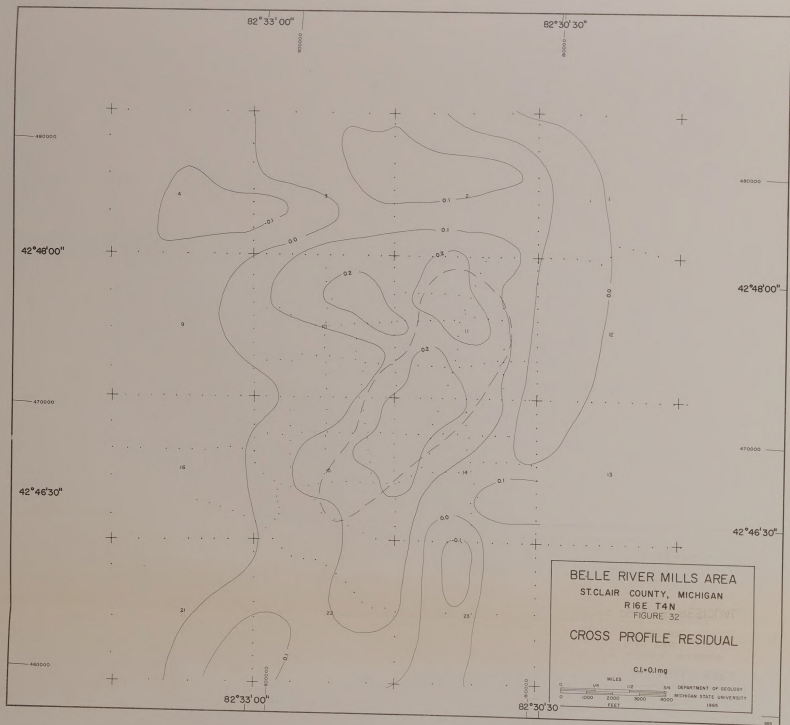
The same techniques applied to the Marine City study were used for the Belle River Mills area. The only combination which successfully isolates the reef anomaly is the downward continuation technique which calculated the values on a plane 5000 feet below the 5000 foot upward continued surface (Figure 39). A gravity high with the same magnitude of the reef anomaly also is isolated to the south of the reef anomaly.

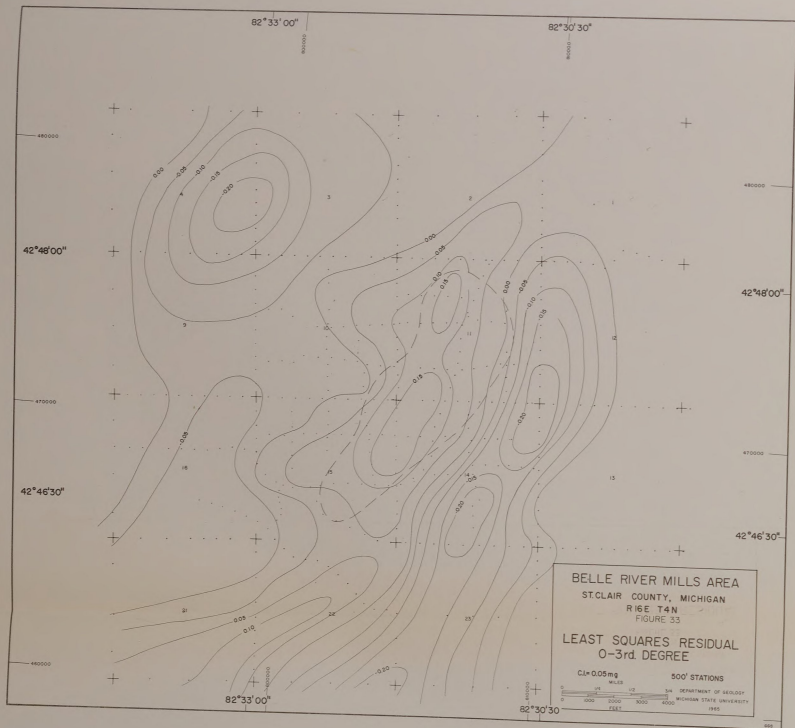
The values calculated 5000 feet below the 2500 and 3000 foot upward continued surfaces failed to isolate the reef, but showed a general gravity high over the area. The only major difference between the Marine City study area and the Belle River Mills study area is the regional gravity gradient. It is possible that the regional gradient of an area can cause the downward continuation techniques to vary in their isolation capabilities.

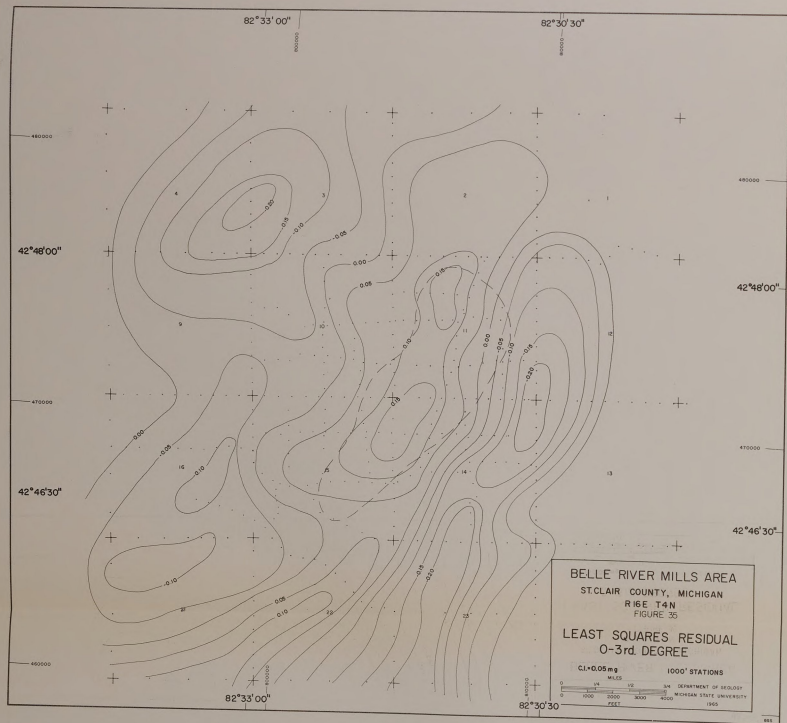
Second Derivatives

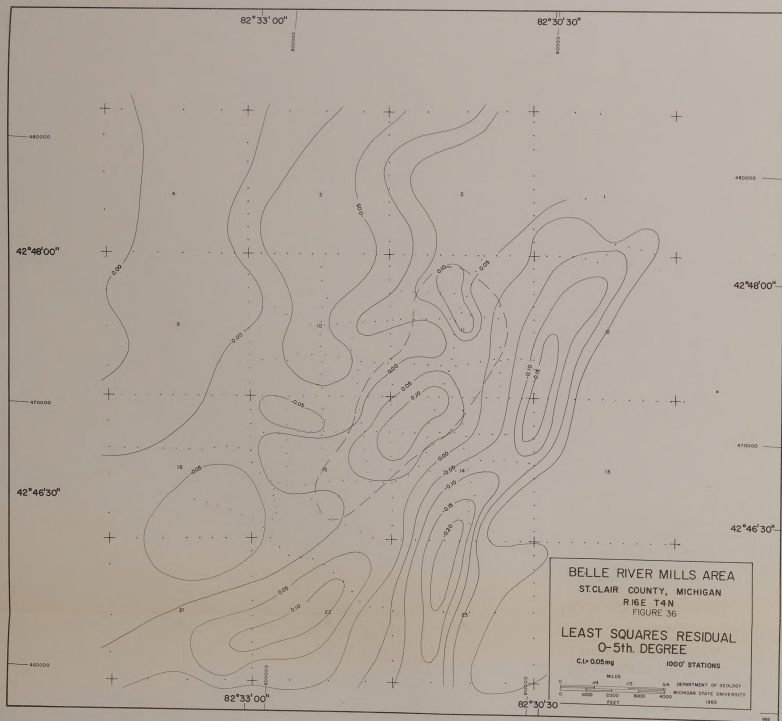
The second derivative values were calculated for the upward continued surfaces of 2500, 3000, and 5000 feet. Each of the second derivative calculations successfully isolate

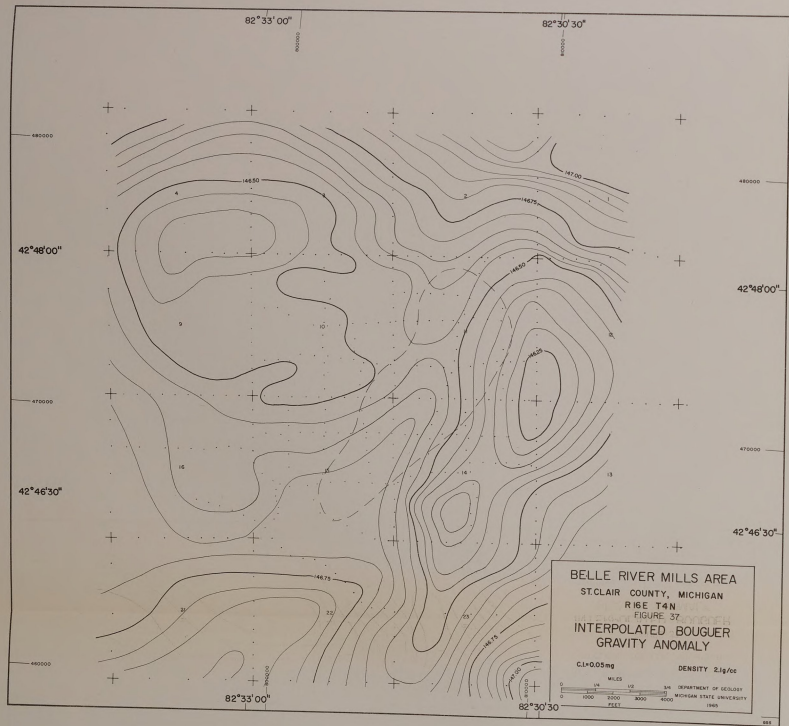


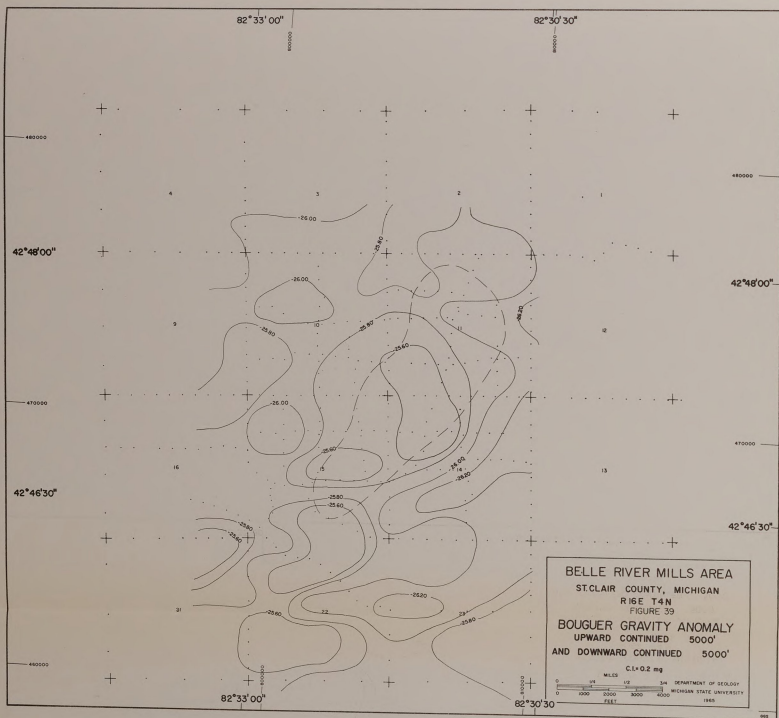


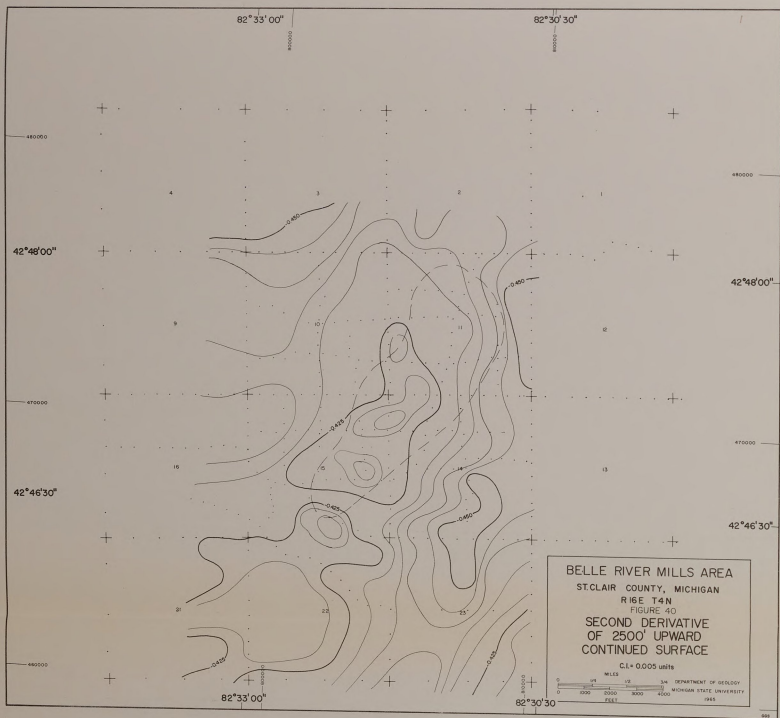


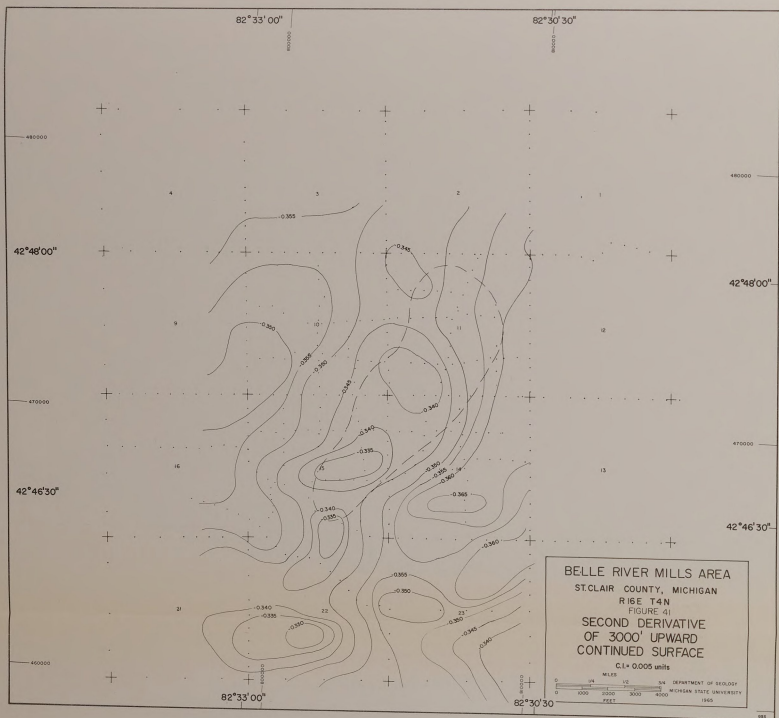


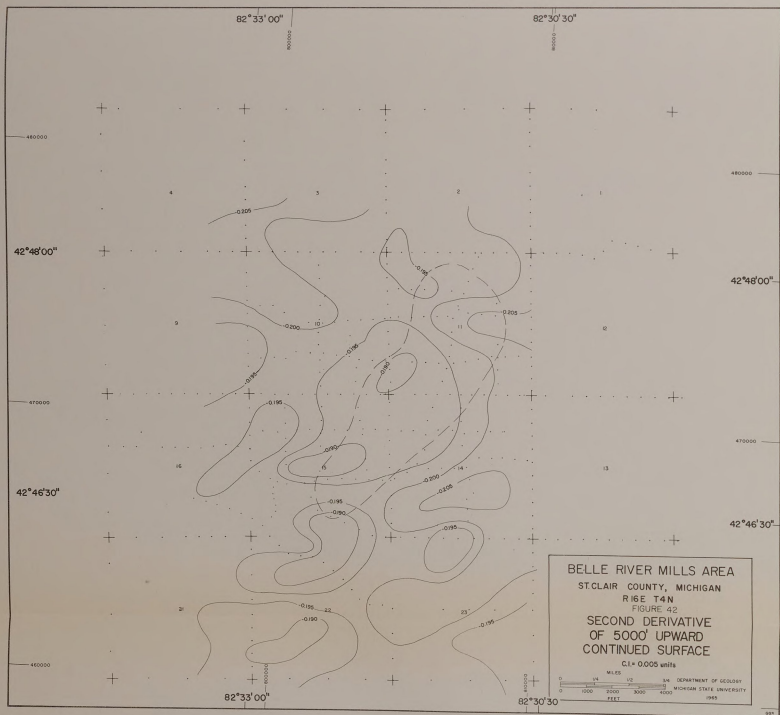












the Belle River Mills reef anomaly (Figures 40, 41 and 42). This is consistent with the Marine City results.

The second derivative techniques also isolate the gravity high to the south of the reef anomaly. The magnitudes of the two anomalies are again about the same. There is a good possibility that another reef may exist to the south of the Belle River Mills reef.

The results of the second derivative method on the Belle River Mills area indicate that the isolation power of the derivative technique is greater than the downward continuation techniques.

Berlin Reef Study

General Statement

The Berlin reef is situated more basinward than the Marine City and Belle River Mills reefs and is buried at a depth of about 3500 feet. The reef has a width of about 2500 feet and a length of one mile. The major portion of the reef mass is salt filled, but there are several producing wells in the reef.

This study was made assuming that nothing was known about the conditions surrounding the reef. A theoretical study was not made and the cross profile method was not employed.

Observed Bouguer Gravity Anomaly Map

The Berlin area, as shown on the regional gravity map (Figure 12) is located near the center of a closed regional gravity minimum. The Bouguer gravity map is shown in Figure 43. The nature of the regional gradient is readily observed on the Bouguer map by the semi-circle pattern of the contours. There are several anomalous areas on the Bouguer map, but the anomaly associated with the reef is not as obvious as in previous areas. Two linear lows flank a small positive trend which enters the area from the north-east.

Well control in this area is limited and no bedrock channels are indicated on the bedrock topography map (Brown, 1963). However, it is reasonable to assume that the linear gravity lows are reflections of bedrock channels.

Results of Isolation Techniques

Least Squares Polynomial Analysis

The results of the least squares polynomial analysis for the Berlin Survey are no different than the Marine City and Belle River Mills areas. The 3rd and 5th degree polynomial approximation for the 500 and 1000 foot station spacing isolate a positive anomaly over the reef. Negative areas are present on the west and east sides of the reef anomaly. The magnitude of the anomaly is again about +0.20 mg. This reaffirms the conclusion that the anomaly is not due to the

reef itself. The least square residual maps are shown in Figures 44, 45, 46 and 47.

Interpolation of Bouguer Gravity

Again a spurious effect was created by the interpolation technique, but it is not in the reef area and, therefore, was disregarded. The interpolated Bouguer gravity map is shown in Figure 48.

Upward Continuation Technique

The results of the gravity values calculated on the plane 2500 feet above the original surface is shown in Figure 49. The 2500 foot plane does not show the effects of the linear gravity lows, indicating further that a possibility of bedrock channels exists. A high is still present in the vicinity of the Berlin reef.

Downward Continuation

The downward continuation techniques failed to isolate the reef anomaly. The gravity values downward continued 5000 feet below the 2500, 3000 and 5000 foot upward continued surface showed a tendency to isolate the reef anomaly, but only indicate a positive area in the reef vicinity.

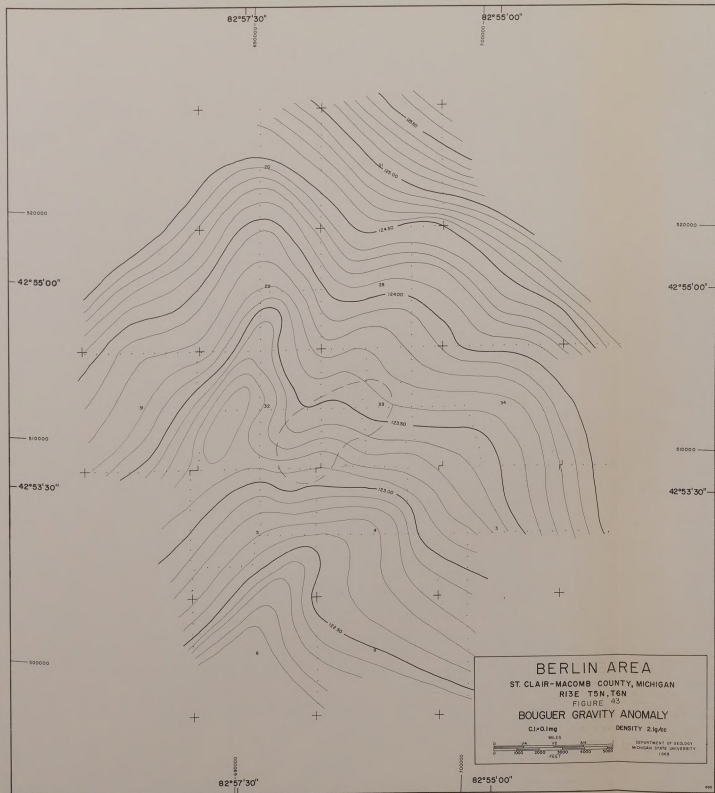
Second Derivative

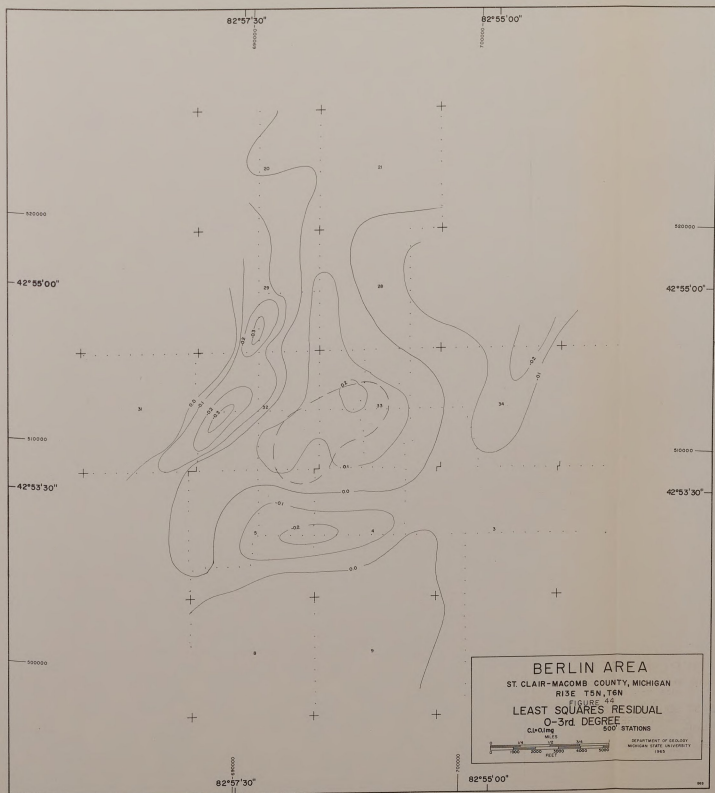
The second derivatives were calculated for the 2500, 3000 and 5000 foot upward continued surfaces. Each of the techniques successfully isolate the anomaly over the reef

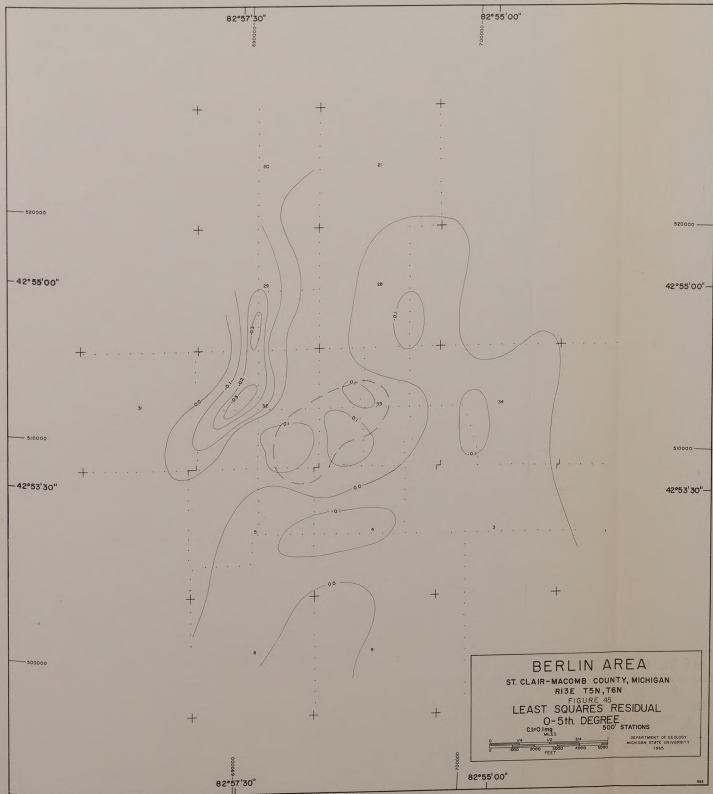
(Figures 50, 51 and 52). For the values calculated from the 2500 and 3000 foot upward continued surfaces the closed contour with the highest value is essentially coincident with the reef pinnacle. The overall anomaly is about 5000 feet wide. The values calculated on the 5000 foot surface show the broad anomaly from the reef, but do not show the closure coincident with the reef pinnacle. This may indicate that the distance between the depth of the reef and the upward continued surface was too great and a portion of the anomaly was lost.

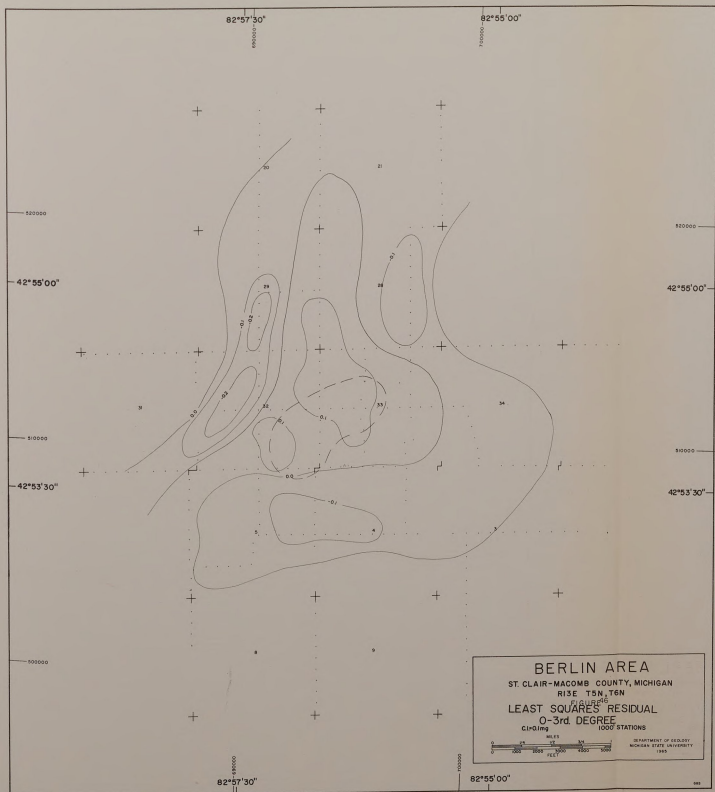
The conclusions reached from the Berlin study are:

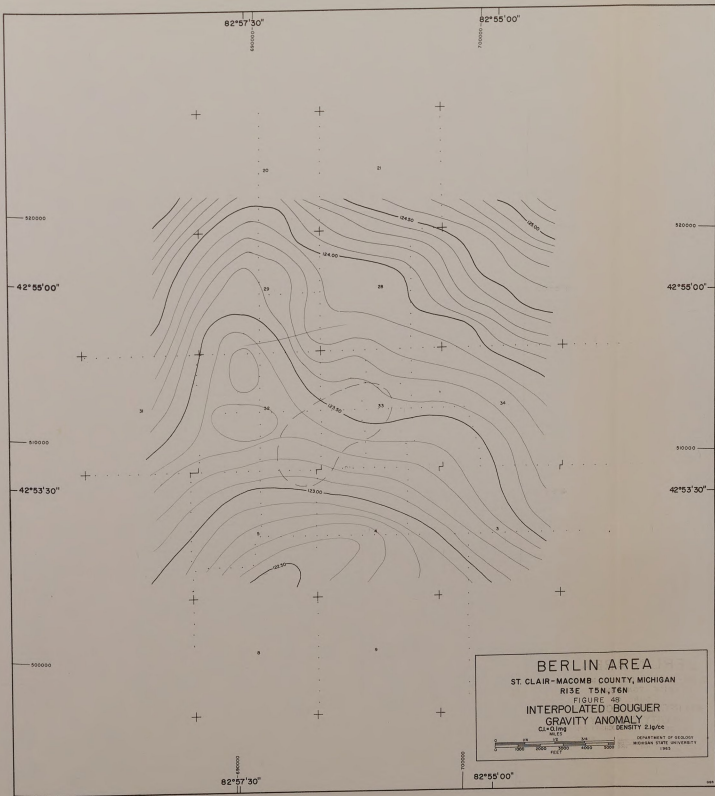
1. The second derivative techniques have a higher resolving power than the downward continuation techniques.
2. The upward continued surface should not be calculated higher than about 7500 feet above the expected reef depth.
3. The salt filling of the reef mass has no bearing on the magnitude of the observed anomaly.

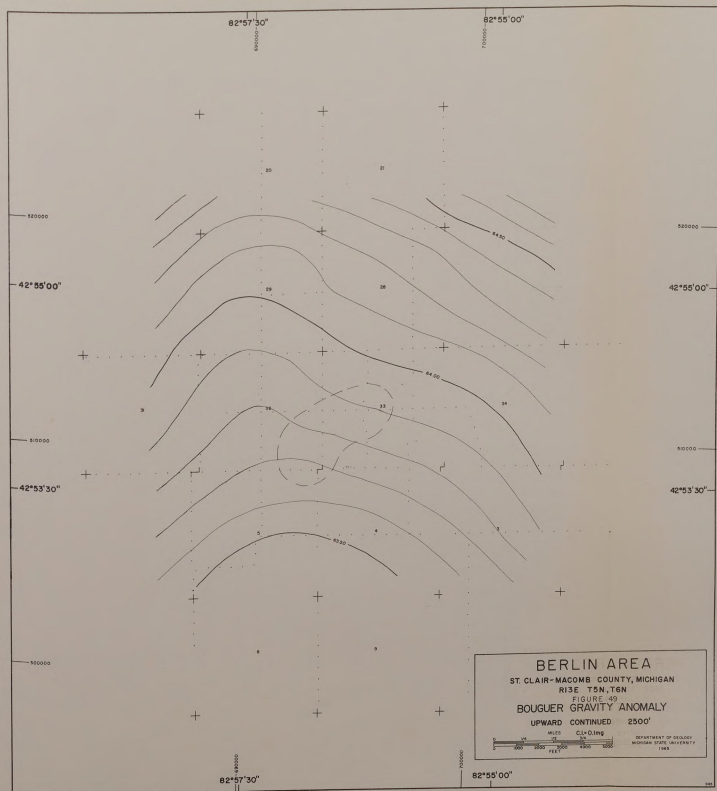


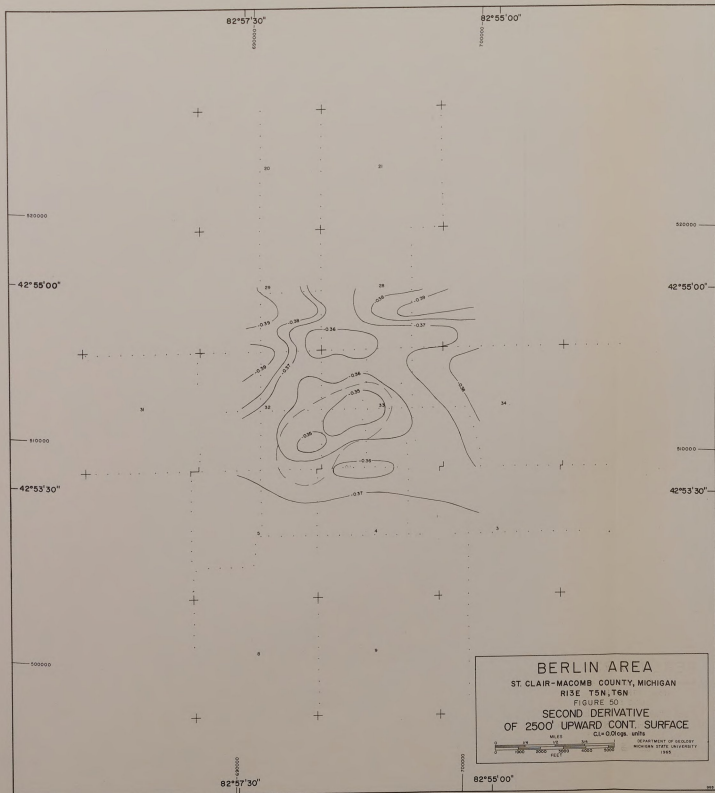


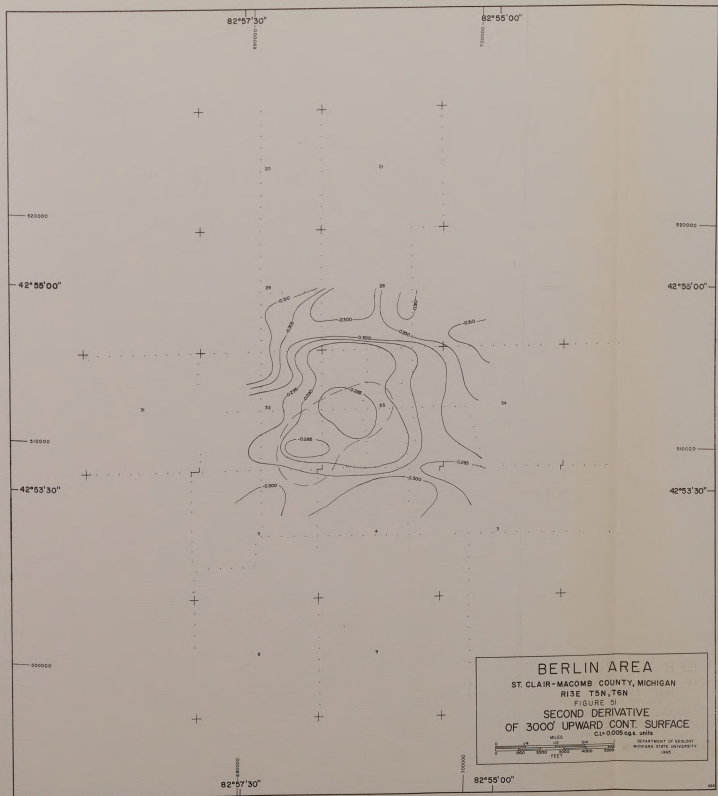


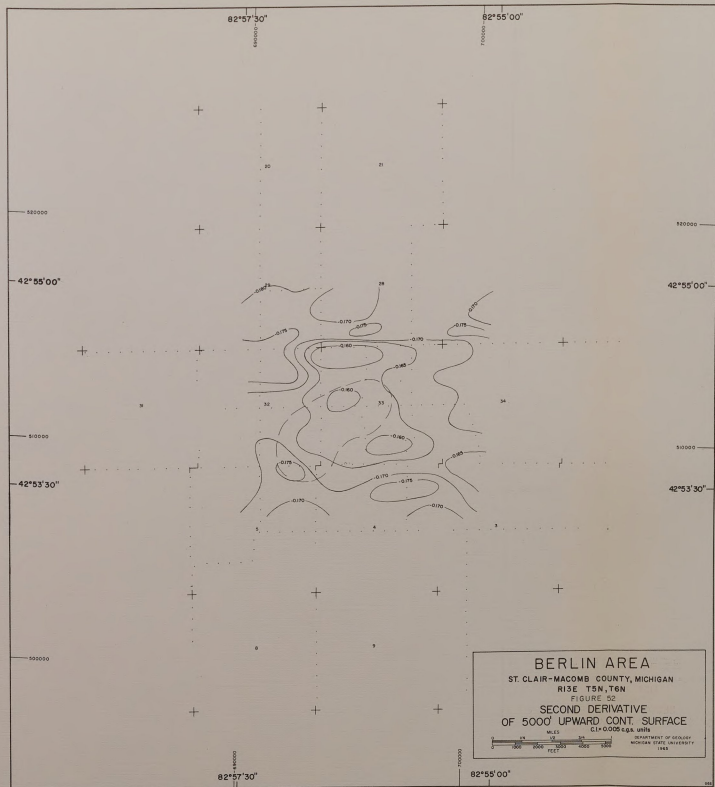












CHAPTER VII

SUMMARY

Detection of Reef Anomalies

The results of this study show conclusively that detailed gravity surveys can detect the anomalies over reefs in Michigan. A known reef buried at 3500 feet was successfully detected and theoretical calculations indicate that reefs buried at depths up to 4000 feet probably can be detected.

Characteristics of Reef Anomalies

Based on observations the characteristics of reef anomalies for the Michigan Basin are summarized as follows.

1. The gravity anomalies over reefs are positive with magnitudes of about $+0.20$ mg.
2. The width of the isolated anomalies varied with the isolation method. The anomalies isolated by the least squares method are about twice as wide as the reef mass. The downward continuation of an upward continued surface method gives a ratio of about 1.3 to 1 for the width of the anomaly to the width of the reef. The second derivative method gives a ratio from 1.3 to 1 for the 2500' upward continued surface up to 1.6 to 1 for the

5000' upward continued surface. The cross profile method on the Marine City reef gives a ratio of 2:1. The graphical and statistical methods of isolation indicate a larger anomaly width to reef width ratio than do the analytical methods. These results are consistent for the Marine City, Belle River Mills, and Berlin reefs.

3. The reef anomalies have adjacent parallel to sub-parallel negative anomalies associated with the positive anomalies. These can be accounted for by theoretical calculation of bedrock topographic effects, however, the coincidence of the negative anomalies indicate they are not fortuitous but may be controlled by structure in the sediments or they are coming from a deeper source.
4. The reef anomalies are not associated with any regional gravity pattern.

Sources of Reef Anomalies

The source of the anomalies observed over reefs in the Michigan Basin are not the reef mass, but the conditions created after reef development. The probable source of the anomalies is the lateral variation in density overlying the reef. In the Michigan Basin these density contrasts are between dolomite and limestone and dolomite and salt.

Optimum Methods for Isolation of
Reef Anomalies in Michigan

A major purpose of this study is to establish optimum methods for the isolation of reef anomalies in this geologic province. The study suggests the following steps as an optimum method of isolation of reef anomalies in the Michigan Basin:

1. A precision detailed gravity survey is necessary. The error for field procedures and basic reduction of the data must be kept to a maximum of 0.05 mg.
2. A station density of 1000 feet is sufficient in searching for reefs by the gravity method. However, the anomalies can change rapidly in a short distance. Thus, it is adviseable to place stations at a greater detail than the road networks will allow. If the survey is being used to detail a suspected reef, the immediate area of interest should contain complete data coverage. The overall area of gravity coverage should extend at least three miles out on every side of the area of interest. This is necessary to allow the use of various isolation techniques and include the regional gravity of the area.
3. The cross profile and least squares polynomial analysis methods are not completely satisfactory

for isolating the reef anomalies. These methods include many anomalies from undesirable sources. It is not recommended that these methods be employed.

4. The upward continuation method is a useful method for eliminating the gravity effects of shallow sources. By calculating the upward continued surface on a plane greater than the suspected reef depth, using a mesh interval of one half this depth, the shallow sources are satisfactorily removed. Total separation between the suspected reef and the upward continued plane should not be greater than about 7500 feet.
5. The reef anomalies may be isolated by downward continuing the upward continuation surfaces to depths not exceeding the suspected reef depth.
6. Second derivative calculations of the upward continued surfaces have a high resolving power in isolating the reef anomalies. Henderson's (1960) formula seems to be optimum for this calculation.

Recommendations for Further Study

The following recommendations are made for future study of reefs in the Michigan Basin by the gravity method.

1. A similar study should be performed over several reefs located around the periphery of the basin.

Geologic conditions of southeastern Michigan are not constant around the basin, thus, gravity anomalies may be different from those observed in this study.

2. A similar study performed over a reef where bedrock topographic features are not present. The study should include an investigation of the relationship of the parallel negative anomalies to the bedrock features and possible structural sources.
3. A regional study of the location of known reef areas in the Michigan Basin and their relationship to the regional structure of the basin.

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APPENDIX

GRAVITY DATA OF ST. CLAIR COUNTY
REEF STUDY

Sample forms of data:

x and y -- 430000(feet)

x's and y's are coordinates based on Michigan Coordinate System, East Zone.

Elevation -- 605.50 feet

Observed Gravity -- 54.27 milligals

Meter Reading -- 542.7 scale divisions

Marine City and Belle River Mills Surveys:

World Wide Meter #45

Calibration Constant 0.10093 mg/S.D.

Berlin Survey

Worden Meter #99

Calibration Constant 0.0995(1)mg/S.D.

The following key is to be used for the data tables on the following pages:

<u>Survey</u>	<u>Station No.</u>	<u>x</u>	<u>y</u>	<u>Elevation</u>	<u>Observed Gravity</u>	<u>Meter Reading</u>
1	2	3	4	5	6	7

MARINE CITY SURVEY

<u>1</u>	<u>2</u>	<u>2</u>	<u>5</u>	<u>6</u>
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MARINECYBASEB	795148437793	60258	5398	
MARINECYBASED	811036442610	58637	5557	
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DIRINECY277MC		807727432553		59261	5294
DIRINECY278MC		808210432349		58523	5338

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DIRINECY279MC		808648432140		58301	5358
DIRINECY280MC		809150431941		58106	5373
DIRINECY281MC		809603431742		58031	5373
DIRINECY282MC		810006431558		58068	5372
DIRINECY283MC		810342431427		58186	5366
DIRINECY289MC		804993448556		58411	5635
DIRINECY290MC		804964448068		58354	5638
DIRINECY291MC		804980447593		58442	5628
DIRINECY292MC		804986447151		58340	5631
DIRINECY293MC		804992446694		58330	5624
DIRINECY294MC		805117445907		58383	5621
DIRINECY295MC		805148445438		58306	5628
DIRINECY296MC		805154445003		58300	5632
DIRINECY297MC		805285444560		58247	5634
DIRINECY298MC		805331444065		58301	5622
MARINECY299MC		805600443250		58233	5613
DIRINECY300MC		805618443049		58316	5610
DIRINECY301MC		805605442624		58212	5600
DIRINECY302MC		807406448712		58504	5634
DIRINECY303MC		807412448247		58515	5624
DIRINECY304MC		807428447762		58491	5626
DIRINECY305MC		807475447263		58511	5618
DIRINECY306MC		807481446788		58420	5617
DIRINECY307MC		807442445938		58438	5607
DIRINECY308MC		807459445383		58374	5609
DIRINECY309MC		807471444838		58478	5598
DIRINECY310MC		807578444320		58593	5585
DIRINECY311MC		807596443765		58745	5568
DIRINECY312MC		807628443228		58850	5556
DIRINECY313MC		807660442679		58925	5543
DIRINECY314MC		808831442956		58466	5569
DIRINECY315MC		808749443518		58492	5576
DIRINECY316MC		808742444030		58486	5583
DIRINECY317MC		808735444593		58487	5583
DIRINECY318MC		808753445093		58483	5591
DIRINECY319MC		808771445625		58451	5596
DIRINECY320MC		808739446175		58443	5605
DIRINECY322MC		808227445183		58485	5601
DIRINECY323MC		807728445142		58448	5607
DIRINECY324MC		807229445060		58360	5611
DIRINECY325MC		806679445003		58261	5622
DIRINECY326MC		806205444947		58417	5607
DIRINECY327MC		805680444925		58491	5617
DIRINECY328MC		808194443868		58584	5580
DIRINECY330MC		807080443808		58657	5574
DIRINECY331MC		806500443776		58445	5597
MARINECY332MC		806000443850		58332	5599
DIRINECY333MC		805471443687		58318	5612
DIRINECY334MC		804896443680		58342	5611
DIRINECY335MC		804372443648		58218	5616
DIRINECY336MC		803847443651		58264	5610
DIRINECY337MC		803626438763		58362	5529

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D1RINECY339MC		804661438765		57800	5554
D1RINECY340MC		805121438758		57985	5538
D1RINECY341MC		805611438764		57993	5537
D1RINECY342MC		806057439030		58956	5464
D1RINECY343MC		806378439374		59976	5402
D1RINECY344MC		806826439545		59698	5419
D1RINECY345MC		807268439771		59990	5393
D1RINECY346MC		807671439911		59195	5441
D1RINECY347MC		808002440191		58896	5468
D1RINECY348MC		808374440450		58628	5494
D1RINECY349MC		808669440829		58488	5510
D1RINECY350MC		808975441146		58482	5518
D1RINECY351MC		809300441558		58451	5529
D1RINECY352MC		809307442100		58604	5524
D1RINECY357MC		805465440375		58046	5568
D1RINECY358MC		806001440306		58946	5499
D1RINECY359MC		806591440297		59320	5472
D1RINECY360MC		807366440315		59259	5460
D1RINECY361MC		807793440155		59071	5454
D1RINECY362MC		805701441462		58124	5580
D1RINECY363MC		805642440985		58091	5570
D1RINECY364MC		805663440515		58159	5558
D1RINECY365MC		805595439989		58096	5553
D1RINECY366MC		805576439489		58010	5544
D1RINECY367MC		805617439039		58038	5534
D1RINECY368MC		811495442651		58627	5568
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D1RINECY370MC		812485442679		58409	5581
D1RINECY371MC		812960442700		58523	5577
D1RINECY372MC		813435442717		58272	5592
D1RINECY373MC		811358446684		58653	5585
D1RINECY374MC		811883446696		58437	5596
D1RINECY375MC		812373446702		58253	5609
D1RINECY376MC		812867446709		58308	5610
D1RINECY377MC		813367446730		58377	5611
D1RINECY379MC		810167459372		59006	5799
D1RINECY380MC		810205458348		58912	5776
D1RINECY381MC		810268457349		58901	5740
D1RINECY382MC		810306456324		58925	5714
D1RINECY383MC		810369455350		58881	5696
D1RINECY385MC		804870459078		59762	5696
D1RINECY386MC		804910457929		59485	5677
D1RINECY387MC		804948456904		59360	5648
D1RINECY388MC		804995455980		59475	5620
D1RINECY401MC		799674454935		61158	5549
D1RINECY402MC		799652455445		61213	5558
D1RINECY403MC		799625455960		61236	5563
D1RINECY404MC		799603456484		61220	5578
D1RINECY405MC		799581457034		61319	5590
D1RINECY406MC		799564457559		61346	5597
D1RINECY407MC		799533458073		61290	5602

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DIRINECY408MC		799501458573	61252		5612	
DIRINECY409MC		799495459063	61311		5624	
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M28BBRIV519BR		804855460211	59811		5727	
M28B MC 3061		794915442177	60353		5444	
M28B MC 3066		795077439404	60428		5410	
ST CLAIR05531		794100459650062083				005543
ST CLAIR05534		794160458235061940				005521
ST CLAIR05537		794240456800061848				005500
ST CLAIR05540		794285455400061840				005480
ST CLAIR05543		794350454250061739				005466
ST CLAIR05546		794395452755061415				005470
ST CLAIR05549		794450451215061198				005460
ST CLAIR05552		794510449680060874				005458
ST CLAIR05554		794545448555060854				005447
ST CLAIR05557		794650447060060720				005452
ST CLAIR05562		794795444900060555				005436
ST CLAIR05578		795490459740062045				005545
ST CLAIR05581		796940459815061867				005557
ST CLAIR05584		798410459895061657				005582
ST CLAIR05586		799430459950061589				005575
ST CLAIR05589		800885460015061325				005587
ST CLAIR05592		802365460095061101				005596
ST CLAIR05595		803825460175060126				005654
ST CLAIR05600		806330460300059821				005675
ST CLAIR05603		807815460395059084				005746
ST CLAIR05606		809410460465059053				005775
ST CLAIR05739		795775454325061540				005473
ST CLAIR05742		797100454400061510				005474
ST CLAIR05745		798400454475061230				005497
ST CLAIR05748		799300454525061217				005488
ST CLAIR05751		801150454625060651				005506
ST CLAIR05754		802450454700060224				005499
ST CLAIR05758		804200454775059761				005558
ST CLAIR05762		806000454825058907				005612
ST CLAIR05765		807450454875058845				005625
ST CLAIR05768		808900454950058966				005636
ST CLAIR05827		795650448600060822				005443
ST CLAIR05830		797050448700060803				005444

BELLE RIVER MILLS SURVEY

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M28BBRIVBASEK		809842465826	59100	5910	
M28BBRIVBASEB		798952470709	61924	5841	
M28BBRIVBASEA		799859467546	61483	5812	
M28BBRIVBASEG		804180470952	60856	5922	
M28BBRIVBASEE		809493476422	59457	6143	
M28BBRIVBASED		804042476476	61329	6024	
M28BBRIVBASEI		804532467732	60617	5865	
M28BBRIVBASEF		809447471196	59797	5965	
M28BBRIVBASEJ		804610465608	60422	5826	
M28BBRIV001BR		799172476057	62105	5944	
M28BBRIV002BR		799662476079	62054	5951	
M28BBRIV003BR		800147476095	62004	5962	
M28BBRIV004BR		800647476117	61897	5971	
M28BBRIV005BR		801096476138	61554	5994	
M28BBRIV006BR		801596476164	61196	6018	
M28BBRIV007BR		802071476185	61097	6027	
M28BBRIV009BR		803070476233	61422	6007	
M28BBRIV010BR		803555476255	61361	6016	
M28BBRIV011BR		804045476281	61363	6015	
M28BBRIV012BR		804535476308	61350	6018	
M28BBRIV013BR		805019476329	61079	6038	
M28BBRIV014BR		805494476345	60894	6054	
M28BBRIV015BR		805979476371	60927	6055	
M28BBRIV016BR		806444476393	60834	6064	
M28BBRIV017BR		806918476414	60647	6075	
M28BBRIV018BR		807418476440	60522	6081	
M28BBRIV019BR		807628476448	60488	6087	
M28BBRIV020BR		808093476469	60449	6090	
M28BBRIV021BR		808567476495	59876	6121	
M28BBRIV023BR		809492476532	59449	6150	
M28BBRIV024BR		809508476073	59613	6121	
M28BBRIV025BR		809534475578	59600	6105	
M28BBRIV026BR		809561475093	59497	6093	
M28BBRIV027BR		809577474623	59476	6079	
M28BBRIV028BR		809598474159	59530	6064	
M28BBRIV029BR		809614473674	59531	6046	
M28BBRIV030BR		809650473400	59520	6032	
M28BBRIV031BR		809668472649	59699	6008	
M28BBRIV032BR		809725472500	59953	5979	
M28BBRIV033BR		809703471835	59953	5968	
M28BBRIV034BR		809734471400	59928	5959	
M28BBRIV035BR		809737471200	59994	5949	
M28BBRIV036BR		809287471184	59677	5978	
M28BBRIV037BR		808837471163	59581	5986	
M28BBRIV038BR		808387471147	58967	6029	
M28BBRIV039BR		807938471127	58960	6034	
M28BBRIV040BR		807488471106	59060	6033	
M28BBRIV041BR		807063471090	59092	6036	
M28BBRIV042BR		806613471069	59016	6044	

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M28BBRIV044BR		805739471033	59882	5993	
M28BBRIV045BR		805289471012	60261	5967	
M28BBRIV047BR		804389470960	60744	5932	
M28BBRIV048BR		803940470939	60813	5925	
M28BBRIV049BR		803465470918	60585	5939	
M28BBRIV050BR		802950470886	60585	5932	
M28BBRIV051BR		802466470855	60895	5914	
M28BBRIV052BR		801966470833	61136	5900	
M28BBRIV053BR		801491470807	61168	5895	
M28BBRIV054BR		800991470786	61572	5870	
M28BBRIV055BR		800467470759	61571	5864	
M28BBRIV056BR		799942470732	61547	5861	
M28BBRIV057BR		799442470715	61752	5850	
M28BBRIV058BR		798921471189	61915	5853	
M28BBRIV059BR		798904471708	61842	5865	
M28BBRIV060BR		798873472188	61835	5880	
M28BBRIV061BR		798841472718	61864	5892	
M28BBRIV062BR		798809473217	61940	5897	
M28BBRIV063BR		798793473727	61989	5906	
M28BBRIV064BR		798756474227	62108	5915	
M28BBRIV065BR		798725474731	62030	5931	
M28BBRIV066BR		798708475256	61988	5946	
M28BBRIV067BR		807520476297	60578	6066	
M28BBRIV068BR		807326475834	60888	6036	
M28BBRIV069BR		807182475352	60879	6025	
M28BBRIV070BR		807023474875	60817	6021	
M28BBRIV071BR		806820474407	60670	6019	
M28BBRIV072BR		806636473935	60022	6047	
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M28BBRIV075BR		806569472509	59872	6014	
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M28BBRIV077BR		806357471556	59605	6021	
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M28BBRIV079BR		804082475327	61369	5992	
M28BBRIV080BR		804114474837	61064	6003	
M28BBRIV081BR		804150474339	61001	5992	
M28BBRIV082BR		804277473854	61029	5984	
M28BBRIV083BR		804208473328	60941	5971	
M28BBRIV084BR		804250472854	60911	5959	
M28BBRIV085BR		804281472379	60694	5964	
M28BBRIV086BR		804312471904	60814	5945	
M28BBRIV087BR		804359471405	60764	5937	
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M28BBRIV089BR		805826470069	59897	5966	
M28BBRIV090BR		805783469518	59858	5955	
M28BBRIV091BR		805771468948	59870	5938	
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M28BBRIV094BR		804656467808	60278	5890	
M28BBRIV095BR		804192467727	60597	5867	
M28BBRIV096BR		803667467720	60359	5883	

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M28BBRIV098BR		802642467707	60943	5841	
M28BBRIV099BR		802083467640	61006	5837	
M28BBRIV100BR		801569467543	61116	5829	
M28BBRIV101BR		801210467458	61356	5820	
M28BBRIV103BR		800135467429	60779	5855	
M28BBRIV104BR		799441467790	61642	5801	
M28BBRIV105BR		799102468071	61847	5789	
M28BBRIV106BR		799060468610	61872	5799	
M28BBRIV107BR		799038469125	61880	5811	
M28BBRIV108BR		799006469640	61908	5820	
M28BBRIV109BR		798974470159	61947	5826	
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M28BBRIV111BR		800381469658	61700	5830	
M28BBRIV112BR		800413469103	61558	5832	
M28BBRIV113BR		800435468598	61532	5826	
M28BBRIV114BR		800452468103	61421	5826	
M28BBRIV115BR		800510467454	61485	5810	
M28BBRIV116BR		801450466900	60887	5829	
M28BBRIV117BR		801725466425	61106	5799	
M28BBRIV118BR		802251466252	61085	5798	
M28BBRIV119BR		802804466044	60805	5812	
M28BBRIV120BR		803392465817	60643	5818	
M28BBRIV121BR		803884465623	60428	5829	
M28BBRIV122BR		804410465605	60386	5829	
M28BBRIV123BR		804959465622	60361	5828	
M28BBRIV124BR		805509465644	59752	5862	
M28BBRIV125BR		806044465666	59674	5856	
M28BBRIV126BR		806609465689	59454	5866	
M28BBRIV127BR		807158465716	59361	5871	
M28BBRIV128BR		807768465744	59234	5888	
M28BBRIV129BR		808333465761	59075	5914	
M28BBRIV130BR		808908465789	58977	5917	
M28BBRIV131BR		809457465816	58736	5933	
M28BBRIV132BR		809982465833	59247	5896	
M28BBRIV133BR		809967476559	59421	6147	
M28BBRIV134BR		810476476580	59440	6145	
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M28BBRIV136BR		811442476568	59108	6172	
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M28BBRIV138BR		812240476733	59558	6158	
M28BBRIV139BR		812544477152	59401	6188	
M28BBRIV140BR		813060477094	59651	6174	
M28BBRIV141BR		813535477125	59472	6189	
M28BBRIV142BR		814012476907	59432	6185	
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M28BBRIV144BR		809850470325	59780	5941	
M28BBRIV145BR		809806469701	59676	5932	
M28BBRIV146BR		809838469221	59638	5929	
M28BBRIV147BR		809859468727	59575	5924	
M28BBRIV148BR		809886468222	59510	5933	

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M28BBRIV150BR		809929467222	59407	5922	
M28BBRIV151BR		809945466728	59305	5920	
M28BBRIV152BR		809962466228	59261	5906	
M28BBRIV153BR		810467465859	59011	5910	
M28BBRIV154BR		810947465866	58997	5918	
M28BBRIV155BR		811441465902	58924	5936	
M28BBRIV156BR		811906465928	58832	5946	
M28BBRIV157BR		812406465955	58743	5964	
M28BBRIV158BR		812880465971	58690	5964	
M28BBRIV159BR		813380465997	58643	5958	
M28BBRIV160BR		813880466014	58599	5964	
M28BBRIV161BR		814430466041	58520	5973	
M28BBRIV162BR		814979466078	58542	5977	
M28BBRIV163BR		815479466100	58614	5982	
M28BBRIV164BR		810261471227	59770	5961	
M28BBRIV166BR		811286471270	59847	5957	
M28BBRIV167BR		811796471292	59270	6014	
M28BBRIV168BR		812336471314	59107	6025	
M28BBRIV169BR		812825471336	59139	6037	
M28BBRIV170BR		813335471352	59158	6039	
M28BBRIV171BR		813875471374	59171	6039	
M28BBRIV172BR		814395471396	59149	6051	
M28BBRIV173BR		814934471428	59251	6048	
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M28BBRIV176BR		809454477532	59780	6164	
M28BBRIV177BR		809432478032	60030	6164	
M28BBRIV178BR		809416478527	60226	6168	
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M28BBRIV180BR		809368479521	60427	6194	
M28BBRIV182BR		809315480520	60416	6222	
M28BBRIV183BR		809298481020	60319	6240	
M28BBRIV184BR		809277481520	60220	6269	
M28BBRIV185BR		809271481920	60359	6274	
M28BBRIV186BR		804014476756	61456	6021	
M28BBRIV188BR		803976477755	61317	6059	
M28BBRIV189BR		803944478245	61330	6076	
M28BBRIV190BR		803923478740	61242	6103	
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M28BBRIV192BR		803875479729	60996	6152	
M28BBRIV194BR		803847480729	61429	6152	
M28BBRIV195BR		803815481224	61347	6171	
M28BBRIV196BR		803800481598	61493	6174	
M28BBRIV198BR		798641476530	62058	5962	
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M28BBRIV200BR		798588477505	62024	5986	
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M28BBRIV205BR		797173475961	62250	5935	

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M28BBRIV211BR		796969470583	62046	5833	
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M28BBRIV245BR		802428464204	61077	5757	
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M28BBRIV322BR		801687471130	61236	5887	
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M28BBRIV331BR		808277474581	59059	6118	
M28BBRIV332BR		808249474106	59014	6113	
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M28BBRIV374BR		808393472593	59201	6058	

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M28BBRIV389BR		807188469202	58872	5996		
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M28BBRIV411BR		799452460416	61465	5648		
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ST CLAIR05381		795945481260062687		006017		
ST CLAIR05386		793555481153063443		005978		
ST CLAIR05473		792940480100063275		005958		
ST CLAIR05476		793005478780062925		005932		

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ST	CLAIR05482	793175475785062605				005869
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ST	CLAIR05488	793325472940062385				005818
ST	CLAIR05491	793420471480062051				005809
ST	CLAIR05493	793480470395060368				005896
ST	CLAIR05495	793530469370062251				005753
ST	CLAIR05497	793580468430061437				005783
ST	CLAIR05500	793725466390062287				005677
ST	CLAIR05520	793800465025062220				005647
ST	CLAIR05522	793870464045062136				005627
ST	CLAIR05526	793955462085062185				005579
ST	CLAIR05529	794045460670062092				005560
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M28BBRIV519BR		804855460211	59811		5727	
ST	CLAIR05531	794100459650062083				005543
ST	CLAIR05578	795490459740062045				005545
ST	CLAIR05581	796940459815061867				005557
ST	CLAIR05584	798410459895061657				005582
ST	CLAIR05586	799430459950061589				005575
ST	CLAIR05589	800885460015061325				005587
ST	CLAIR05592	802365460095061101				005596
ST	CLAIR05595	803825460175060126				005654
ST	CLAIR05600	806330460300059821				005675
ST	CLAIR05603	807815460395059084				005746
ST	CLAIR05606	809410460465059053				005775

BERLIN SURVEY

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00BERLIN00002		693287512074	81675	4480	
00BERLIN00003		693270512624	81730	4496	
00EERLIN00004		693248513149	81739	4511	
00BERLIN00005		693231513674	81701	4536	
00BERLIN00006		693215514174	81700	4558	
00BERLIN00007		692690514152	81239	4576	
00BERLIN00008		692200514130	81166	4577	
00BERLIN00009		691685514104	81174	4577	
00BERLIN00010		691161514077	80629	4605	
00BERLIN00011		690566514039	80083	4622	
00BERLIN00012		690583513544	79874	4622	
00BERLIN00013		690599513029	79552	4624	
00BERLIN00014		690616512515	79276	4624	
00BERLIN00015		690623511985	79289	4603	
00BERLIN00016		690645511440	79261	4596	
00BERLIN00017		691160511457	79167	4613	
00BERLIN00018		691670511478	79429	4606	
00BERLIN00020		692699511517	80446	4540	
00BERLIN00021		693804511566	81456	4481	
00BERLIN00022		694319511588	81586	4475	
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00BERLIN00024		695318511626	81380	4493	
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00BERLIN00026		696288511664	81256	4498	
00BERLIN00027		696817511691	81104	4516	
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00BERLIN00029		697255512251	81072	4537	
00BERLIN00031		697227513286	81056	4570	
00BERLIN00032		697210513801	80907	4598	
00BERLIN00033		697182514371	81116	4602	
00BERLIN00034		696703514344	81249	4594	
00BERLIN00036		695658514296	81321	4583	
00BERLIN00037		695193514275	81097	4590	
00BERLIN00038		694659514248	81074	4593	
00BERLIN00039		694194514227	81260	4583	
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00BERLIN00044		693376509475	79403	4536	
00BERLIN00045		693393508926	79155	4530	
00EERLIN00046		693209508473	78725	4544	
00BERLIN00048		693238507423	78578	4509	
00BERLIN00049		693255506899	78504	4486	
00BERLIN00050		693267506374	78484	4466	
00BERLIN00051		693283505914	78436	4448	
00BERLIN00052		692768505907	78309	4456	
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00BERLIN00054		691718505868	78340	4461	

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00BERLIN00061		690720508366	78596	4546	
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00BERLIN00065		690675510340	79238	4585	
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00BERLIN00068		694267505952	79019	4417	
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00BERLIN00072		696312506009	79399	4401	
00BERLIN00073		696792506020	79400	4416	
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00BERLIN00087		704264506298	79384	4513	
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00BERLIN00095		690423517747	81990	4626	
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00BERLIN00097		690384518812	81944	4664	
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00BERLIN00100		690337520447	81679	4745	
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00BERLIN00103		690302522011	80753	4878	
00BERLIN00104		690295522566	80527	4917	
00BERLIN00105		690283523086	80563	4932	
00BERLIN00106		690266523611	80305	4962	
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00BERLIN00116		693065518372	81320	4721	
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00BERLIN00121		692980521046	80629	4873	
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