GRAVITY ANOMALIES AND BASEMENT ELEVATIONS IN THE MIDCONTINENT

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ABSTRACT

GRAVITY ANOMALIES AND BASEMENT ELEVATIONS IN THE MIDCONTINENT

By

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The relationship of Bouguer and Free-air gravity anomalies with basement elevations are studied for the Midcontinent of the United States.

The gravity anomalies, both Bouguer and Free-air, show an inverse relationship with basement elevations in the eastern Midcontinent in areas where basement elevation is less than sea level. However, in the western Midcontinent, west of 96°W meridian, this relationship is distorted by surface elevation effect and by diastrophism associated with the Cordilleran mountain systems.

The basins exhibit Bouguer and Free-air gravity anomalies inversely related to the basement elevations in the eastern Midcontinent and a possible inverse correlation in the western Midcontinent. The relationships are particularly well defined in the Michigan, Illinois and Williston Basins, Other basins do not have any definable relationship. This fact together with the equivalance of average gravity anomalies in the deepest portion of

basins and some cratonic areas suggest that basins were not developed by elastic deformation in response to the added mass of basic rocks in the basement complex. The relationship is not a cause and effect relationship, but it is suggested that both the increased mass of the basement complex in the center of the basins, which produces the gravity anomalies, and development of basins result from stages of the same process, perhaps late Precambrian crustal rifting.

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INTRODUCTION

Statement of Problem

Bouguer gravity anomalies have proven to be of great value in exploration for mineral resources and in determining the structures within the earth's crust. The Bouguer gravity anomaly is the difference between the observed gravity and the theoritical gravity which takes into account the variation of gravity with latitude and the combined effect of the elevation and the mass included between the station elevation and the sea level datum. Thus, the variation of the Bouguer gravity anomalies over the surface of the earth reflects the lateral variation in the mass or the density of the underlying rock formations. As a result sedimentary basins, filled with low density sediments compared to the density of the basement rocks enclosing them, should produce relative negative Bouguer gravity anomalies. However, many of these sedimentary basins exhibit positive Bouguer gravity anomalies which cannot be accounted for by the sediments.

The correlation of gravity maxima with some sedimentary basins is well documented in geophysical literature. Martin (1954) pointed out that " gravity work in Argentina has shown maximal values over the deepest part of some sedimentary basins." Lyons (1959) noted a series of Paleozoic basins associated with the Midcontinent gravity high. Woollard (1962, 1966) observed that major sedimentary basins are marked by positive gravity anomalies and major uplifts by negative gravity anomalies. The inverse relationship between gravity anomalies and basement elevations in Indiana was noted by Henderson and Zietz (1958). Similar relationships have been discussed by Hinze (1963) and McGinnis (1966) in Michigan and Illinois Basins respectively. Innes, et al., (1967) have related positive gravity anomalies to the embayments of Paleozoic rocks of the Hudson Bay Lowlands and Interior Plains and furthermore, they state that several Proterozoic basins of Precambrian Shield, such as the Cobalt, Blind River and Mississippi Basins have positive gravity anomalies that cannot be accounted for by the igneous and sedimentary rocks of the basins.

Despite this well known inverse relationship between gravity anomalies and basement elevations, the only attempt to quantify this relationship has been made by McGinnis (1966) for the Illinois Basin. Therefore, the purpose of this study is to establish the relationship of gravity anomalies to basement elevations, particularly over basins, in the Midcontinent between the Appalachian Basin and the Rocky Mountains and discuss the implications of these relationships.

Approach to the Problem

The relationship between gravity anomalies and basement elevations are studied by plotting average Bouguer and Free-air gravity anomalies against average basement elevations for $1^{\circ}\text{x } 1^{\circ}$ quadrangles as well as $2^{\circ}\text{x } 2^{\circ}$ quadrangles. The $2^{\circ}\text{x } 2^{\circ}$ area (approximately 120 miles east-west and 150 miles north-south) were investigated to minimize the effect of local gravity anomalies and to determine the possible effect of isostatic adjustment on the relationship between gravity anomalies and basement elevations. Woollard and Strange (1966) have pointed out that in general, isostatic equilibrium can be achieved over areas of $2^{\circ}\text{x } 2^{\circ}$ size or larger. Average basement elevations and gravity anomalies were also plotted against average surface elevations to observe their inter relationship and to determine the complicating effect of surface elevations on the gravity anomaly basement elevation relationship. First degree least square lines were calculated for plotted relationships, wherever possible, and their correlation coefficients and confidence levels were determined. Approximate geological corrections for the mass deficiency of the sediments were determined to remove the effect of the sediments from the observed relationships.

Area of Investigation

The area of investigation covers north-central United States between the Appalachian Basin and the Rocky

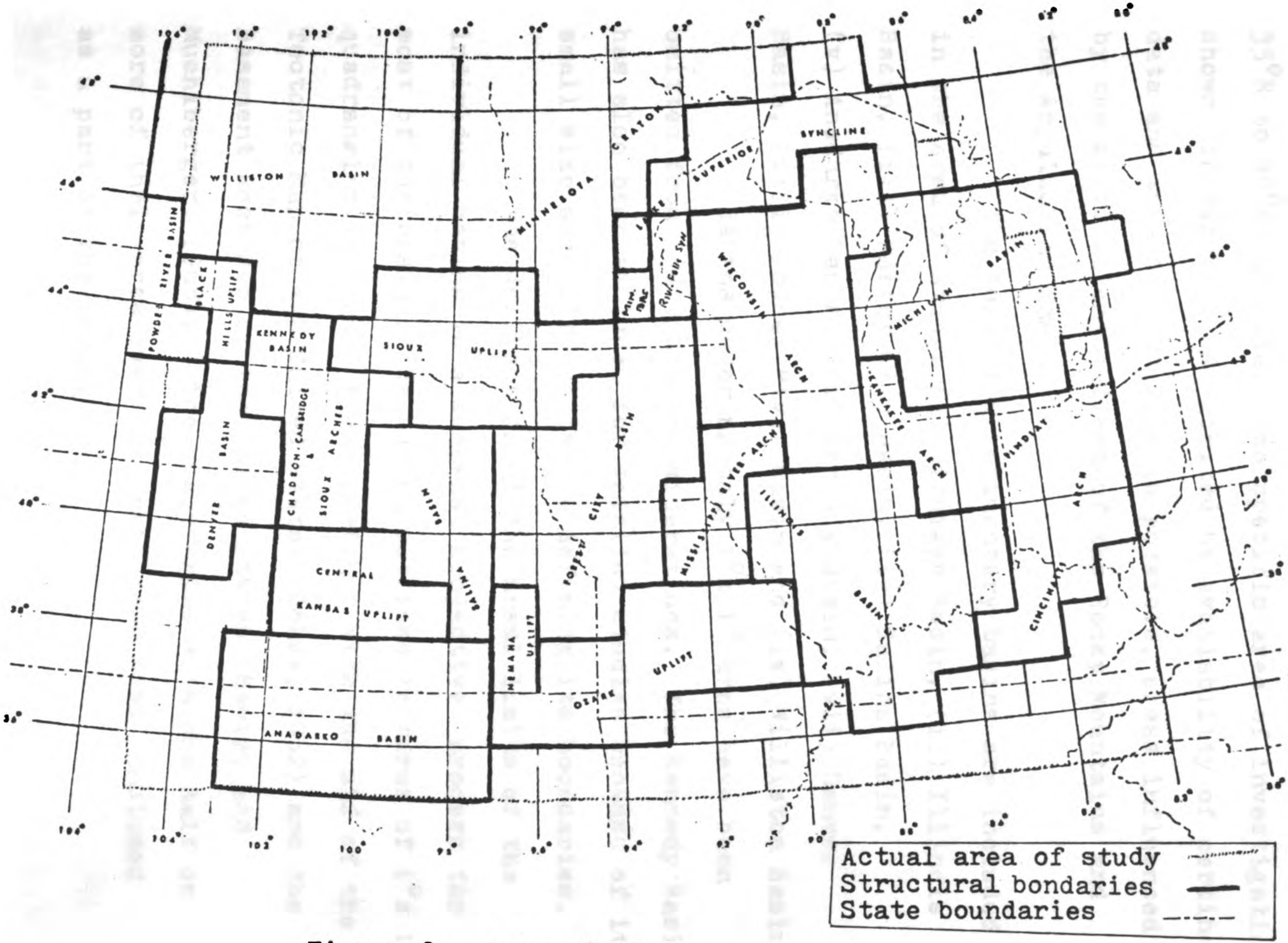


Figure 2. Area of study

Mountains from approximately 82°W to 105°W longitude and 35°N to 49°N latitude. The specific area of investigation, shown in Figure 1, is limited by availability of pertinent data and to avoid, as much as possible, areas influenced by the gravitational effect of the Rocky Mountains and the Appalachian Basin.

The following sedimentary basins are included in the area of study: (i) Michigan Basin, (ii) Illinois Basin, (iii) Forest City Basin, (iv) Salina Basin, (v) Anadarko Basin, (vi) Kennedy Basin, (vii) Denver Basin, (viii) Powder River Basin and (ix) Williston Basin.

Basins covering only $1^\circ \times 1^\circ$ area have been omitted from individual considerations. The Kennedy Basin has also been excluded for detailed studies because of its small size and difficulties in defining its boundaries.

The delineation of the areal limits of the individual basins is a somewhat subjective process for most of the basins. The basins outlined in terms of $1^\circ \times 1^\circ$ quadrangles in Figure 1 were defined with the aid of the Tectonic Map of the United States (Cohee, 1962) and the Basement Rock Map of the United States (Bayley and Muehlberger, 1968). The quadrangles with one half or more of their area over the basin have been included as a part of the basin.

GRAVITY AND BASEMENT ELEVATION DATA

Source of Data

The gravity data and surface elevations used in this study were obtained from the U. S. Air Force Aeronautical Charts and Information Center. The data consists of average Bouguer and Free-air gravity anomalies and surface elevations of $1^{o} x 1^{o}$ quadrangles. The average Bouguer gravity anomalies were checked at random over the area of study with average values obtained from the Bouguer Gravity Anomaly Map of the United States (Woollard and Joesting, 1964). The only available summarized Free-air gravity anomaly and surface elevation data were used in this study. Therefore, their accuracy could not be checked.

Basement elevations were determined from the Basement Rock Map of the United States (Bayley and Muehlberger, 1968).

Reduction of Data

Averaging Technique

Determining average values from contour maps by considering the area between contours is a difficult and time consuming process. Thus a procedure was developed for statistical averaging of values.

Seventeen $1^\circ \times 1^\circ$ quadrangles distributed throughout the area of study were chosen for the purpose of testing the averaging procedures. The contours of the areas varied from smooth and regularly spaced to extremely complex and irregularly spaced. The average values of the quadrangles were first determined by finding the area within successive contours. The average value is given by the equation, $X_{av} = \frac{a_1x_1 + a_2x_2 + \ldots\ldots\ldots + a_nx_n}{a_1 + a_2 + \ldots\ldots\ldots\ldots + a_n}$ where "a" is the area within the two consecutive contours, "x" is the corresponding average value of the two contours and "n" is the number of intervals between contour pairs in a quadrangle. As this was the most accurate averaging method, the results of all other averaging techniques were compared with this standard to establish the optimum grid averaging method. The grid patterns tested were:

Five point average: The $1^\circ \times 1^\circ$ quadrangle was divided in four equal parts, i.e., four equal sub-quadrangles, and the numerical values at the centers of these sub-quadrangles along with the value at the center of the quadrangle were averaged.

Seven point average: A hexagon was constructed in a quadrangle and the values at the six corners of the hexagon along with the value in the center were averaged.

Nine point average: The quadrangle was divided in nine equal parts or sub-quadrangles and the values at the center of these areas were averaged.

Sixteen point average: The $1^\circ \times 1^\circ$ quadrangle was divided

TABLE 1. Comparision of averaging techniques.

Area		Standard average in ft.	Percent deviation from standard value by				Remarks
Lat	Long		Five point method	Seven point method	Nine point method	Sixteen point method	
36°N	100°W	18240	23.2	28.0	12.7	2.9	Small portion of the area irregular and complex.
36°	101°	8052	4.3	12.0	7.4	4.2	Complex area with faults and irregular and repeated contours.
37°	105°	2450	32.5	7.5	17.5	0.04	Repeated contours but smooth.
37°	104°	2012	5.0	1.1	25.0	0.75	Repeated contours but smooth.
37°	101°	9180	1.5	1.5	1.5	0.70	Regular but occasionally narrow contours.
37°	100°	10950	3.2	4.0	1.1	1.0	Regular but occasionally narrow contours.
38°	105°	1940	25.0	17.5	10.0	0.45	Contours uniform but repeated.
38°	104°	1498	66.6	26.6	40.0	2.3	Repeated and narrow contours.
39°	88°	10387	-	-	-	2.3	Regular contours.
44°	85°	11600	1.3	1.3	1.2	0.1	Regular and smooth contours.
44°	84°	8552	1.4	1.3	1.3	0.2	Regular and smooth contours.
45°	109°	8316	-	-	3.1	1.4	Contours irregular.
45°	85°	10120	-	-	-	0.1	Regular and smooth contours.
48°	104°	11950	1.9	1.4	5.2	2.9	Smooth but higher value contours repeated.
48°	103°	12420	0.2	0.5	5.0	0.1	Smooth and regular contours.
49°	104°	11546	3.0	1.2	0.2	2.5	Higher value contours repeated.
49°	103°	10242	0.1	1.2	1.5	0.7	Smooth and regular contours.

The area gives the location of 1°x 1° quadrangles. The values of latitude and longitude is given for the north-west corner of the quadrangle.

into sixteen equal sub-quadrangles and the values at the center these sub-quadrangles were averaged.

The results obtained from the above averaging techniques were compared with the results of numerical integration technique. In areas where contours were regular and smooth all the techniques gave nearly the same average value within the practical limits possible and differed from the standard average by no more than 1.5 percent. However, in areas where contours were complex the average values varied considerably, not only with each other, but also from standard values. The results obtained from the sixteen point average is the single exception. In the areas of complex basement topography errors as large as 66 percent were obtained. The sixteen point averaging method was accurate usually within 1.5 percent and the maximum error obtained was approximately 4.2 percent in a complex area. A comparision of results obtained by different averaging techniques is shown in Table 1.

Based on the above results the sixteen point technique was used to average the basement elevations for $1^{\circ} x\ 1^{\circ}$ quadrangles and also to obtain average Bouguer gravity anomalies from Bouguer gravity anomaly contours to check the values obtained from the U. S. Air Force. The difference between the Air Force average values and the average Bouguer gravity obtained from the contour map usually did not exceed one milligal.

The average values for 2°x 2° quadrangles were obtained by numerically averaging the values of the four 1°x 1° quadrangles involved.

Basement Data

The basement is normally defined as the crystalline igneous and metamorphic complex lying beneath a sedimentary sequence. However, in this study the use of the term is broadened to include the Precambrian complex outcropping or subcropping beneath the glacial drift and some Precambrian supracrustal rocks such as Keweenawan volcanics and clastics. This more general definition follows the usage of the term by Bayley and Muehlberger (1968) in preparation of the Basement Rock Map of the United States in the Precambrian craton basement province. The basement elevations were calculated by sixteen point averaging technique from basement elevation contours given by Bayley and Muehlberger (1968).

Gravity Data

Gravity anomalies, both Bouguer and Free-air, were calculated in normal manner (Heiskanen and Vening Meinesz, 1958) utilising the 1930 international gravity formula and a density of 2.67 gm/cc for the earth material between sea level and observation sites. No terrain correction has been used because of generally low relief in the area studied.

The number of gravity observations used in obtaining the average values varies from only a few to more than a thousand per $1^{o}x\ 1^{o}$ quadrangle. The quadrangles with only a few observations are in general limited to those areas overlapping the Rocky Mountains and the Great Lakes. The average values of quadrangles having few observations will undoubtedly be in error, but their influence on the results of this study should be minimal as such areas are few in number.

Residual Bouguer gravity anomalies reflect local geological effects and are obtained by subtracting the regional Bouguer gravity anomaly at the observation site from the observed Bouguer gravity anomaly. The meaning of regional and residual varies depending upon individual purposes. The division between regional and residual is dictated by the lateral extent of the effect. Strange and Woollard (1964) have discussed the limitations of several methods of seperating residuals from regional anomalies on a continental basis for purposes of studying relationships between anomalies and geology. In this study the regional Bouguer gravity anomaly is represented by the mean curve obtained from the Bouguer gravity anomaly-surface elevation relationship. The difference between the average Bouguer gravity anomaly for $1^{o}x\ 1^{o}$ quadrangle areas and the regional Bouguer gravity anomaly, corresponding to the mean elevation for the quadrangle, gives the residual anomaly. Residual gravity anomaly for

2^ox 2^o area are obtained in a similar manner.

The effect of the deficiencies of mass within basins due to the density contrast between low density sedimentary rocks of the basins and the enclosing basement rocks has been calculated for individual basins of the Midcontinent and applied to the Bouguer gravity anomaly resulting in a geologically corrected Bouguer gravity anomaly. The mean density of the sedimentary rocks of the basins is assumed to be 2.52 gm/cc resulting in a density contrst of 0.15 gm/cc with the enclosing rocks of 2.67 gm/cc density. The geological correction is the same as the gravitational effect of a horizontal slab of density 0.15 gm/cc and is calculated to be 0.0019 mgals per foot. This correction is added to the observed Bouguer gravity anomaly to obtain geologically corrected Bouguer gravity anomaly.

Statistical Procedures

Regression coefficients for least square lines of first order have been calculated, wherever possible, to indicate the linear relationships. This line is represented by an equation of the form Y = A + BX, where Y is the dependent variable, X is independent variable, A is the intercept and B is the regression coefficient. A and B are calculated in the following manner:

$B = \frac{\Sigma xy}{\Sigma x^2}$; where $x = X-\overline{X}$, $\overline{X} = \frac{\Sigma X}{n}$, n is number of data pairs and

$$y = Y - \overline{Y} \text{ ; and}$$

$$A = \overline{Y} - B\overline{X}, \quad \text{where } \overline{Y} = \frac{\Sigma Y}{n} .$$

The confidence level for the least square line is established by calculating the critical values of t-distribution, using the equation,

$$t = \frac{B}{S} ,$$ where S is the standard error of regression coefficient and is given by equation,

$$S = \sqrt{\frac{s}{\Sigma x^2}} ,$$ where "s" is given by

$$s = \frac{\Sigma d_y^2}{(n-2)} \quad \text{and } \Sigma d_y^2 = \Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2} .$$

The correlation coefficient, "r", between the two parameters "X" and "Y" is obtained by the relation

$$r = \frac{\Sigma xy}{\sqrt{(\Sigma x^2)(\Sigma y^2)}} .$$

The correlation coefficient, "r", also may be calculated by using the equation,

$$r^2 = \frac{t^2/(n-2)}{1+t^2/(n-2)} .$$

The value of "r" varies from +1 to -1. These extreme values indicate 100 percent correlation, either positive or negative. A zero value of "r" indicates no correlation. Intermediate values represent the degree of correlation.

In calculating the regression coefficients for this study, basement elevation has been considered the independent variable and Bouguer and Free-air gravity anomalies and surface elevation the dependent variables.

GEOLOGY

The Midcontinent area of the United States under investigation in this study generally falls within the central stable region which is bordered on the west by the Rocky Mountains and on the east and partially on the south by Paleozoic orogenic belts. Tectonically the north-central portion of the area lies within the southern extension of the Canadian Shield and in the south-central portion the Mississippi embayment overlaps the area of study.

The southern extension of the Precambrian Canadian Shield in Minnesota, Wisconsin and Michigan consists primarily of felsic crystalline rocks with common east to northeast striking metasedimentary belts and minor mafic intrusives and extrusives. The age of these basement rocks vary from greater than 2.5 b.y. to 1.2 b.y. in a complicated geographic pattern, but in general the ages decrease to the south. Superimposed on and intruded into these rocks are Keweenawan extrusives and intrusives, primarily basic in composition and late Keweenawan clastics.

Drill holes and geophysical data indicate that these Keweenawan supra-basement rocks extend beneath the Paleozoic sedimentary rocks from the southwest corner of Lake Superior along a linear belt into Kansas and from eastern Lake Superior into the Southern Peninsula of Michigan. Isolated patches of these rocks are also indicated in Indiana, Illinois and Ohio. The basement of the central and major portion of the central stable region is largely composed of felsic rocks dated from 1.2 b.y. to 1.5 b.y., the so called Central province. This province is bounded on the east and south by the Grenville province (0.9 to 1.1 b.y.), on the northwest by the Superior province (2.5 b.y.) and on the west primarily by the Penokean province (1.6 to 1.8 b.y.). In many areas of the central stable region evidence suggests overprinting of Central province ages on the Penokean province. Details on Midcontinent basement rock types and ages from limited exposures and drill holes penetrating the basement are given by Goldich, et al., (1966a), Goldich, et al., (1966b), Muehlberger, et al., (1966), Lidiak, et al., (1966) and Bayley and Muehlberger (1968).

In the central stable region shallow water sedimentary rocks of variable thickness overly the Precambrian basement reflecting numerous broad basins, domes and arches. The strata have only gentle dips and give evidence for "... slow and prolonged vertical movements that created basins , arches and domes" (Eardley,1951, p. 12). "The arches and basins developed chiefly in the Paleozoic era, but later, during the Mesozoic and tertiary, vast amount of clastic sediments from the evolving

Cordilleran mountain systems were spread eastward over the Paleozoic strata as far as Lake Superior and beyond the Mississippi River" (Eardley, 1951, p.12). Following the Appalachian orogeny, the Mississippi embayment developed in the southern portion of the area.

The Illinois, Michigan and Williston Basins are similar features which had their origin in early Paleozoic time. Subsequent to their formation they have undergone mild deformations as evidenced by numerous minor folds and faults and a few major anticlines; e.g., the La Salle, Howell and Cedar Creek anticlines. The depth of the basement in the center of each of these basins is nearly 15000 feet below sea level. The central portion of the Midcontinent is underlain by the ill defined Forest City and Salina Basins which have maximum sedimentary rock thickness of about 4000 feet. These basins are separated by the Nemaha uplift of early Pennsylvanian age. The assymetrical Denver Basin and Powder River Basin which occur along the edge of the Front Range and Bighorn Uplifts respectively are of tertiary age. The Anadarko Basin which is asymmetrical trough bordering the Wichita Mountains to the south contains over 30,000 feet of Paleozoic sediments which were deformed during the Wichita orogeny in late Mississippian and early Pennsylvanian time. The geological history and structural relationships of these basins can be found in reviews by Eardley (1951) and King (1969).

CORRELATION OF GRAVITY ANOMALIES WITH BASEMENT ELEVATIONS

Results of Investigation

Midcontinent Area

Bouguer Gravity Anomaly Relationships

Bouguer Gravity Anomaly-Basement Elevation Relationship for $1^{\circ}\mathrm{x}\ 1^{\circ}$ Quadrangles: The average Bouguer gravity anomaly for $1^{\circ}\mathrm{x}\ 1^{\circ}$ quadrangle areas are plotted against average basement elevations for $1^{\circ}\mathrm{x}\ 1^{\circ}$ quadrangle areas for the entire area of study (Figure 2). The points are widely scattered and no obvious relationships can be established between these two parameters for the area. Therefore, for the purposes of studying the relationships in greater detail the area is divided into an eastern and western portions along 96°W meridian. West of the 96°W meridian the regional surface elevations increase rather regularly towards the Rocky Mountain front.

In the eastern portion of the Midcontinent (Figure 3) the points are quite scattered, but considering basement elevations less than -1000 feet and neglecting the points falling in the area adjacent to the Appalachian Basin, an inverse linear relationship is observed between Bouguer gravity anomaly and basement elevation. This relationship can be represented by the equation,

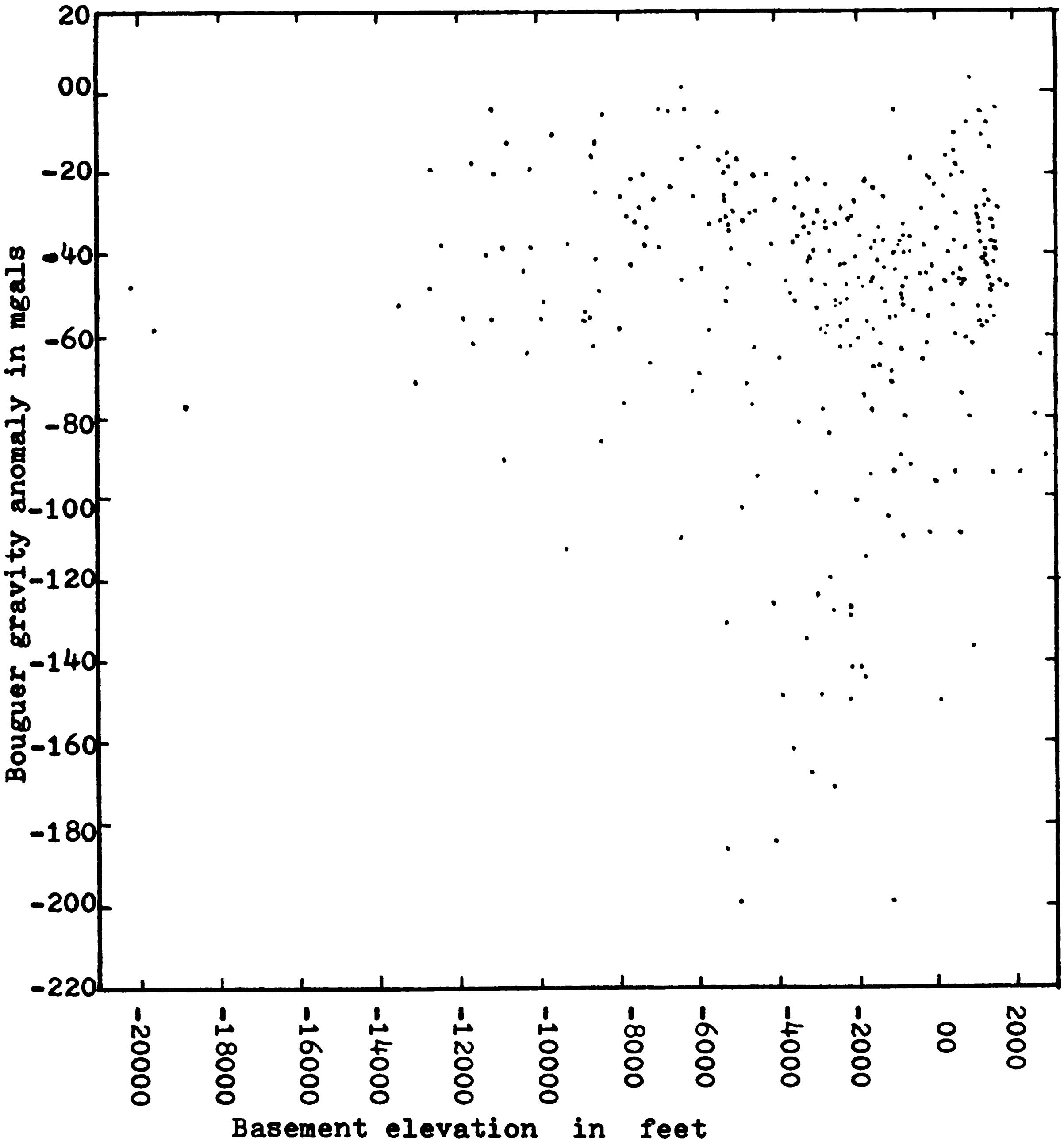
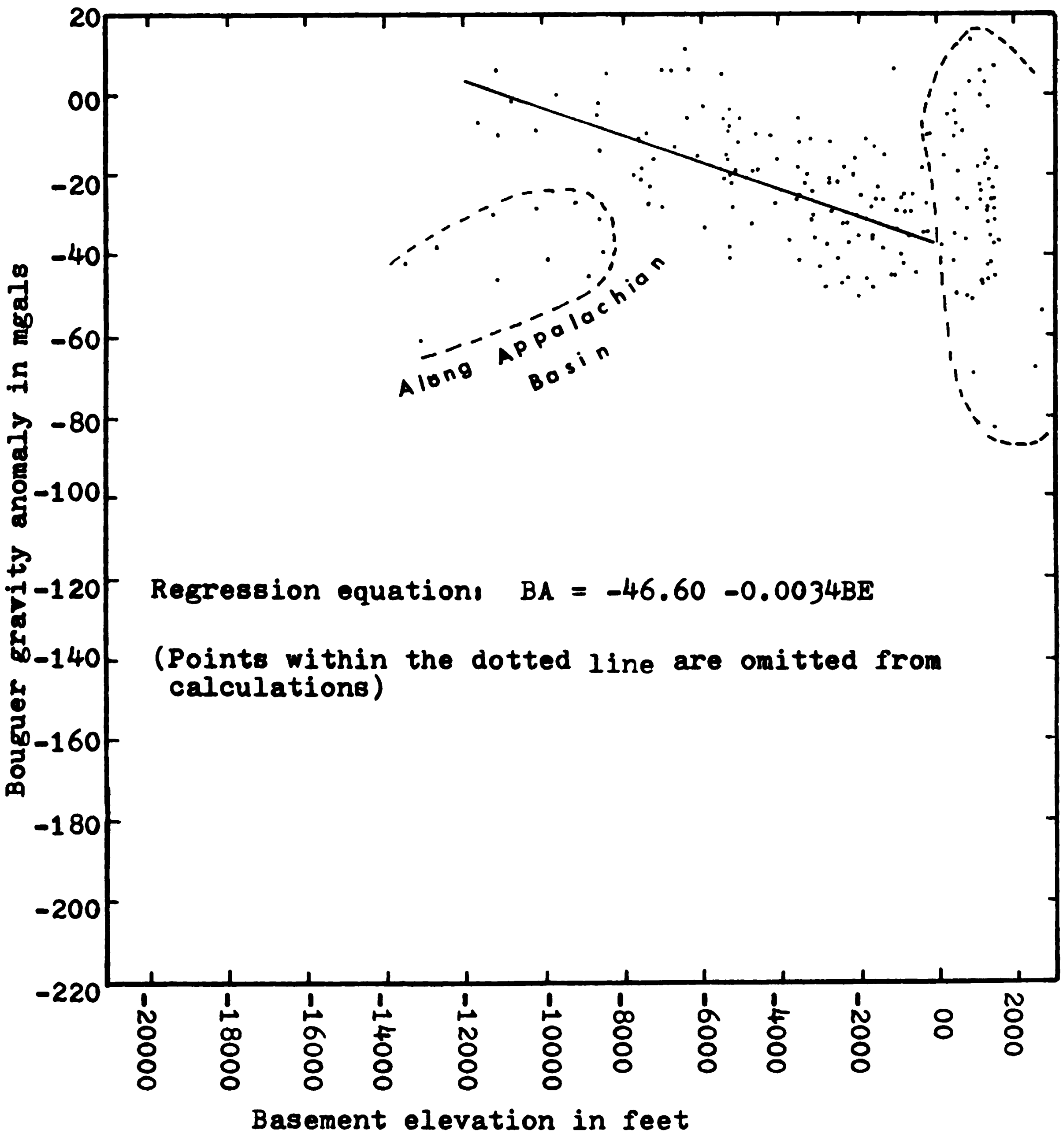


Figure 2. Bouguer anomaly- basement elevation relationship (Midcontinent; 1^{o}x 1^{o})



Regression equation: BA = -46.60 -0.0034BE

(Points within the dotted line are omitted from calculations)

Figure 3. Bouguer anomaly-basement elevation relationship (Eastern Midcontinent; 1^{o}x 1^{o})

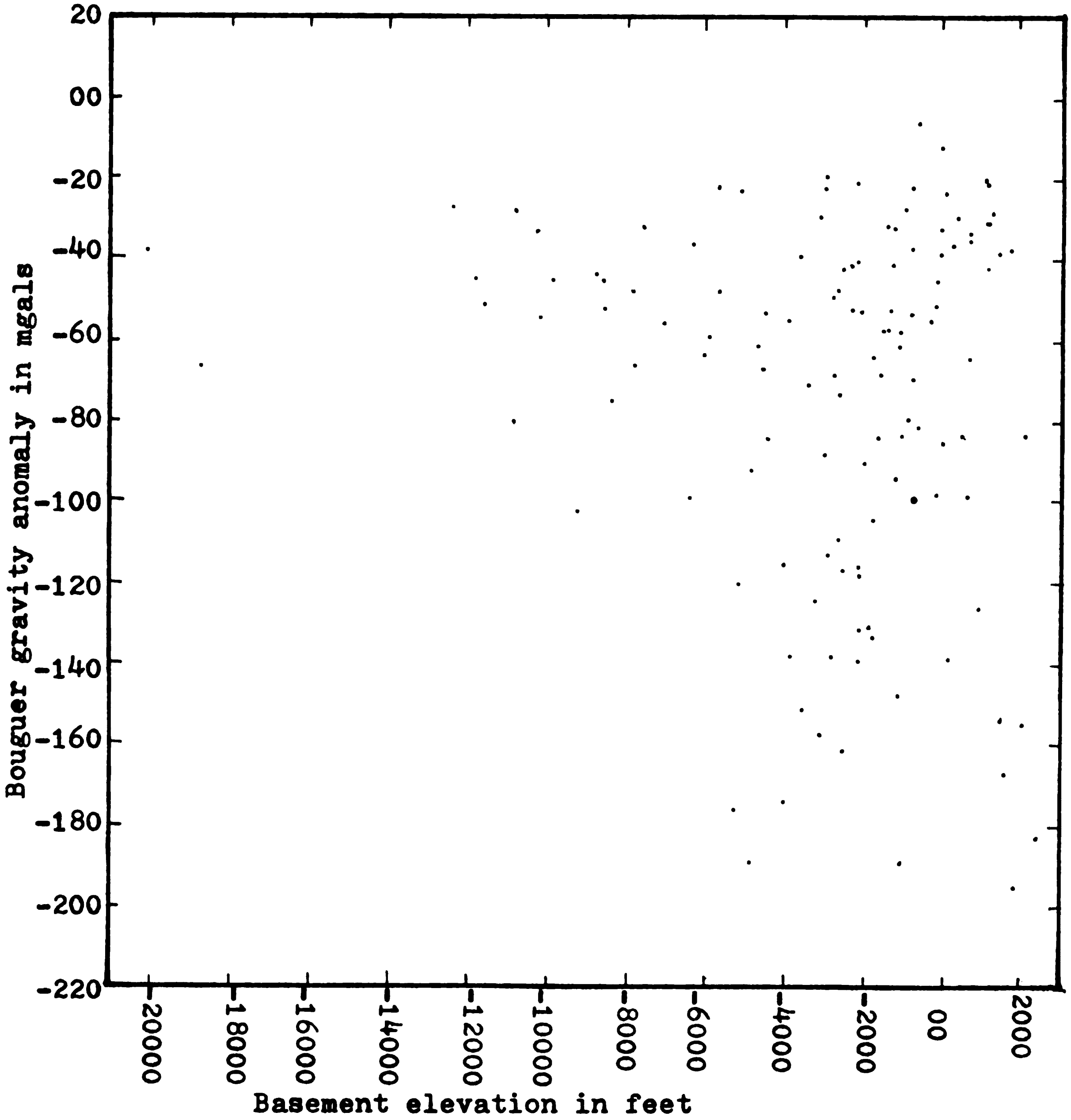


Figure 4. Bouguer anomaly-basement elevation relationship (Western Midcontinent; 1^{o}x 1^{o})

$BA = -46.60 - 0.0034BE$, where BA is the Bouguer gravity anomaly in milligals and BE is the basement elevation in feet relative to the sea level. This notation will be used in all subsequent equations. This relationship is highly significant, having a confidence level of over 99.9 percent and a correlation coefficient of -0.62. In the areas where basement elevations are greater than sea level the Bouguer gravity anomalies are independent of the basement elevations.

The western portion of the Midcontinent shows a wide scatter of points (Figure 4) so that no obvious relationship is observable.

<u>Bouguer Gravity Anomaly-Basement Elevation Relationship for 2^ox 2^o Quadrangles</u>: The average values of Bouguer gravity anomaly and basement elevation for 2^ox 2^o quadrangle areas are plotted in Figure 5. The effect of local geology on the Bouguer gravity anomaly is averaged out by using 2^ox 2^o quadrangles, as a result the points are less scattered than in case of 1^ox 1^o area. The wide scatter of points makes it impossible to discern a correlation although there is an obvious linear trend indicating an inverse relationship between Bouguer gravity anomaly and basement elevation for the areas with an average basement elevation between sea level and 9000 feet below sea level. Those points generally falling in the eastern part of the Midcontinent, show a highly significant relationship, with more than 99.9 percent

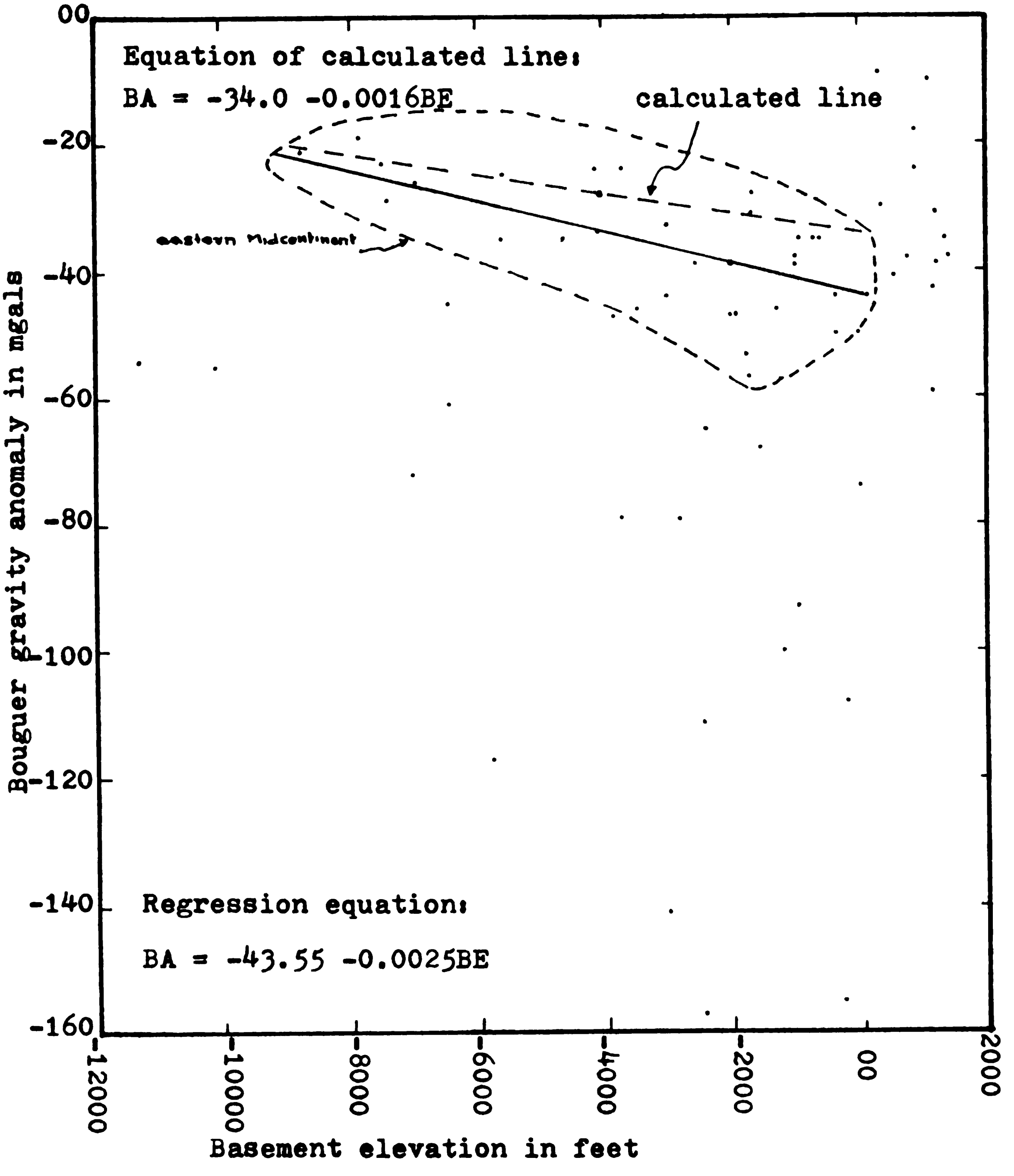


Figure 5. Bouguer anomaly-basement elevation relationship (Midcontinent; 2°x 2°)

Regression equations calculated for eastern Midcont.

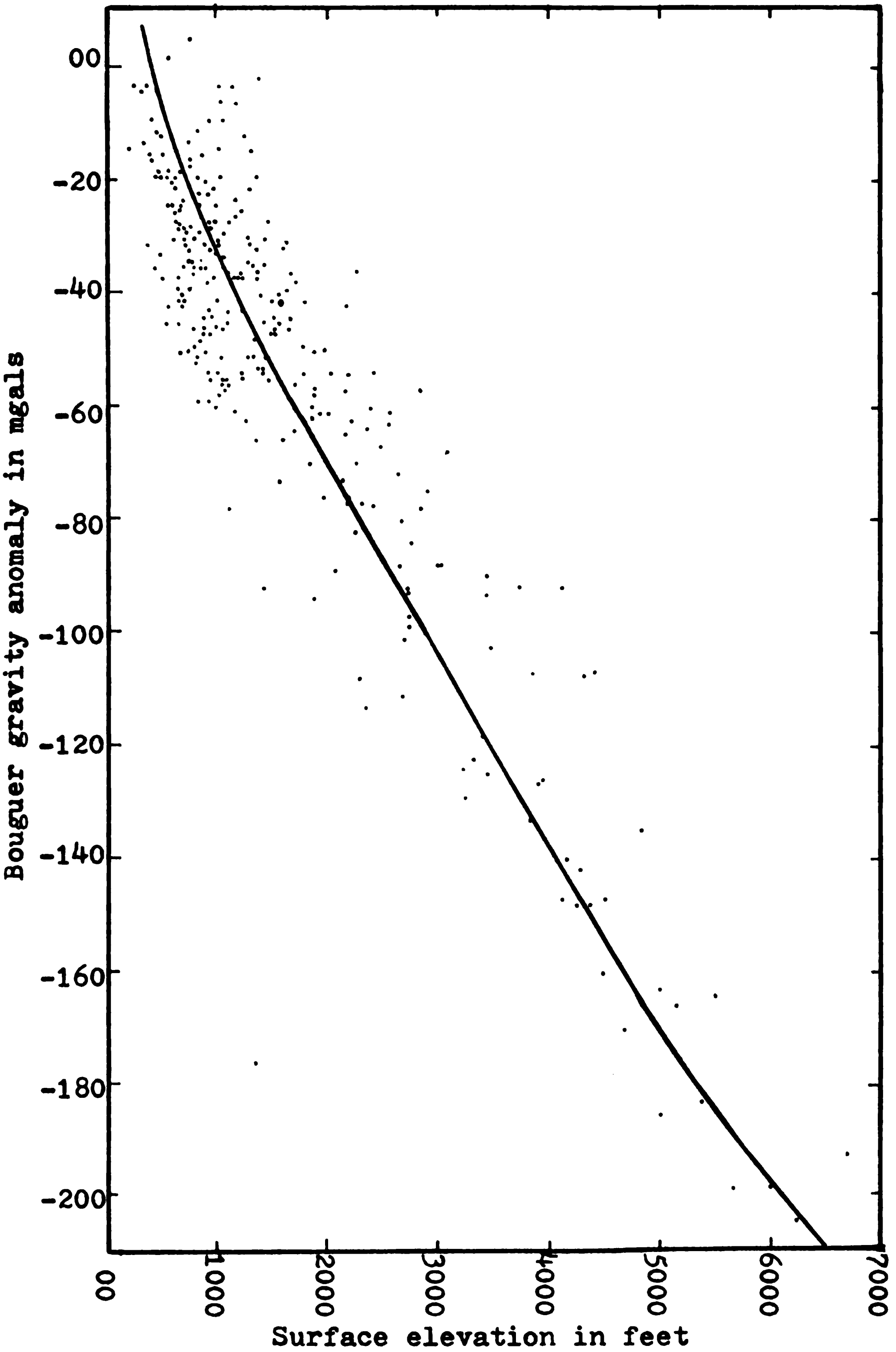


Figure 6. Bouguer anomaly-surface elevation relationship (Midcontinent; 1°x 1°)

confidence level and a -0.66 correlation coefficient. The least square line is given by the equation,

$BA = -43.55 - 0.0025BE$.

Bouguer gravity anomalies, in areas where basement elevations are greater than sea level are independent of the basement elevations. The points obtained from the western portion, generally less than -60 mgals Bouguer gravity anomaly, shows a wide scatter. There is no single possible relationship for this area.

Bouguer Gravity Anomaly-Surface Elevation Relationship for 1^{o}x 1^{o} Quadrangles: Figure 6 shows the relationship of Bouguer gravity anomalies to surface elevations for the entire Midcontinent. The relationship between Bouguer gravity anomaly and basement elevation are distorted to some degree by this relationship between Bouguer anomaly and surface elevation. The Bouguer gravity anomaly in general shows a continuous decrease with increase in surface elevation. The relationship between the two as shown in Figure 6 is determined by inspection. This relationship is nearly a straight line following the gravitational effect of an infinite horizontal slab of density 2.67 gm/cc. Thus, the gravity anomaly is approximately given by,

$\Delta g(\text{mgals}) = 2\pi\gamma\sigma\Delta h = 0.01276 \times 2.67 \times \Delta h(\text{ft.}) = 0.0341\Delta h.$

Deviations from this line assuming isostatic equilibrium represent the effects of local geology. These effects cause the change in the slope of the line,

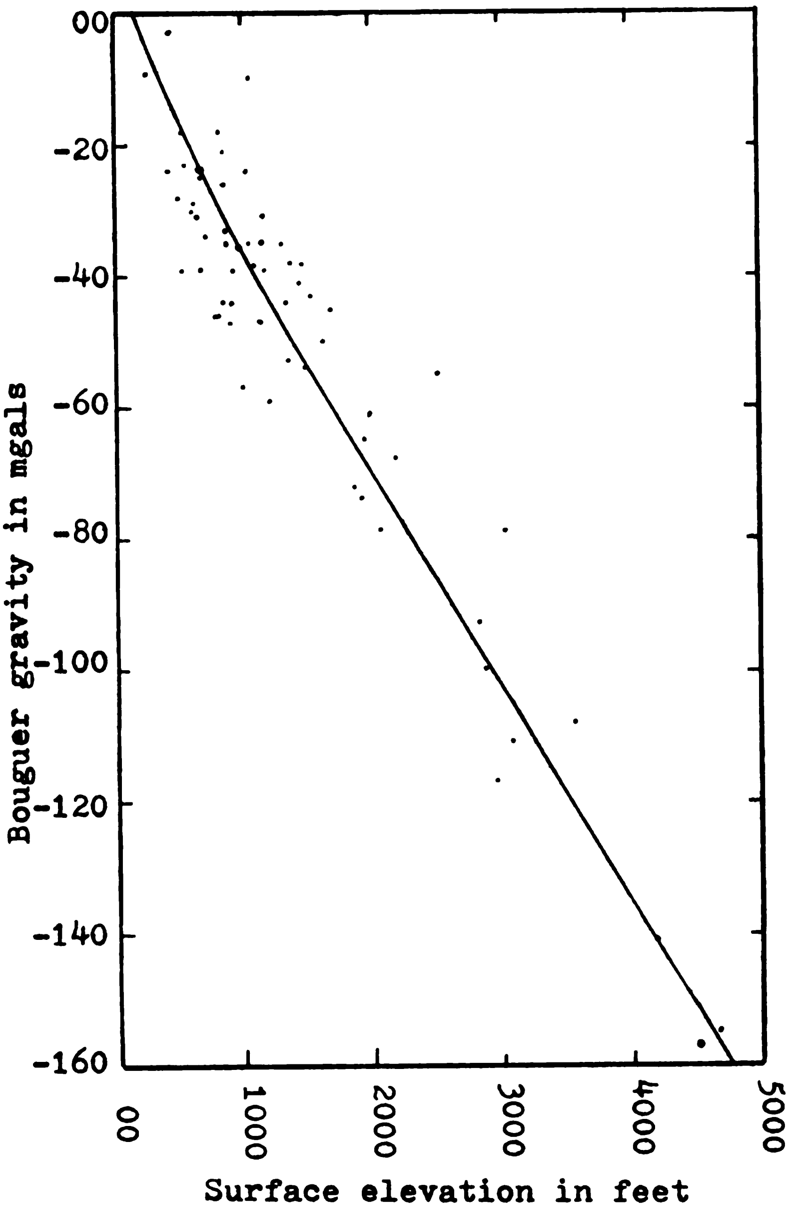


Figure 7. Bouguer anomaly-surface elevation relationship (Midcontinent; 2^o x 2^o)

increasing the slope at less than 1000 feet and decreasing it around 6000 feet. However, the latter effect may be due to the paucity of data and hence not valid, or it may be caused by the lateral effect of anomalies originating from the Rocky Mountains.

Bouguer Gravity Anomaly-Surface Elevation Relationship for 2^ox 2^o Quadrangles: This relationship is similar to the one obtained from 1^ox 1^o quadrangle averages. The points are less scattered due to averaging of the local geological effects and hence deviation from the straight line is less (Figure 7). Thus the relationship follows the effect of the slab more closely. The major difference between the 1^ox 1^o line and 2^ox 2^o line is in areas of surface elevation less than 1000 feet.

Surface Elevation-Basement Elevation Relationship: Considering the entire Midcontinent area on 1^ox 1^o quadrangle basis no single obvious relationship between surface and basement elevations is observed (Figure 8). The points are widely scattered and the straight line relationship, exhibited by points in areas above sea level, is primarily in areas where basement elevation and surface are considered equivalent. However, the data tend to cluster into fields which exhibit an increasing surface elevation with decreasing basement elevation.

Study of the relationship between surface elevation and basement elevation on 2^ox 2^o quadrangle

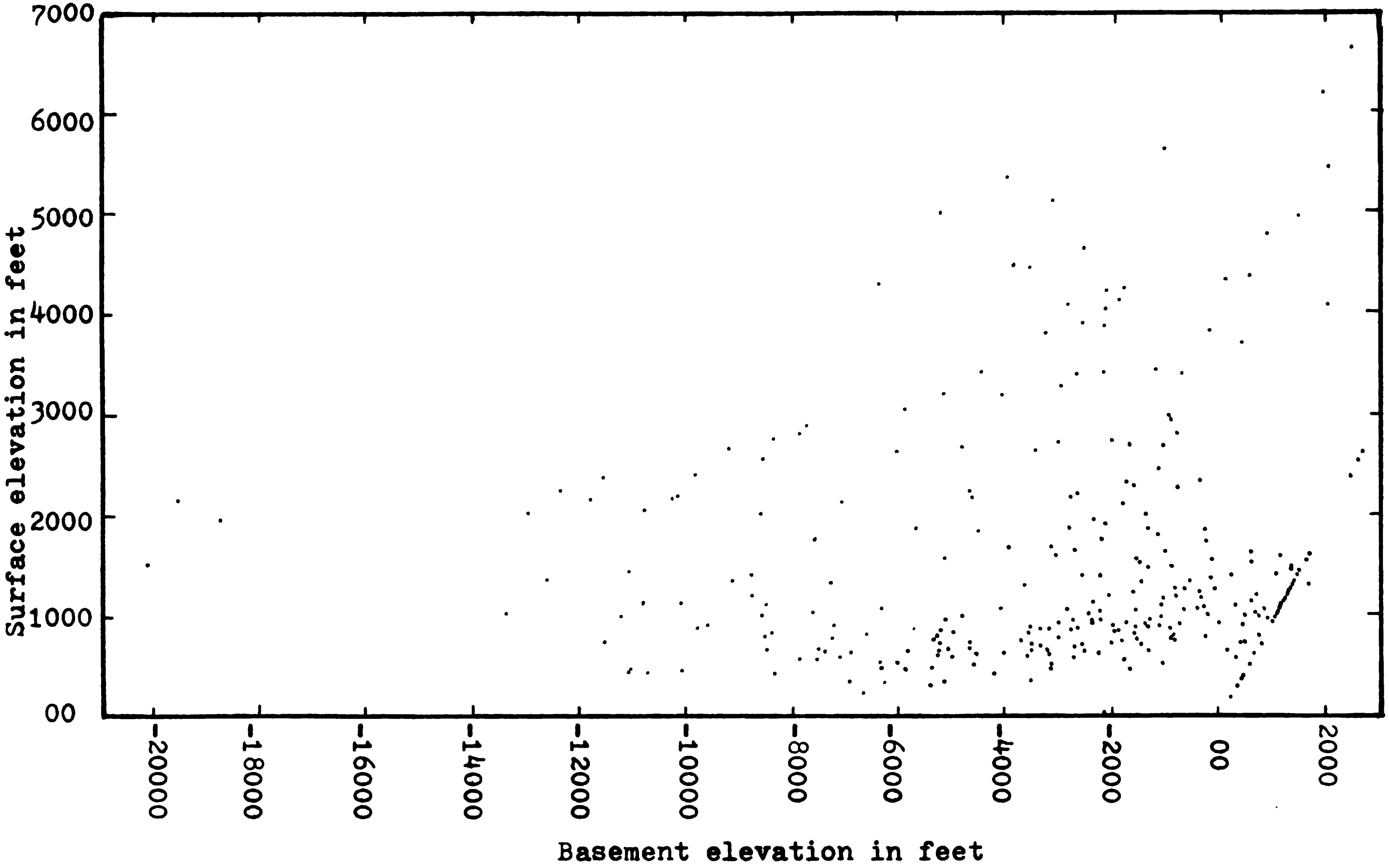


Figure 8. Surface elevation-basement elevation relationship (Midcontinent $1^{o}x1^{o}$)

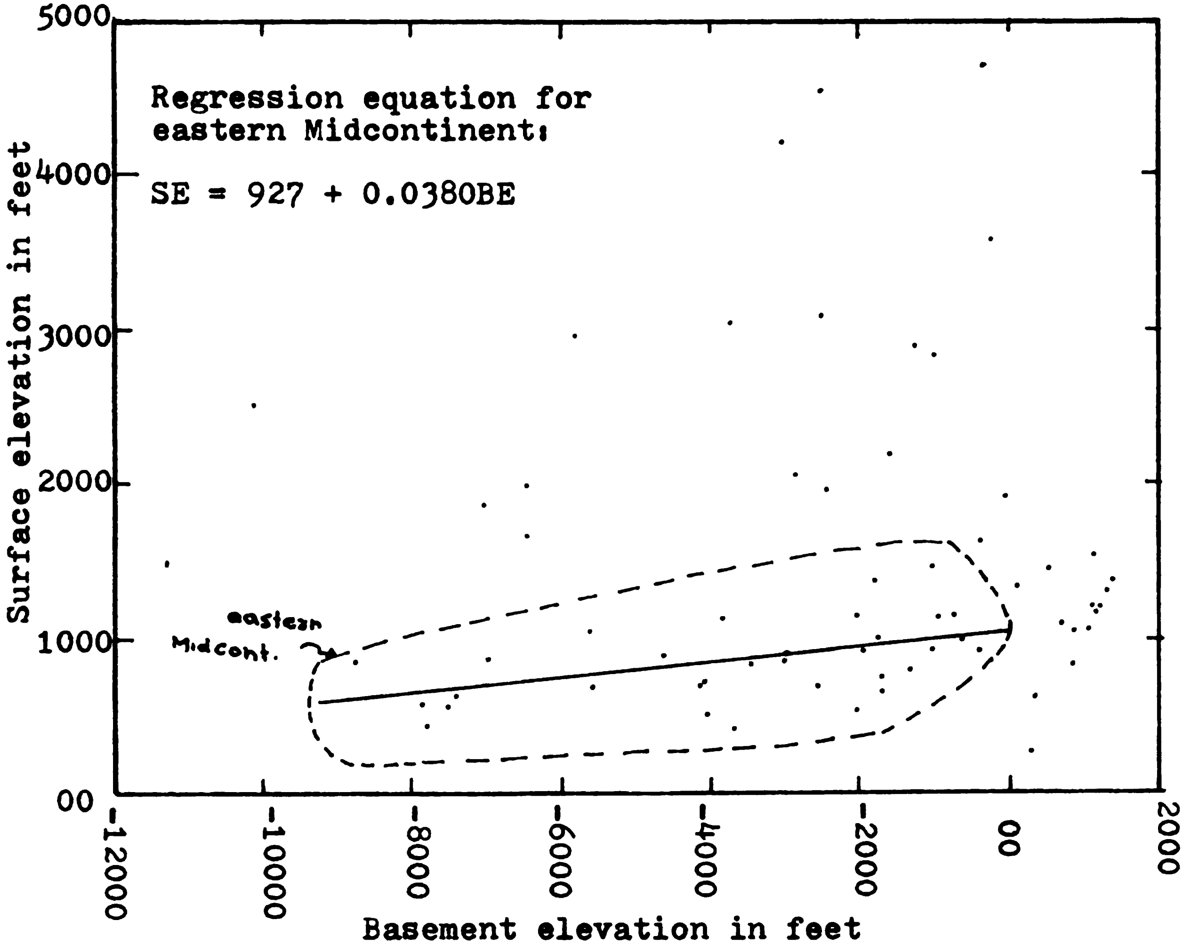


Figure 9. Surface elevation-basement elevation relationship (Midcontinent; $2^{o}x\ 2^{o}$)

average basis indicates the tendency of points to generally fall into two groups in areas where basement elevations are below sea level (Figure 9). One group which has the surface elevations in general greater than 1500 feet shows a wide scatter of points and lies entirely in the western part of the Midcontinent. The other group in general has surface elevations less than 1500 feet and the points form a coherent field. Both these groups exhibit a general increase in surface elevation with increase in basement elevation. A least square line drawn for the eastern area where elevations are less than 1500 feet shows a linear relationship between surface elevations and basement elevations and is represented by the equation $SE = 927 + 0.0380BE$, where SE is the surface elevation in feet above sea level. This relationship is significant, having over 98 percent confidence and has a correlation coefficient of 0.47.

The effect of this relationship between surface and basement elevations will be to cause an inverse correlation between Bouguer gravity anomaly and basement elevation. A Bouguer gravity anomaly-basement elevation relationship was calculated using relations in Figure 7 and Figure 9 and is given by equation $BA = -34.0 - 0.0016BE$. This line is shown in Figure 5 and closely follows the least square line drawn showing the relationship of Bouguer gravity anomaly to the basement elevation in the eastern part of the Midcontinent.

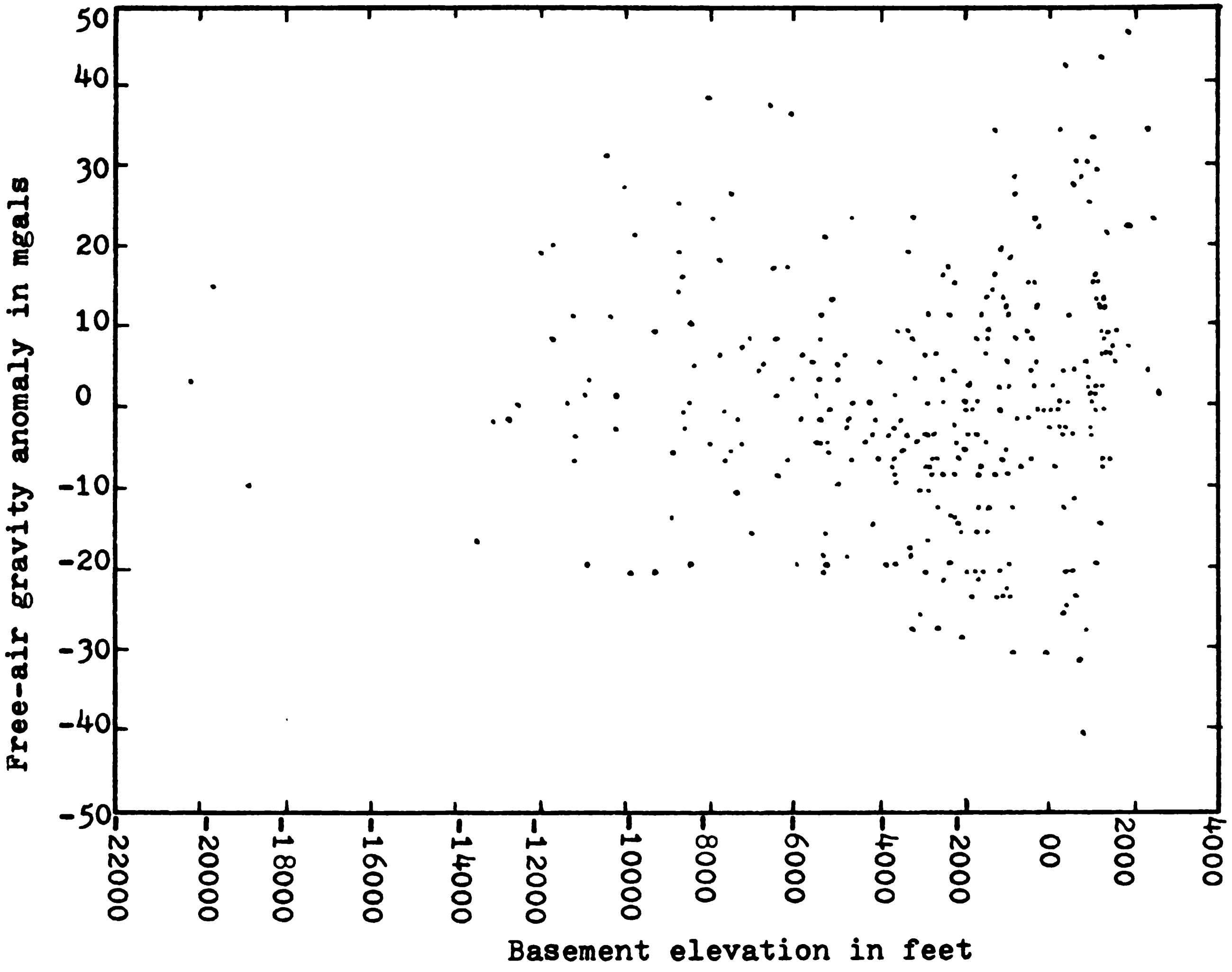


Figure 10. Free-air anomaly-basement elevation relationship (Midcontinent; $1^{o}x1^{o}$)

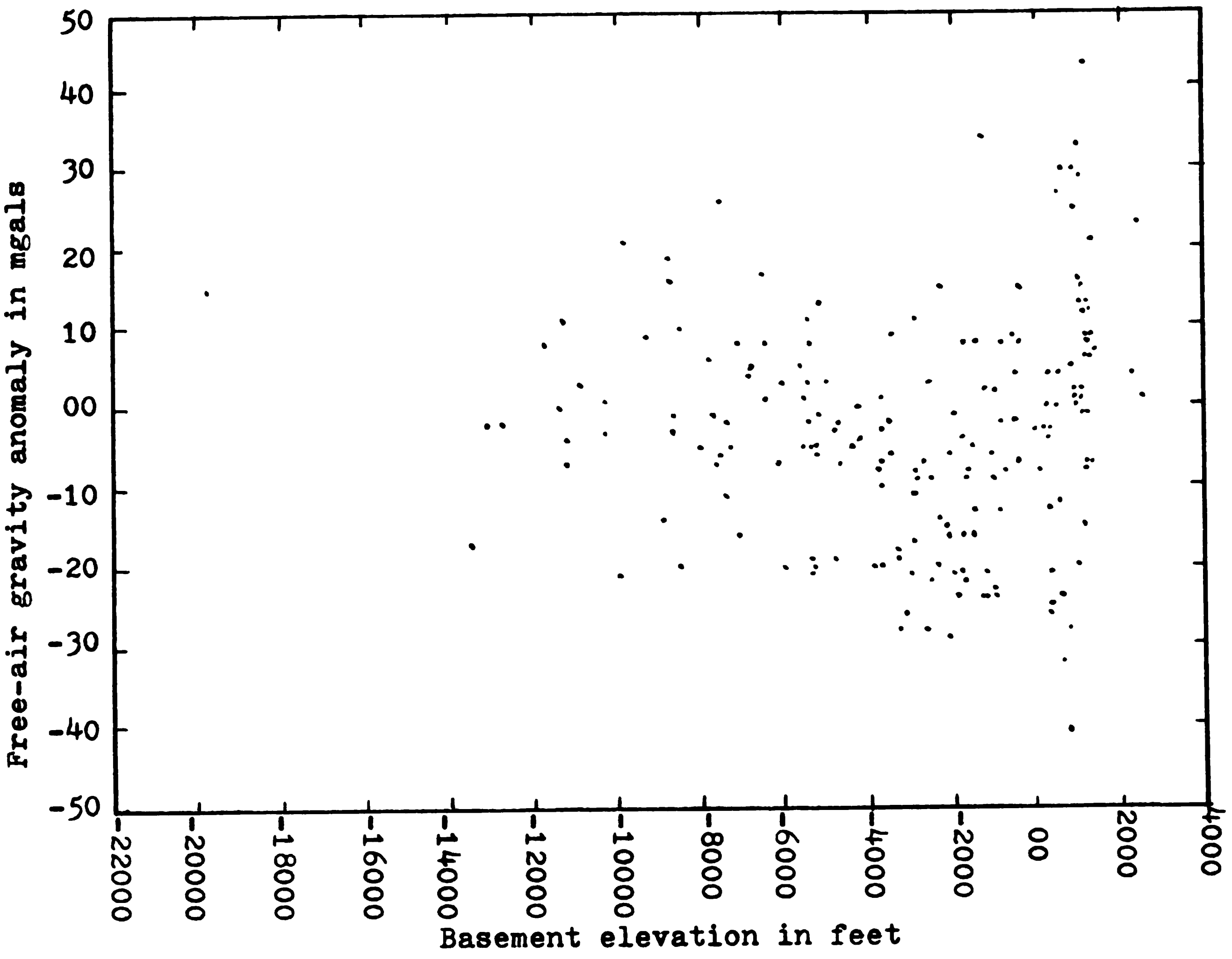


Figure 11. Free-air anomaly-basement elevation relationship (Eastern Midcontinent; 1^{o}x 1^{o}).

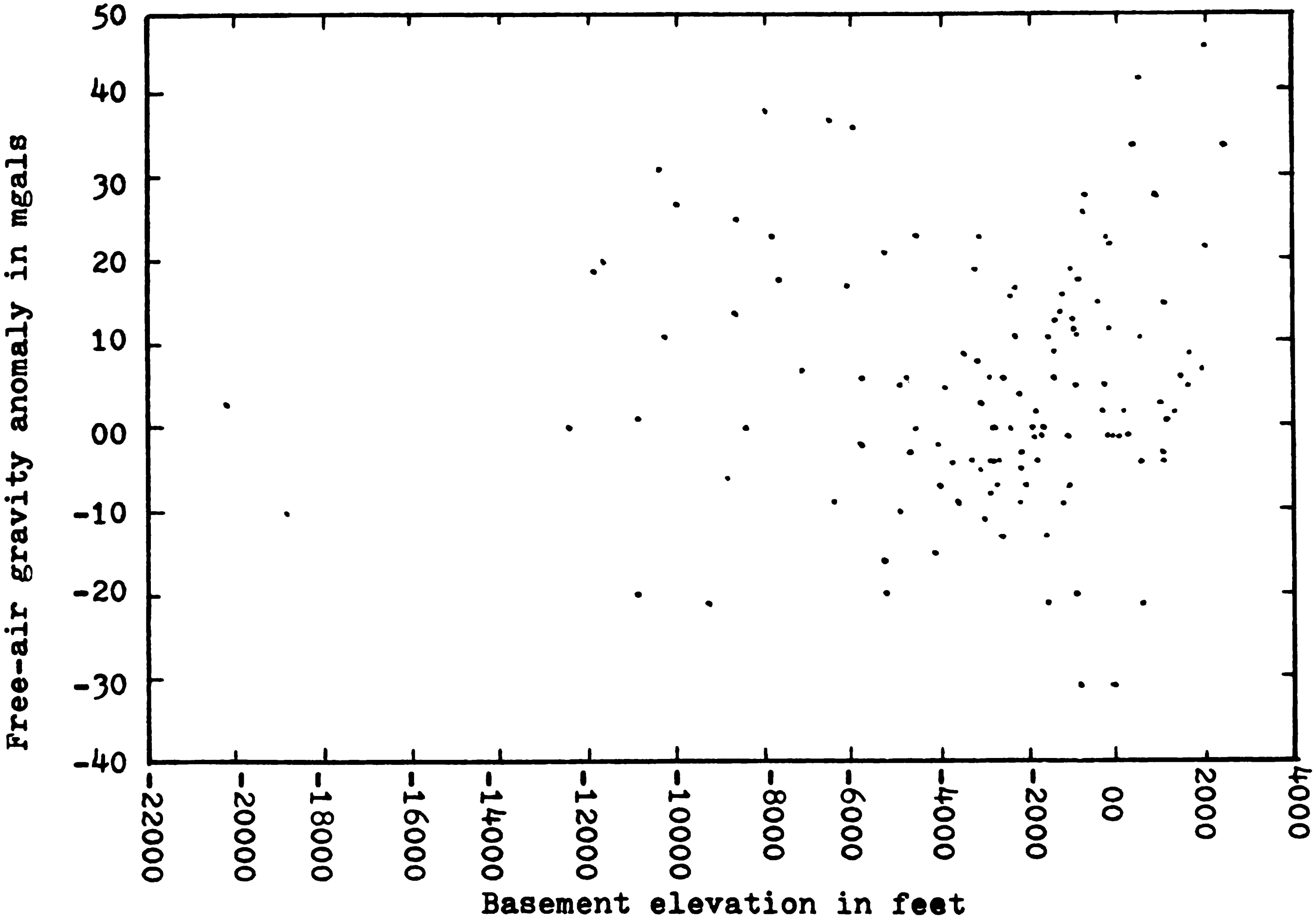


Figure 12. Free-air anomaly-basement elevation relationship (Western Midcontinent $1^{o}x\ 1^{o}$).

The calculated relationship generally falls within the 95 percent prediction limit of the observed relationships. Thus the observed general relationship between Bouguer anomalies and basement elevations in the eastern Midcontinent can be explained by the surface elevation.

In the western part of the area, west of 96°W longitude, the Bouguer gravity anomaly and basement elevations do not exhibit a definable relationship.

Free-air Gravity Anomaly Relationships

Free-air gravity anomalies are best suited to studying the tectonic adjustments as they do not take into consideration the gravitational attractions due to the mass included between sea level datum and elevation of the observation site. The Free-air anomaly is measure of the mass of the subjacent earth.

Free-air Gravity Anomaly-Basement Elevation Relationship: The relationship between Free-air gravity anomalies and basement elevations are studied for 1°x 1° as well as 2°x 2° mean values. The values for 1°x 1° quadrangles are shown in Figure 10 for the entire Midcontinent and Figures 11 and 12 show the relationships for the eastern and western portion respectively. The points are so widely scattered in these figures that no relationship is possible.

The Free-air gravity anomaly-basement elevation relationship for the entire area for 2°x 2° quadrangle

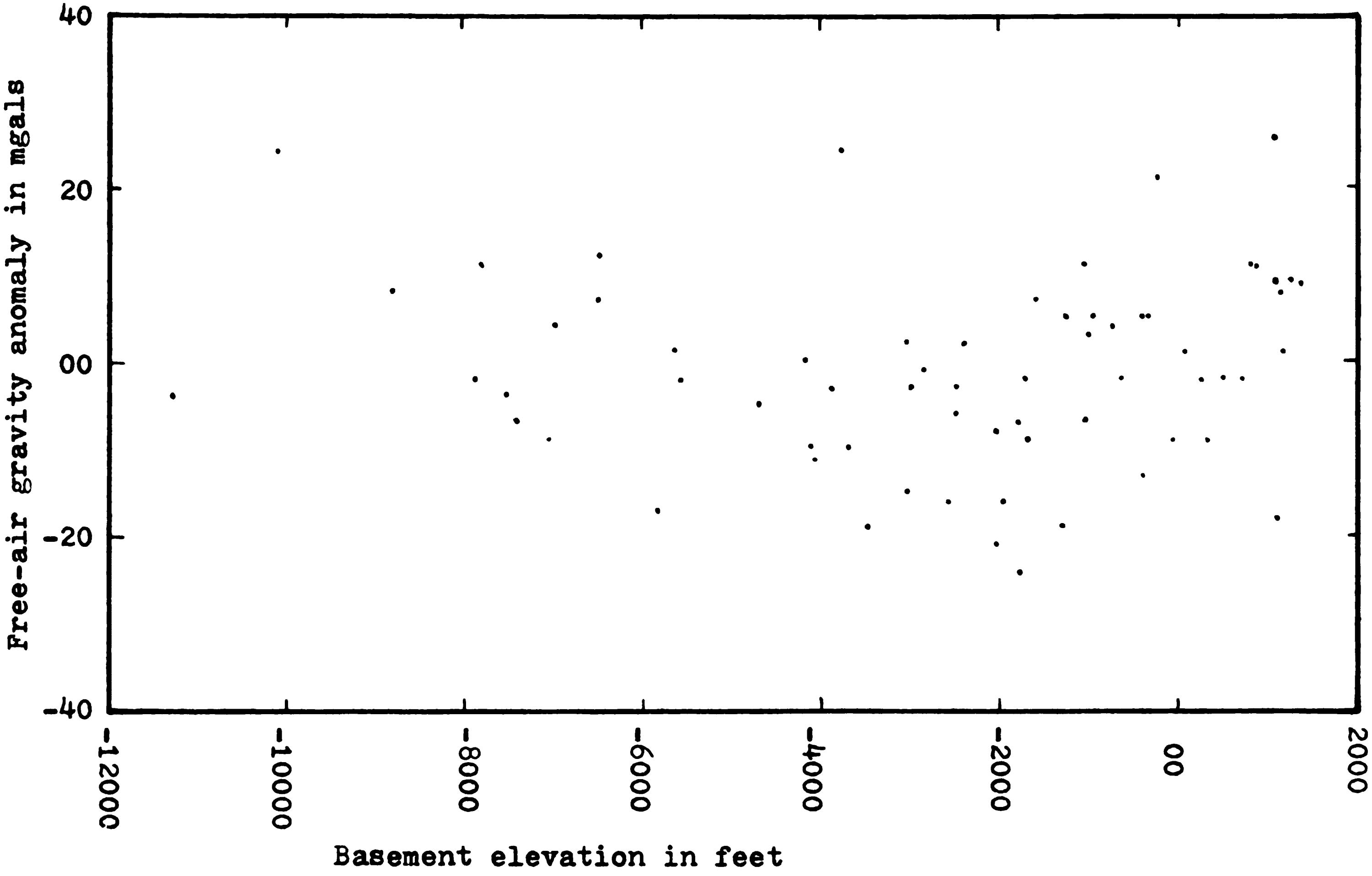


Figure 13. Free-air anomaly-basement elevation relationship (Midcontinent; $2^o x 2^o$)

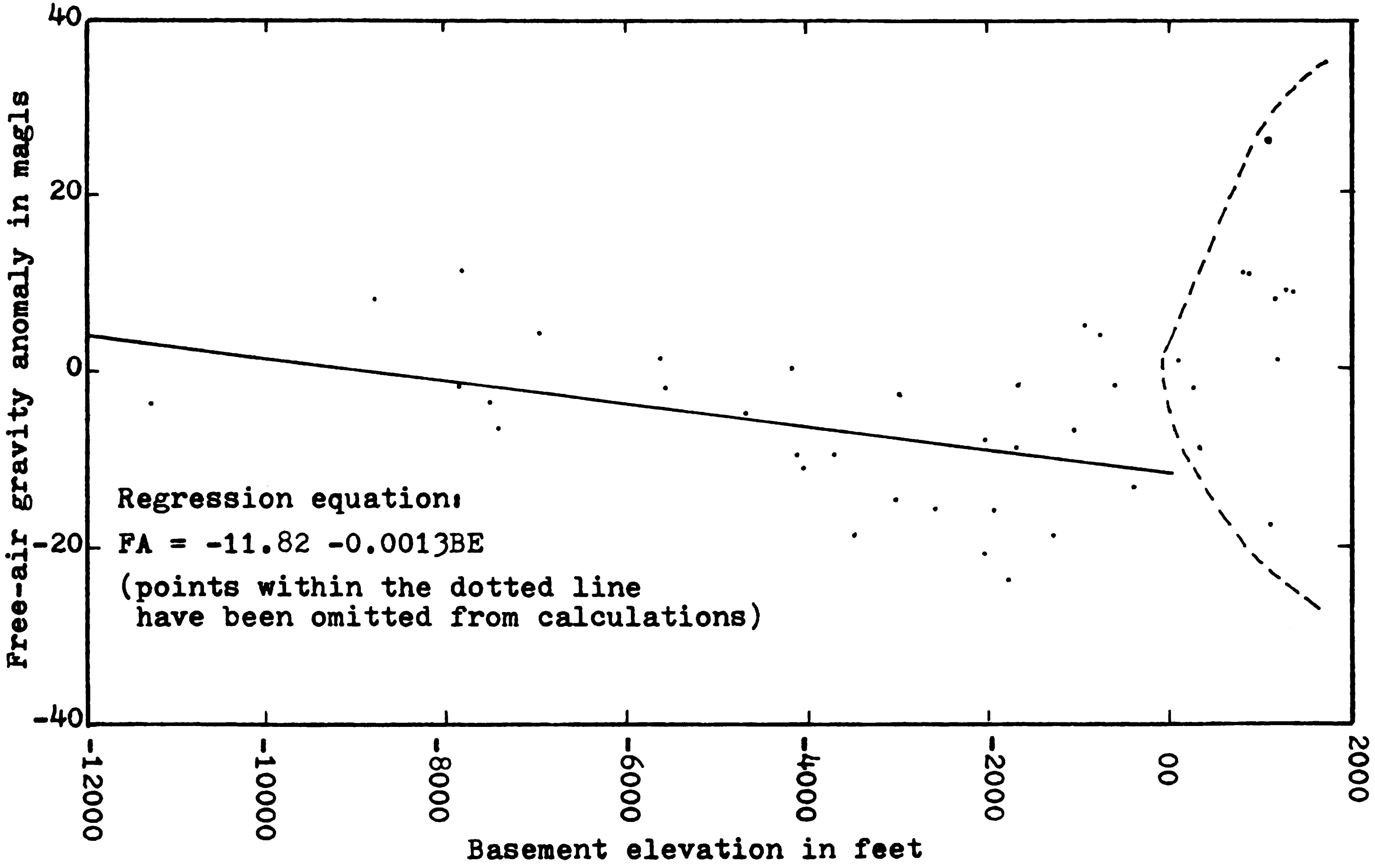


Figure 14. Free air anomaly-basement elevation relationship (Eastern Midcontinent; 2^ox 2^o)

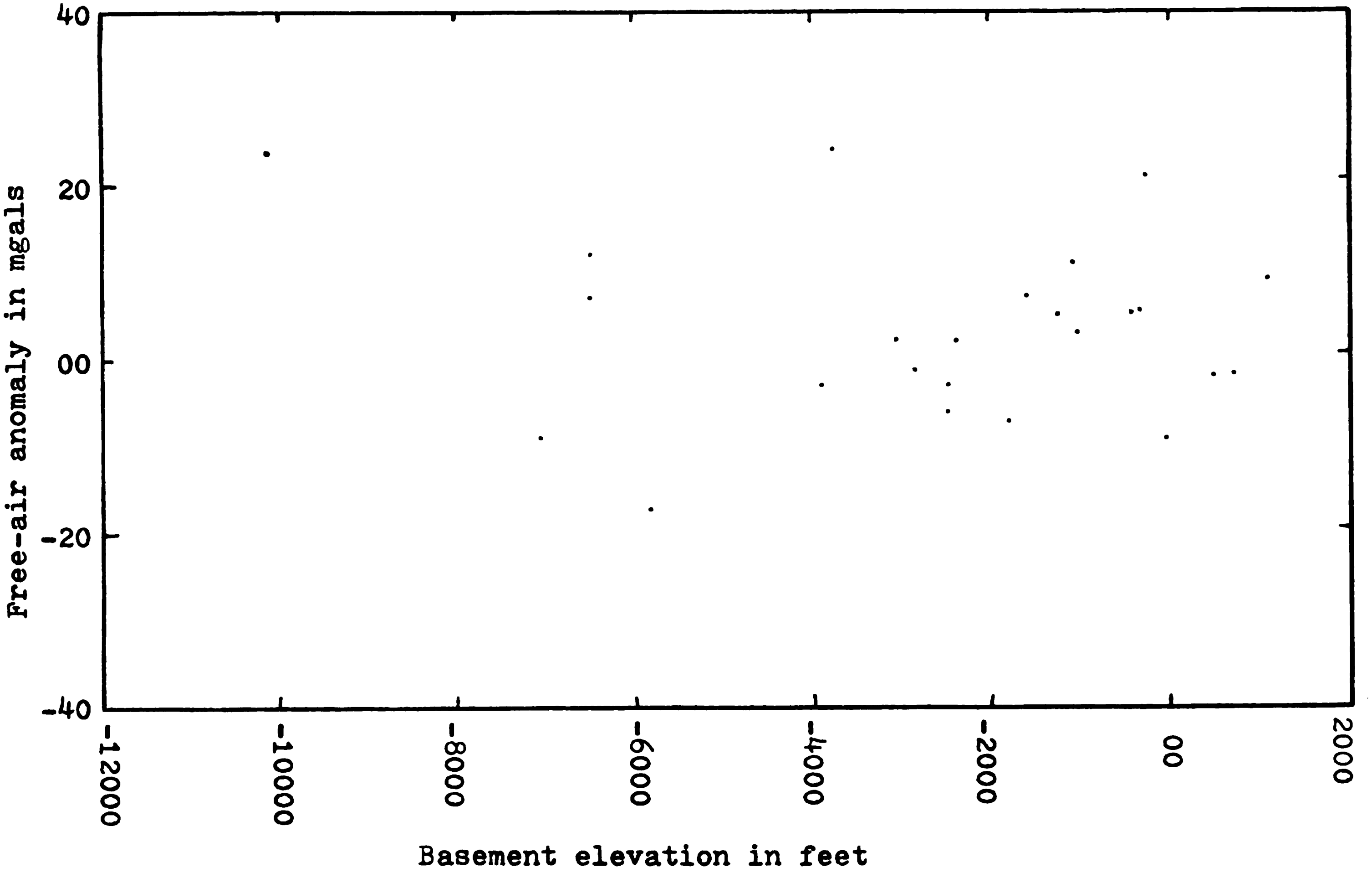


Figure 15. Free-air anomaly-basement elevation relationship (Western Midcontinent; 2^{o}x 2^{o})

mean values is shown in Figure 13. The widely scattered values ranging between ±25 mgals indicate no apparent relationship. Study of the relationship in eastern portion (Figure 14) reveals a linear relationship for values where basement elevations are less than sea level. The Free-air anomaly decreases with increasing basement elevation and the relationship can be expressed in terms of the equation, $FA = -11.82 - 0.0013BE$ where FA is the Free-air gravity anomaly in milligals. This relationship is probably significant as indicated by a confidence level of over 95 percent and a -0.44 correlation coefficient. In areas where basement elevations are greater than sea level there is an indication of increasing Free-air gravity anomaly with increasing basement elevation. This increase in anomaly with surface elevation may indicate that the area is under compensated. However, even if the area is in regional isostatic compensation the great depths of the compensating mass deficit for the mass excess at the surface may lead to positive Free-air anomalies.

The western portion of the area shows more incoherency and no apparent relationship is exhibited (Figure 15). However, there is a general bias towards positive Free-air anomaly values indicating an over all under compensation of the area.

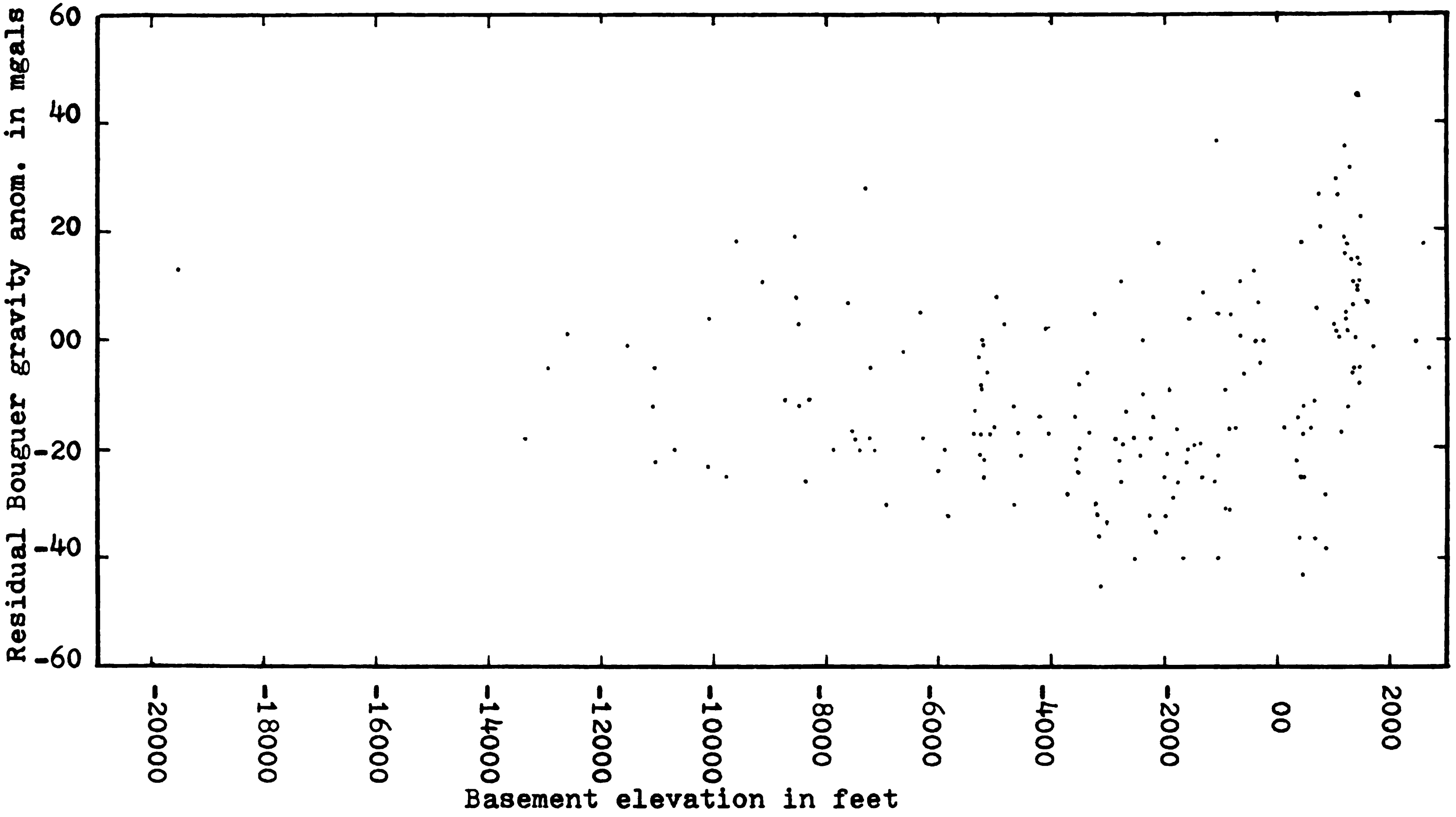


Figure 16. Residual Bouguer anomaly-basement elevation relationship (Eastern Midcontinent; 1^{o}x 1^{o})

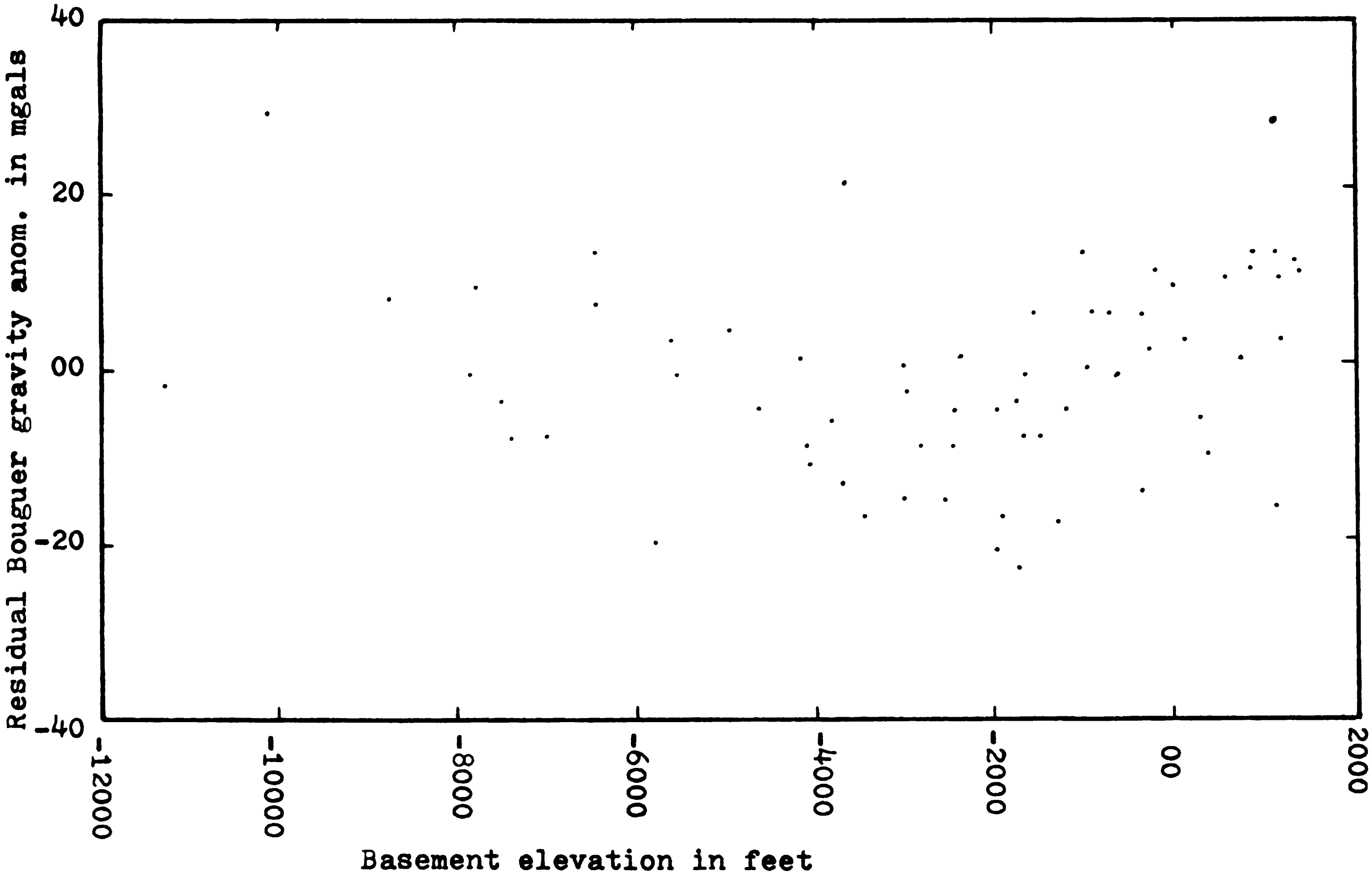


Figure 17. Residual Bouguer anomaly-basement elevation relationship (Midcontinent; 2°x 2°)

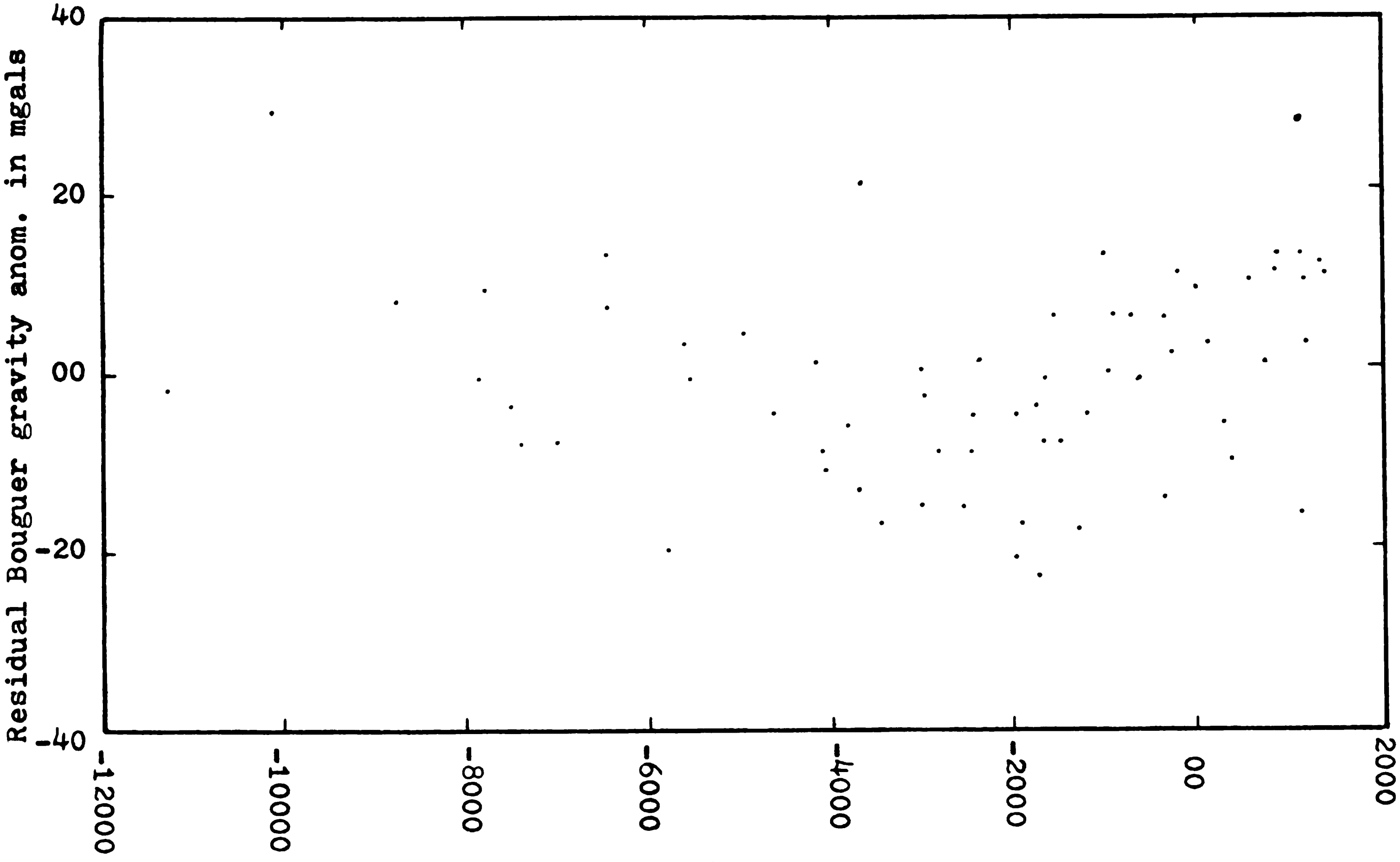


Figure 17. Residual Bouguer anomaly-basement elevation relationship (Midcontinent; 2°x 2°)

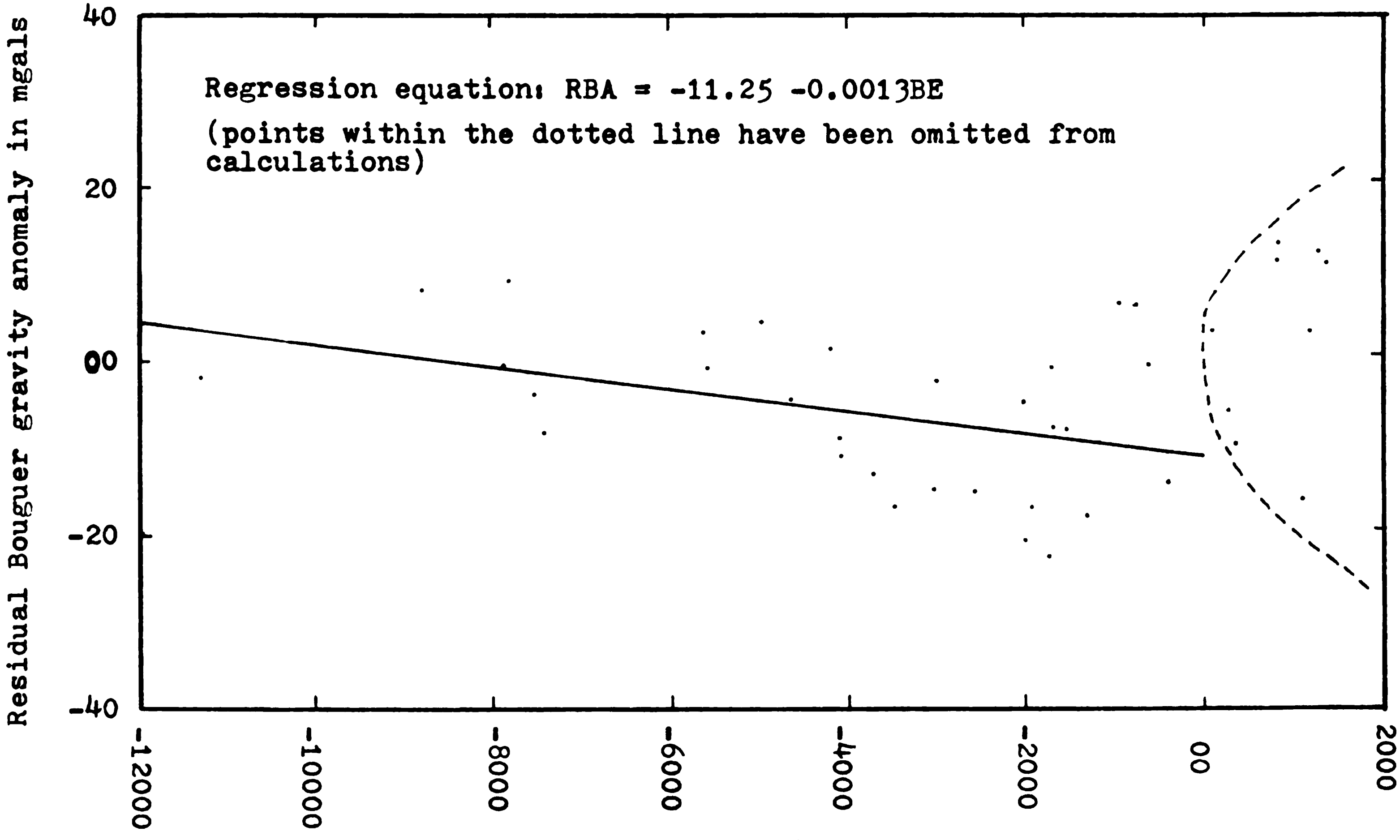


Figure 18. Residual Bouguer anomaly-basement elevation relationship (Eastern Midcontinent; 2^ox 2^o)

Residual Bouguer Anomaly-Basement Elevation Relationship: The nature and magnitude of the residual Bouguer gravity anomaly obtained from the mean surface elevation using the Bouguer gravity-surface elevation relationship is similar to the Free-air anomaly. No obvious relationship is observed in the Midcontinent between residual and basement elevation of $1^{o}x\ 1^{o}$ areas. Figure 16 shows the residual anomaly for the eastern portion of the area. The $2^{o}x\ 2^{o}$ mean values of the entire Midcontinent also show wide scatter and no single correlation is possible (Figure 17). However, in the eastern portion of the area where basement elevations are below sea level an inverse relationship is observed similar to Free-air anomaly-basement elevation relationship (Figure 18). This inverse relationship can be represented by a least square line, RBA = -11.25 - 0.0013BE, where RBA is the residual Bouguer gravity anomaly in milligals. This relationship has a probable significance with 95 percent confidence level and a correlation coefficient of -0.42. In the western portion of the area, shown in Figure 19, no apparent correlation is possible, but there is a bias towards positive values similar to the Free-air gravity anomaly.

The deviation of residual Bouguer gravity anomaly from the Free-air gravity anomaly is maximum in areas where the surface elevation is less than 1000 feet. This deviation is less for $2^{o}x\ 2^{o}$ area than for $1^{o}x\ 1^{o}$.

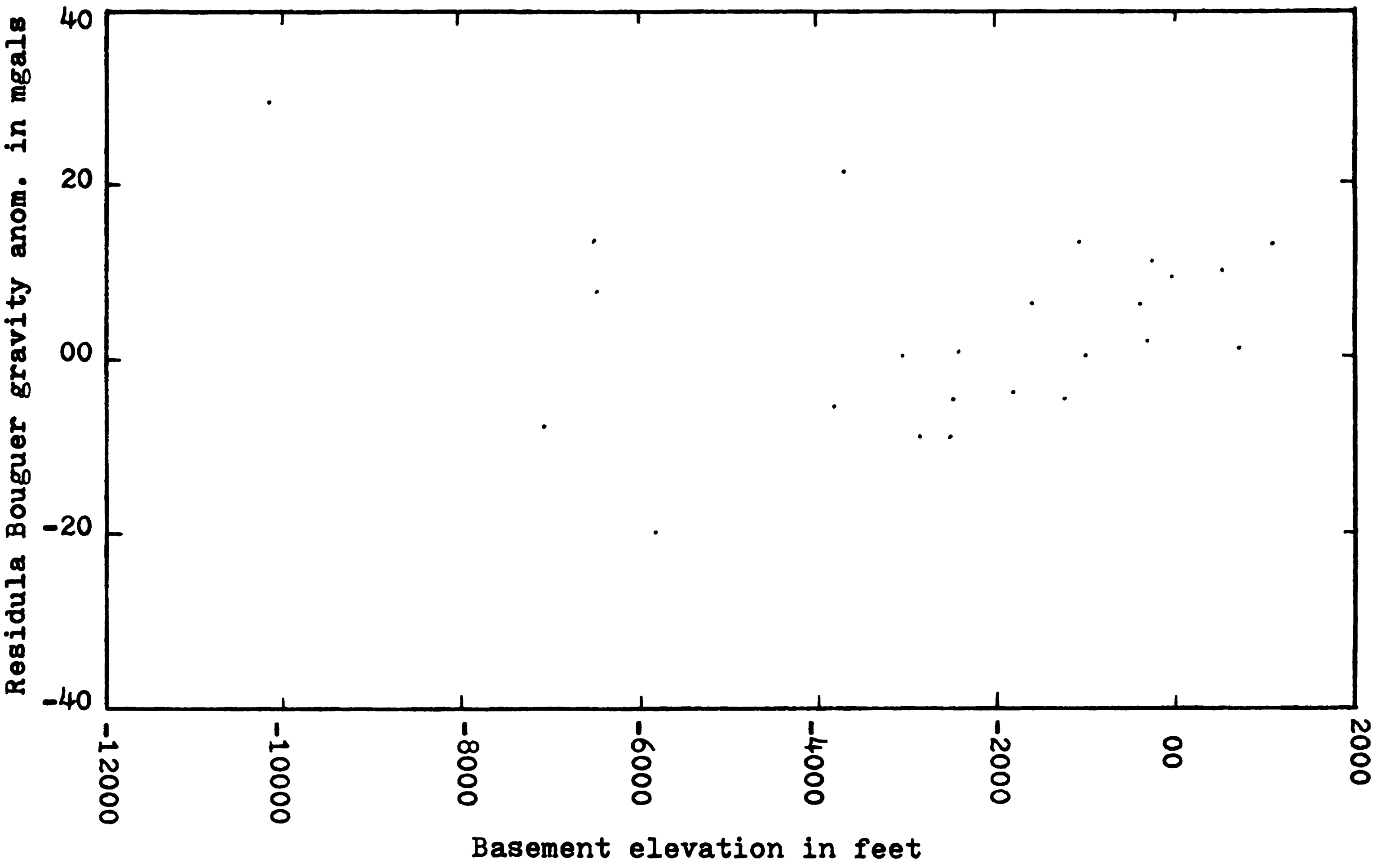


Figure19. Residual Bouguer anomaly-basement elevation relationship (Western Midcontinent

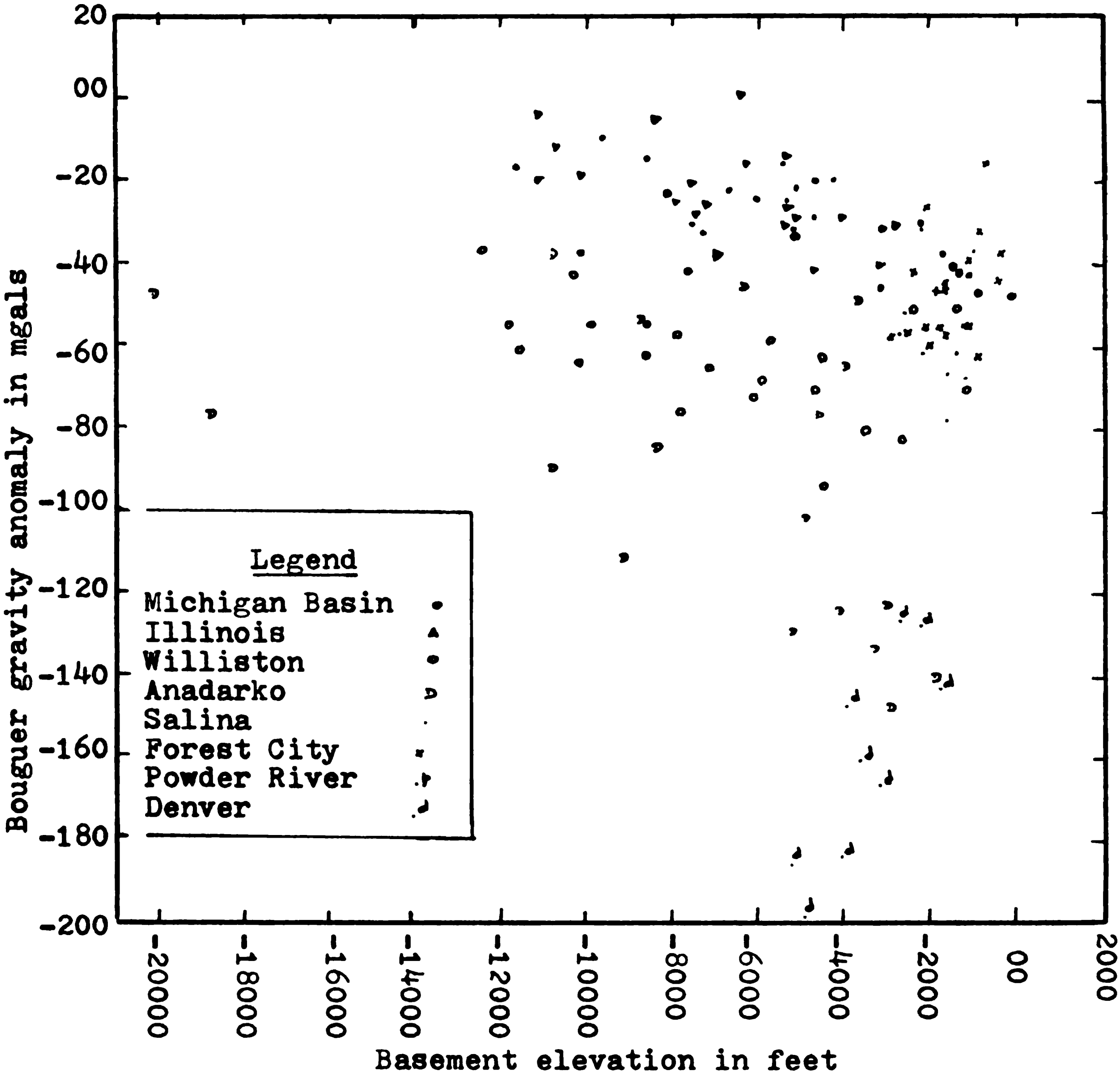


Figure 20. Bouguer anomaly-basement elevation relationship (Basins; 1° x 1°)

Basins

General Relationships

<u>Bouguer Gravity Anomaly-Basement Elevation Relationships for 1°x 1° Quadrangles</u>: Bouguer gravity anomaly and basement elevation relationships for 1°x 1° quadrangles within the basins widely distributed and no correlation is possible (Figure 20). No single correlation is indicated even within the individual basins except for the Michigan and Illinois Basins which exhibit an inverse relationship of Bouguer gravity anomaly to the basement elevation. However, the Williston Basin, excluding the area bordering the Minnesota craston, and the Anadarko Basin except for the area bordering the Ozark and Nemaha uplifts tend to exhibit a possible inverse relationship between Bouguer gravity anomaly and basement elevation.

<u>Bouguer Gravity Anomaly-Basement Elevation Relationship for 2°x 2° Quadrangles</u>: The relationship between Bouguer gravity anomaly and basement elevation for 2°x 2° quadrangles within the basins is indicated in Figure 21. The values are widely scattered, but they tend to fall in two general groups. One group consists of values corresponding to the Michigan, Illinois, Salina, Forest City and a part of the Williston Basins. This group shows an inverse relationship of Bouguer gravity anomalies to basement elevations and can be represented by a straight line given by the equation,

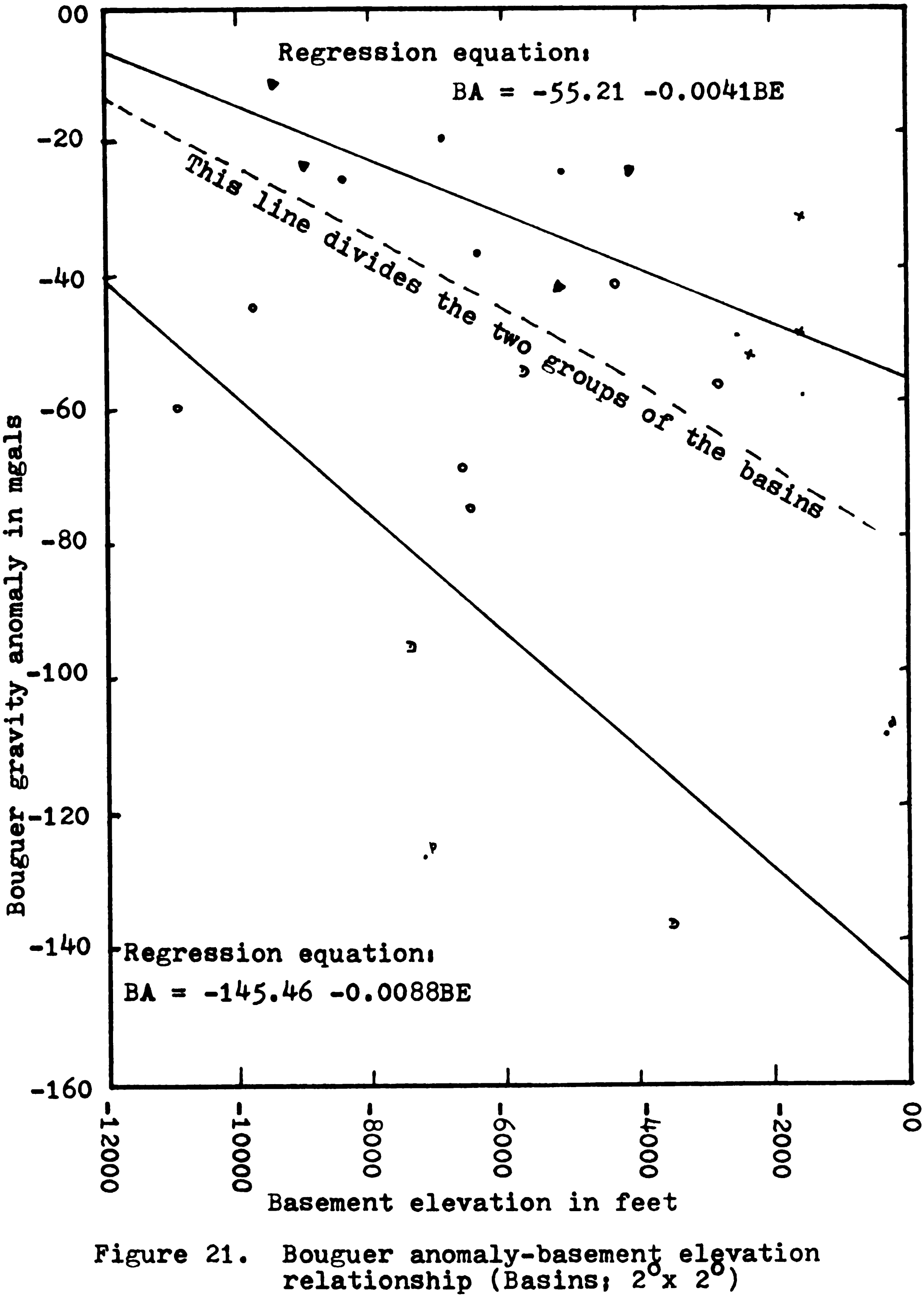


Figure 21. Bouguer anomaly-basement elevation relationship (Basins; 2° x 2°)

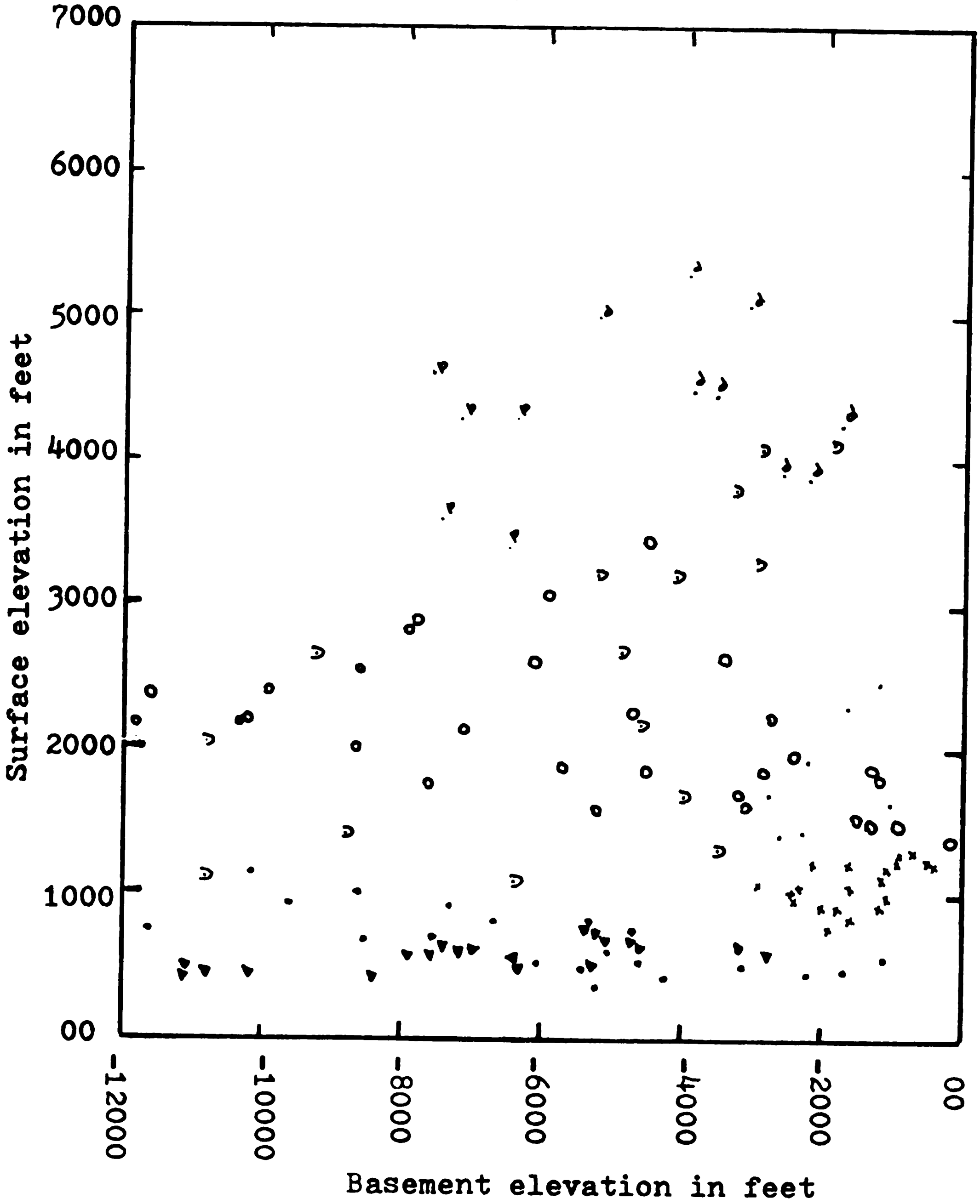


Figure 22. Surface elevation-basement elevation relationship (Basins; $1^{\circ} \times 1^{\circ}$)
(Deeper point of Anadarko Basin has been neglected.)

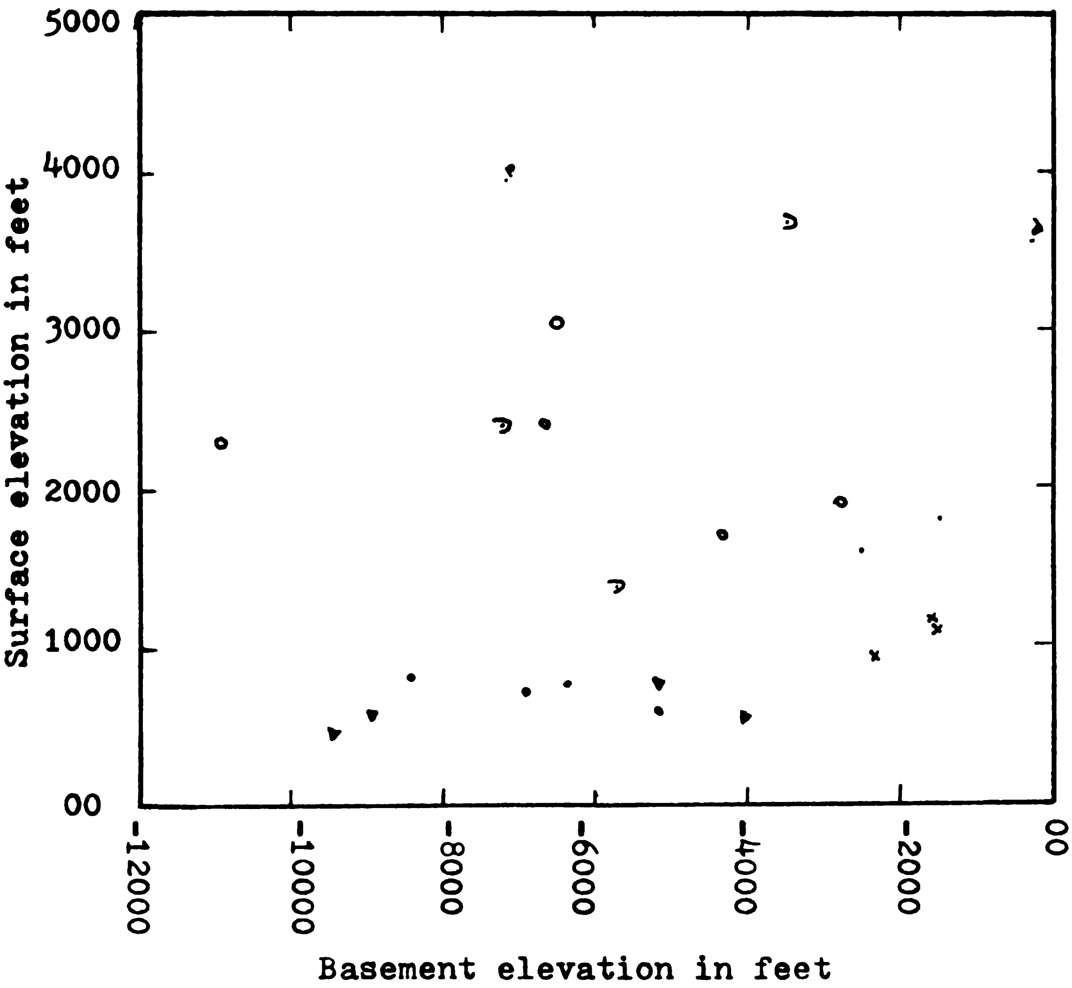


Figure 23. Surface elevation-basement elevation relationship (Basins; 2°x 2°)

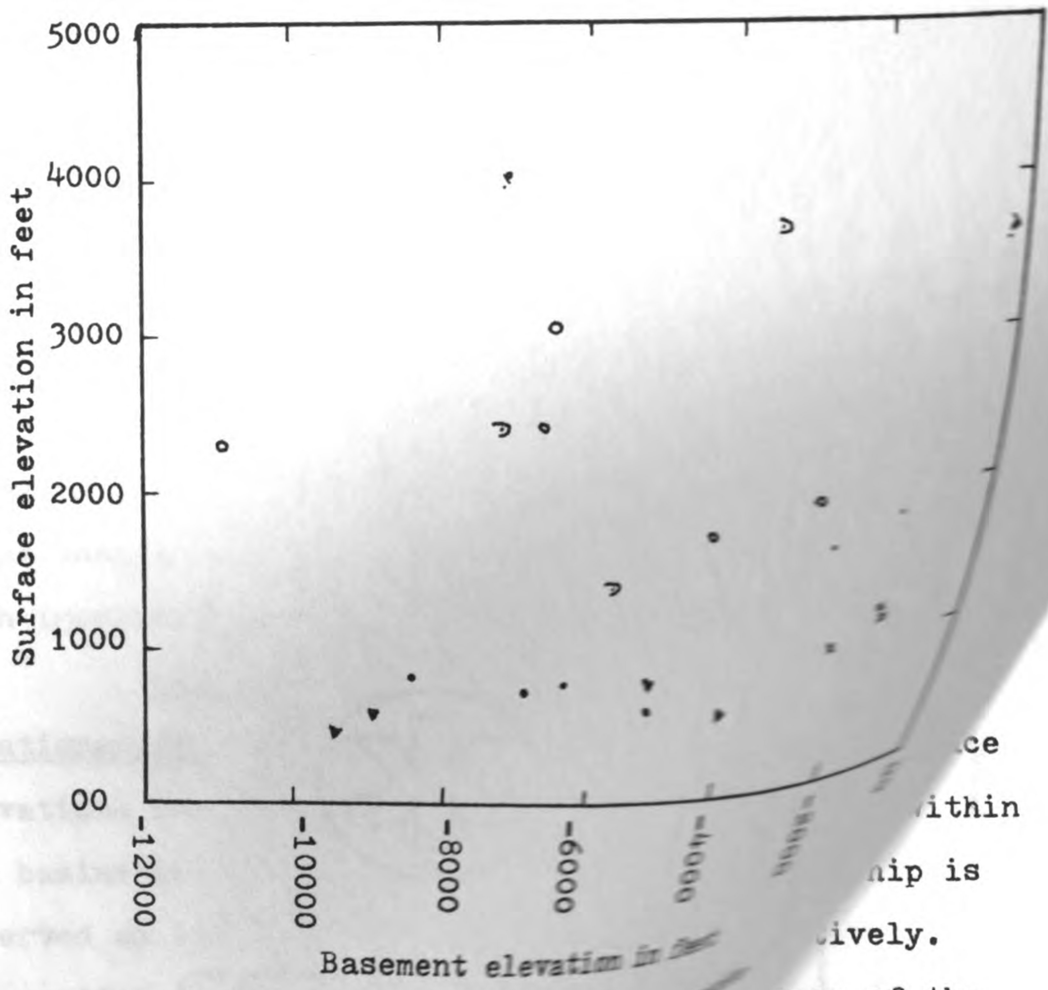


Figure 23. Surface elevation-basement
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BA = -55.21 - 0.0041BE with a highly significant relationship, having over 99.9 percent confidence level and a correlation coefficient of -0.78.

The second group is much more scattered and consists of the values falling within the Williston, Anadarko, Powder River and Denver Basins. The relationship between Bouguer gravity anomaly and basement elevation is represented by the equation,
BA = -145.46 - 0.0088BE and has a correlation coefficient of -0.60, but the significance of this relationship is doubtful having only 90 percent confidence level. The negative slope of the line clearly shows the inverse relationship, i.e., Bouguer gravity anomaly decreasing with increasing basement elevations.

Basement Elevation-Surface Elevation Relationships: The points relating basement to surface elevations for both 1^ox 1^o and 2^ox 2^o quadrangles within the basins are widely scattered and no relationship is observed as shown in Figures 22 and 23 respectively. The scatter is much more pronounced in the case of the Williston, Anadarko, Denver and Powder River Basins as compared to the Michigan, Illinois and Forest City Basins.

The lack of correlation of basement elevations to surface elevations for the basins makes it impossible to develop a Bouguer gravity anomaly-basement elevation relationship as noted in Figure 5 for the entire eastern Midcontinent using the Bouguer gravity anomaly-surface

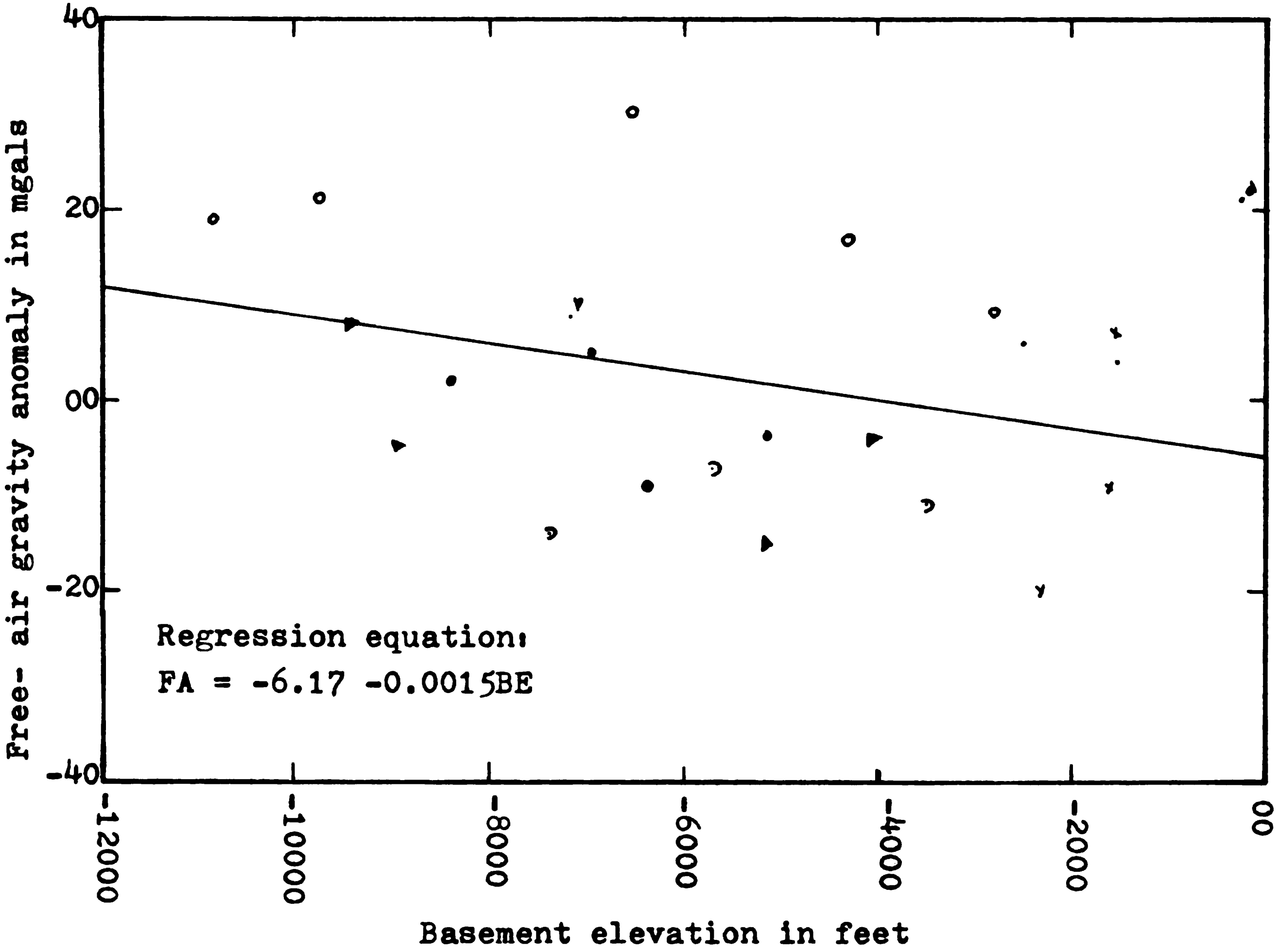


Figure 24. Free-air anomaly-basement elevation relationship (Basins $2^{o} x 2^{o}$)

elevation relationship shown in Figure 7.

Free-air Gravity Anomaly-Basement Elevation Relationships: Free-air gravity anomaly-basement elevation points using $1^{\circ} \times 1^{\circ}$ average values from within the basins are so widely scattered that there is no obvious correlation. However, the average values from $2^{\circ} \times 2^{\circ}$ quadrangles (Figure 24) show an inverse relationship, similar to the one shown by Bouguer anomaly-basement elevation relationship. However, its slope is considerably less, about one third of the latter relationship. The equation of the least square line representing the relationship between Free-air anomalies and basement elevations is given by $FA = -6.17 - 0.0015BE$. The wide scatter of Free-air anomaly values with basement elevation is reflected in its correlation coefficient of -0.33 and in a confidence level of only 90 percent which makes the significance of the correlation doubtful.

Individual Basins

Michigan Basin: Surface elevation, Bouguer gravity anomaly and Free-air gravity anomaly are plotted against basement elevations for $1^{\circ} \times 1^{\circ}$ area in Figure 25. The surface elevation-basement elevation relationship (Figure 25a) shows an opposite trend to that observed when considering the entire Midcontinent area (Figure 9). The surface elevation decreases with increasing basement elevation and this inverse straight line relationship is

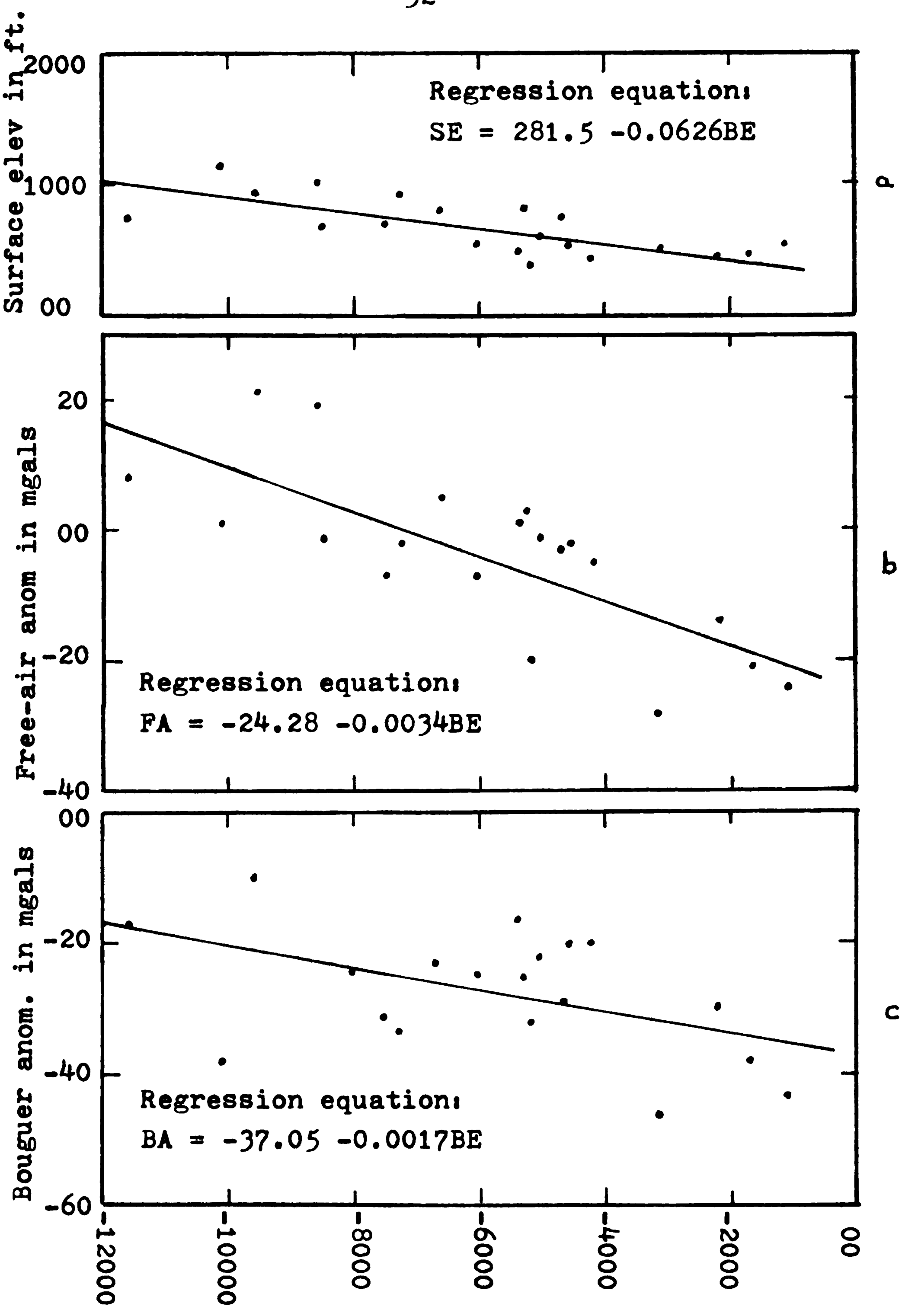


Figure 25. Michigan Basin; 1°x 1° relationship

expressed by the equation, SE = 281 - 0.0626BE and has a correlation coefficient of -0.71. This relationship is definitely significant as indicated by a 99.9 percent confidence level . As a result of this inverse relationship between surface and basement elevations and the general Bouguer gravity anomaly-surface elevation relationship, the effect of the surface elevation should be to cause a direct Bouguer anomaly-basement elevation relationship. However, an inverse relationship is shown in Figure 25c. The Bouguer gravity anomaly-basement elevation relationship for the Michigan Basin (Figure 25c) is given by the equation, BA = -37.05 - 0.0017BE . This relationship is probably significant as reflected by over 95 percent confidence level and has a correlation coefficient of -0.51 .

The Free-air gravity anomaly basement elevation relationship (Figure 25b) is also inverse, but the slope is greater than the Bouguer gravity anomaly-basement elevation relationship (Figure 25c). The least square line is given by the equation FA = -24.28 - 0.0034BE with 99.9 percent confidence level and -0.76 correlation coefficient.

Illinois Basin: Surface elevation, Bouguer gravity anomaly and Free-air gravity anomaly are plotted against basement elevation for $1^{o} x\ 1^{o}$ area of the Illinois Basin in a similar manner as the Michigan Basin in Figure 26.

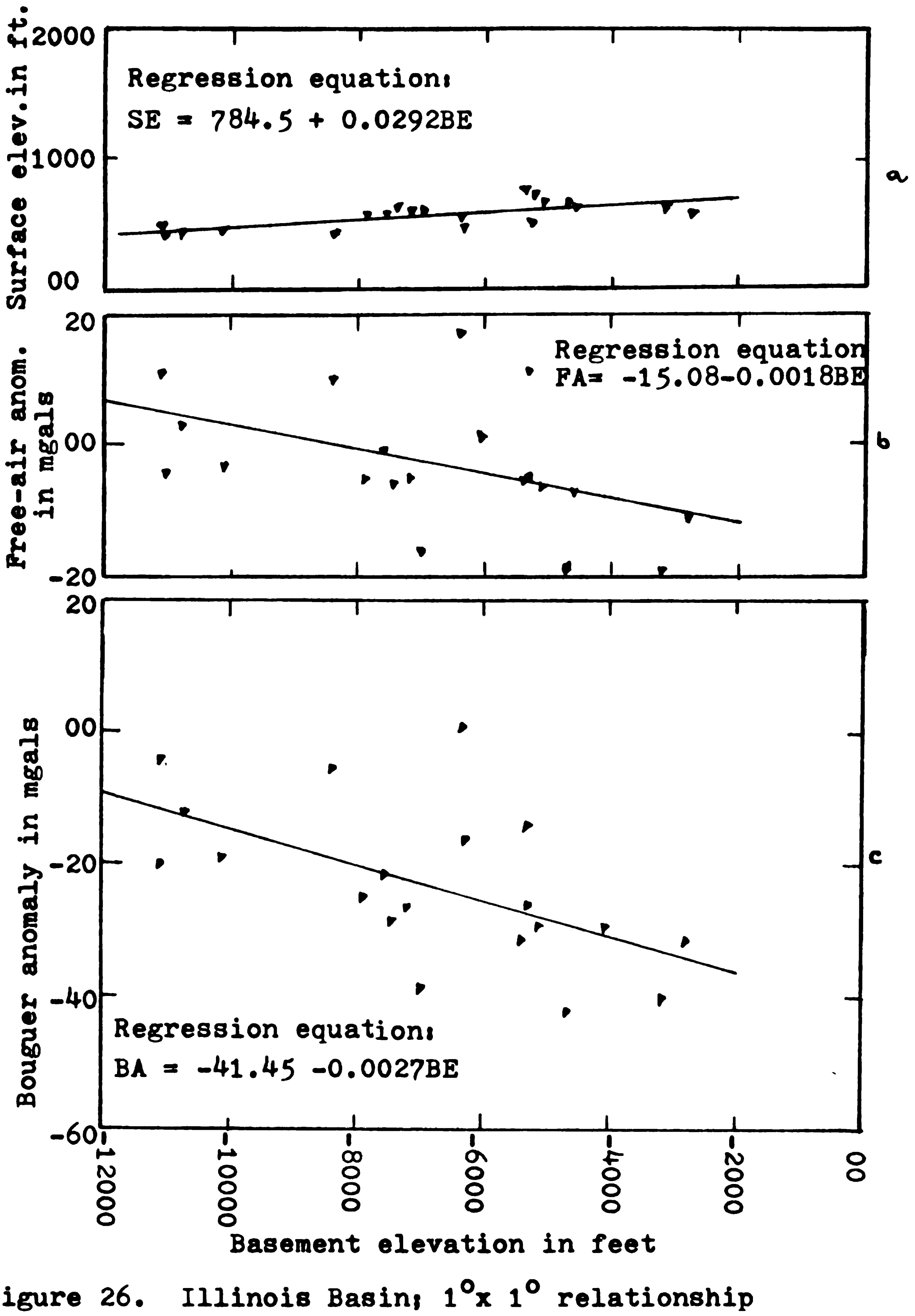


Figure 26. Illinois Basin; 1^{o}x 1^{o} relationship

The surface elevation-basement elevation relationship is direct (Figure 26a), similar to the one obtained for Midcontinent area as shown in Figure 9. This straight line relationship is given by the equation, SE = 784.5 + 0.0292BE with a correlation coefficient of 0.72. The relationship is definitely significant as indicated by over 99.9 percent confidence level. As a result of this relationship, the inverse Bouguer gravity anomaly-basement elevation relationship will be slightly increased by the surface elevation effect.

The Bouguer gravity anomaly-basement elevation relationship is shown in Figure 26c. The least square line representing the inverse relationship, that is the decrease in Bouguer gravity anomaly with increase in basement elevation, is given by the equation, BA = -41.45 - 0.0027BE and has 99 percent confidence level and a correlation coefficient of -0.57 .

The Free-air gravity anomaly-basement elevation relationship (Figure 26b) is similar to the Bouguer gravity anomaly basement elevation relationship, but with smaller slope. This relationship is represented by the equation, FA = -15.08 - 0.0018BE. Its correlation coefficient is -0.45 and has a confidence level of 95 percent.

Williston Basin: Surface elevation, Bouguer and Free-air gravity anomalies are plotted against basement elevation for 1^{o}x 1^{o} area of the Williston Basin in

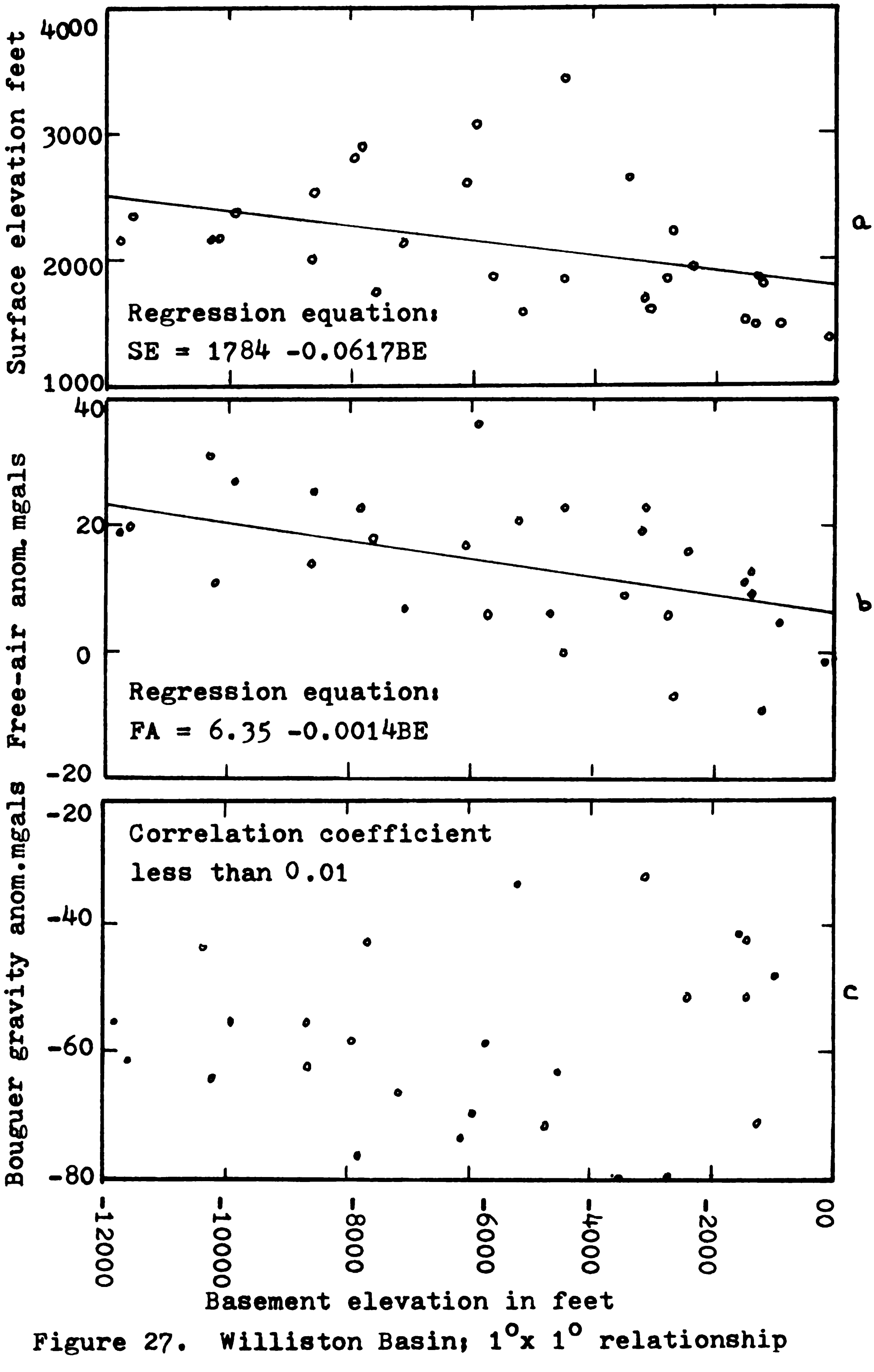


Figure 27. Williston Basin; 1°x 1° relationship

Figure 27.

The surface elevation-basement elevation relationship (Figure 27a) shows scattered points which are much more pronounced above 2500 feet surface elevation and basement elevations of -3000 feet to -9000 feet. The surface elevation shows an inverse relationship to the basement elevation and the scatter of points is reflected in its correlation coefficient of -0.44. This relationship is expressed by the equation, SE = 1784 - 0.0617BE and the relationship appears significant as reflected by the confidence level of 98 percent.

The Bouguer gravity anomaly-basement elevation relationship has no correlation (calculated correlation coefficient is less than o.2 and the confidence level is less than 10 percent). The points show a wide and irregular scattering. Hence no relationship is indicated in Figure 27c.

In contrast to the lack of correlation in the Bouguer gravity anomaly-basement elevation relationship, the Free-air gravity anomaly-basement elevation relationship show a linearity in trend even though the points are somewhat scattered (Figure 27b). The correlation is inverse, i.e., Free-air gravity anomaly decreases with increasing basement elevations. This relationship is likely to be significant as indicated by Over 98 percent confidence level. The least square line showing the

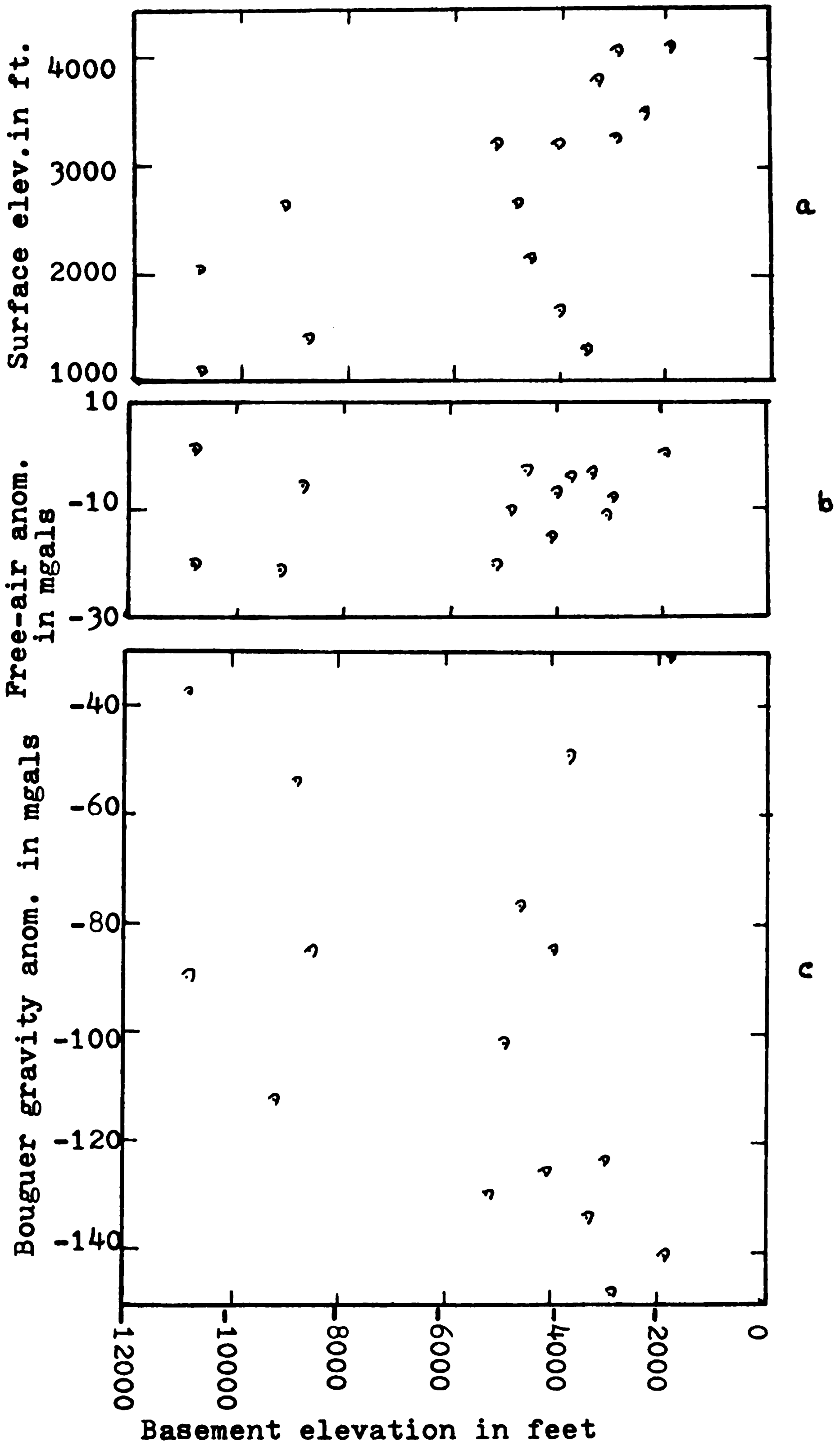
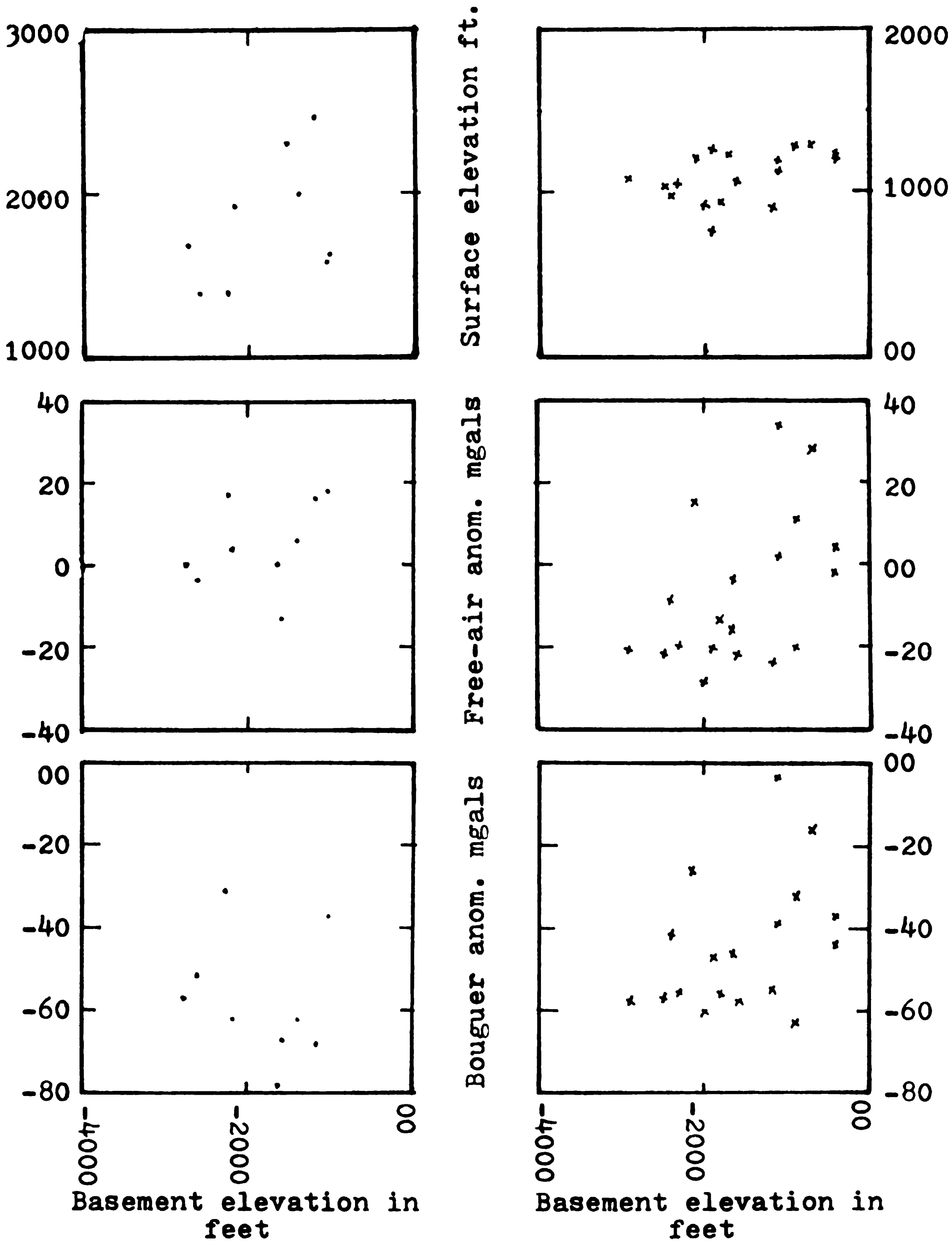


Figure 28. Anadarko Basin; $1^o \times 1^o$ relationship
(Points below -12000 feet neglected)

inverse relationship of Free-air gravity anomaly-basement elevation relationship is expressed by the equation, FA = 6.35 - 0.0014BE and has a correlation coefficient of -0.43. The Free-air gravity anomaly of the Williston Basin is generally positive suggesting an isostatically undercompensated region.

Anadarko Basin: Within the studied portion of the Anadarko Basin the surface elevation-basement elevation relationship (Figure 28a) shows such a wide scatter that no correlation is possible. The Bouguer gravityanomaly-basement elevation relationship also exhibits a wide scatter (Figure 28c). However, the values less than -80 mgals tend to fall in a group showing an inverse relationship of Bouguer gravity anomaly with basement elevation. This relationship seems significant with 99 percent confidence level and -0.84 correlation coefficient, and is given by the equation, BA = -147.82 - 0.0050BE. Widely scattered points make any relationship between Free-air gravity anomaly and basement elevation impossible.

Other Basins: No obvious correlation exists between basement elevation and surface elevation, Free-air gravity anomaly or Bouguer gravity anomaly within the Salina Basin (Figure 29A), Forest City Basin (Figure 29B), and Denver and Powder River Basins (Figure 30). The scatter of points is high and the range of basement elevation is limited. As a result it is impossible to establish a correlation with any reasonable certainity.



A. Salina Basin

B. Forest City Basin

Figure 29. Salina and Forest City Basins, 1° x 1° relationships.

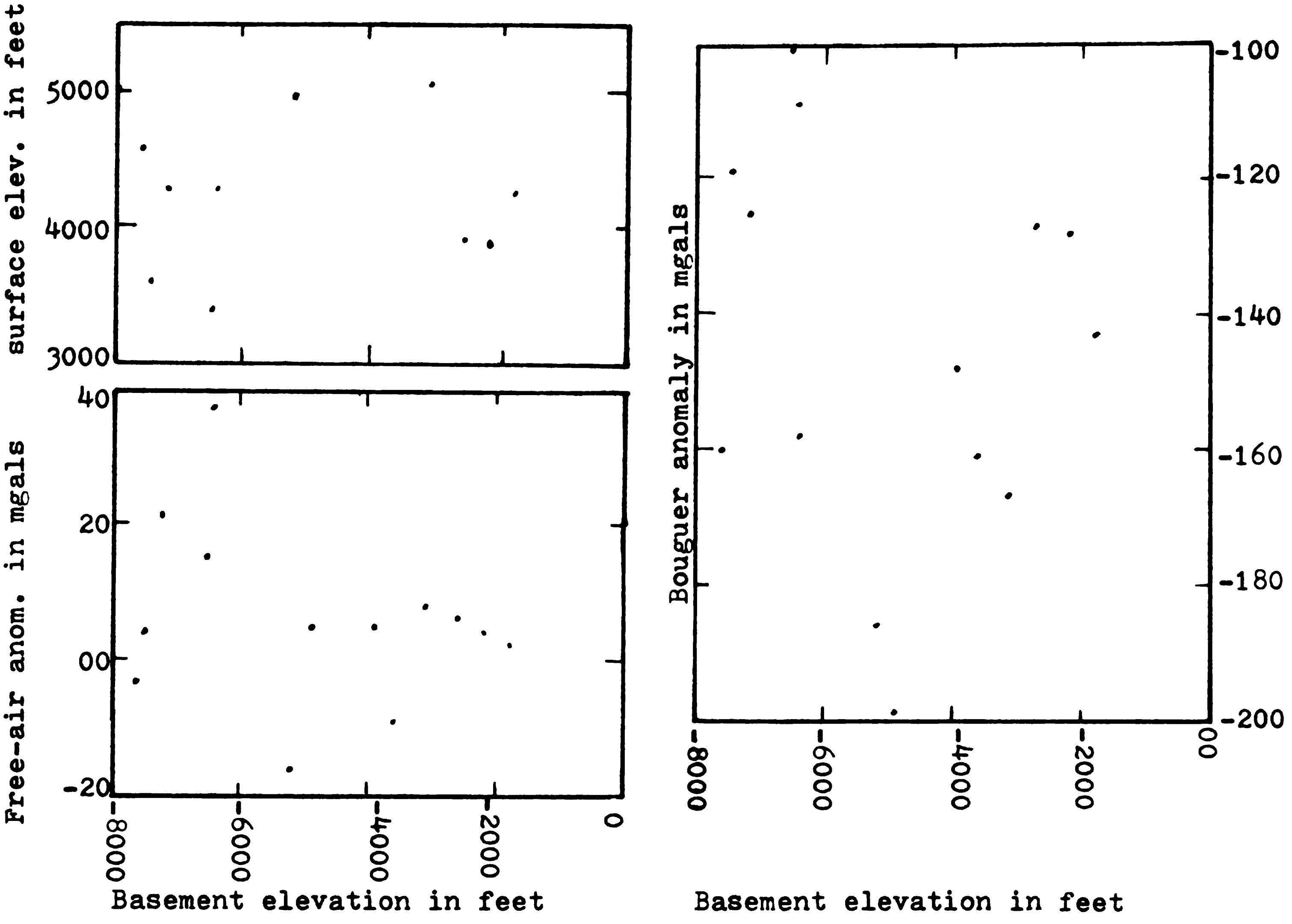


Figure 30. Powder River and Denver Basins; 1°x 1° relationship

However, there are indications of an inverse relationship between Bouguer gravity anomaly and basement elevation.

Geological Correction For Basin Sedimentary Rocks

Assuming that the sedimentary rocks of the basins are less dense than the enclosing basement rocks, the effect of the geological correction to the Bouguer gravity anomaly for the deficiencies of mass within the basins is to increase the Bouguer gravity anomaly with decreasing basement elevation. The geologically corrected Bouguer gravity anomaly based on an assumed density contrast of -0.15 gm/cc between the basement and the basin formations is plotted against basement elevations for Michigan Basin (Figure 31), Illinois Basin (Figure 32) and Williston Basin (Figure 33). The equation of the least square line of the Michigan Basin is given by $CBA = -37.00 - 0.0036BE$ where CBA is the geologically corrected Bouguer anomaly in milligals, with confidence level of 99.9 percent and -0.78 correlation coefficient. The increase in slope of the inverse correlation between Bouguer gravity anomaly and basement elevation is apparent on comparision of this equation with the equation of the least square line for the uncorrected Bouguer gravity anomaly, $BA = -37.05 - 0.0017BE$. The slope of the least square line for Illinois Basin is also increased by an additional 0.0019 in milligals per foot resulting in the equation $CBA = -41.35 - 0.0046BE$.

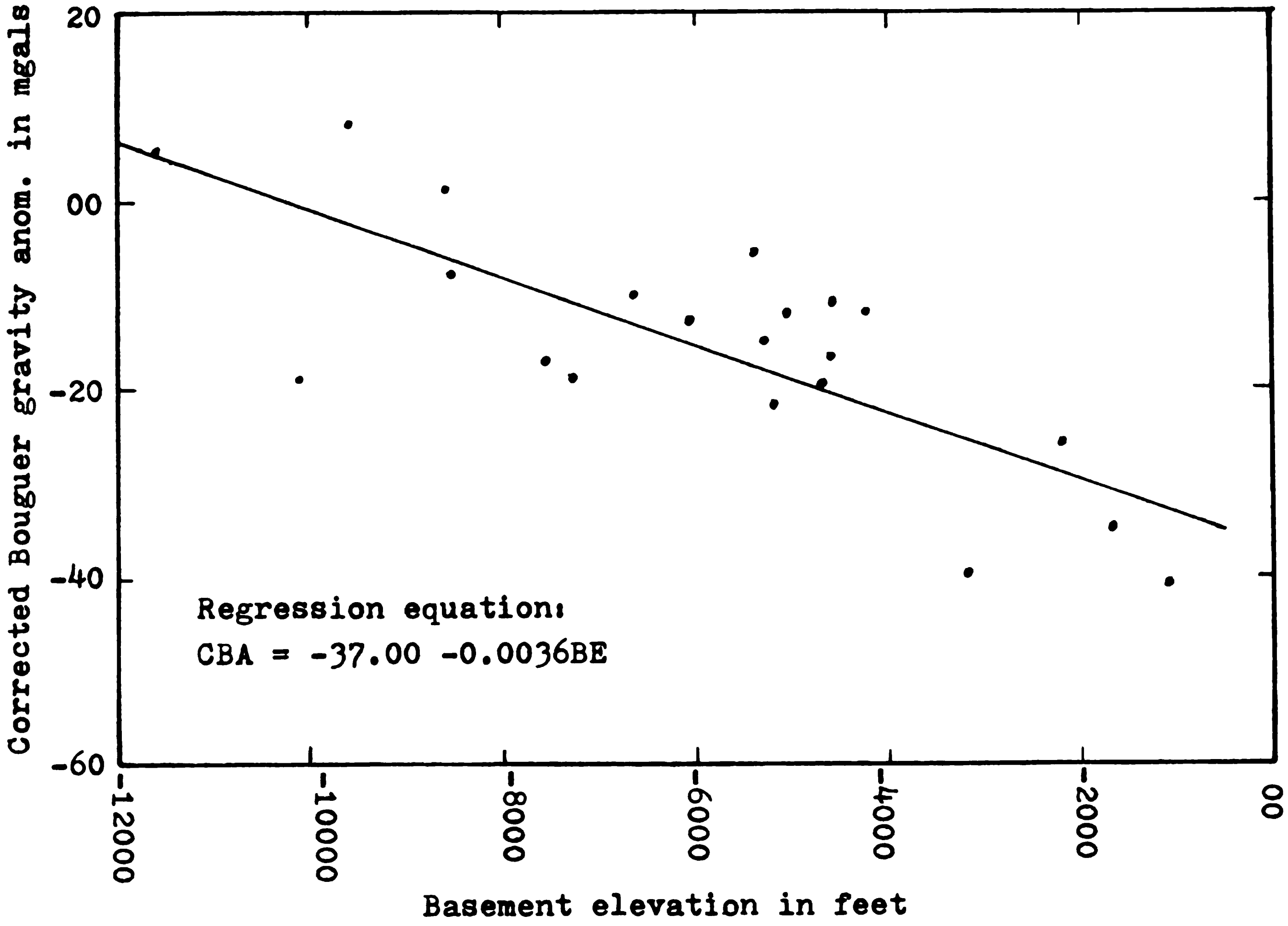


Figure 31. Corrected Bouguer anomaly-basement elevation relationship (Michigan Basin; 1° x 1°)

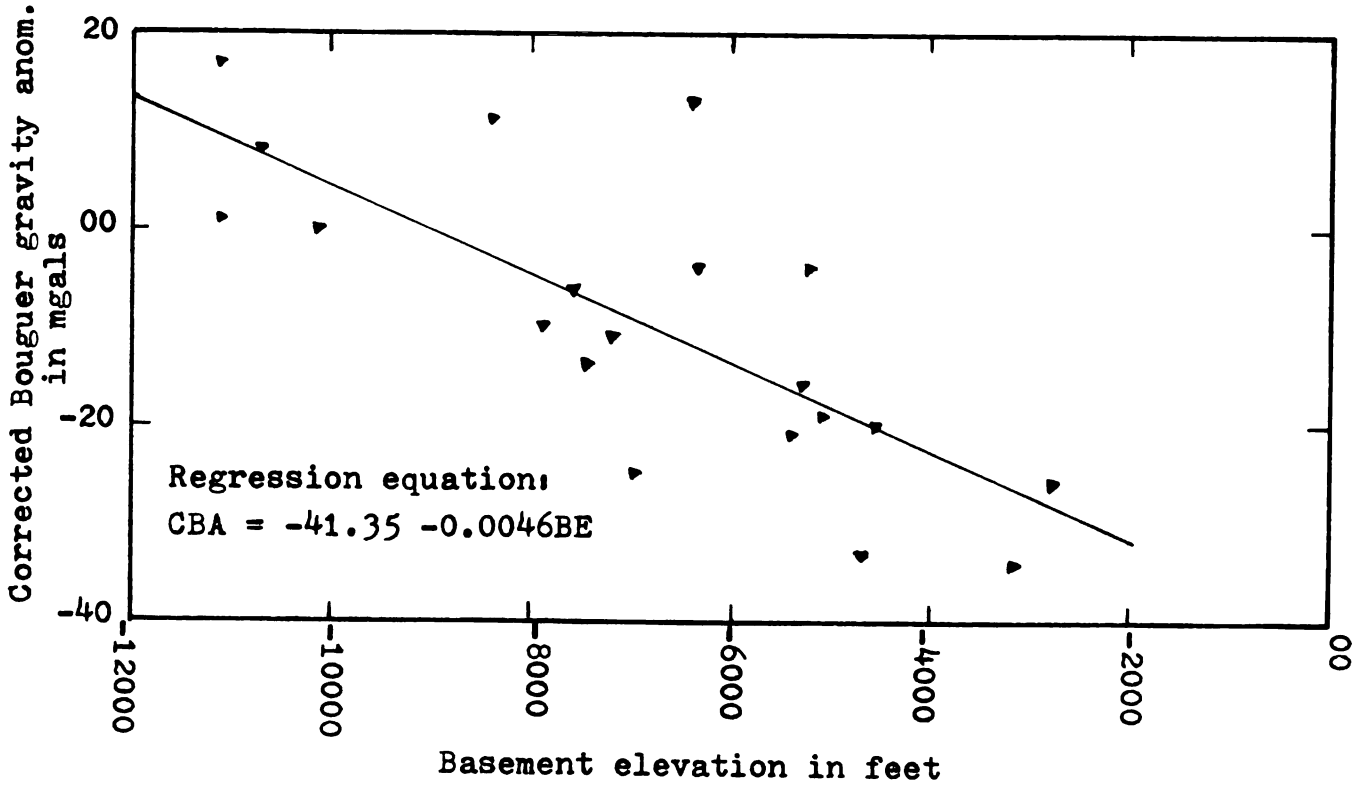


Figure 32. Corrected Bouguer anomaly-basement elevation relationship (Illinois Basin; 1° x 1°)

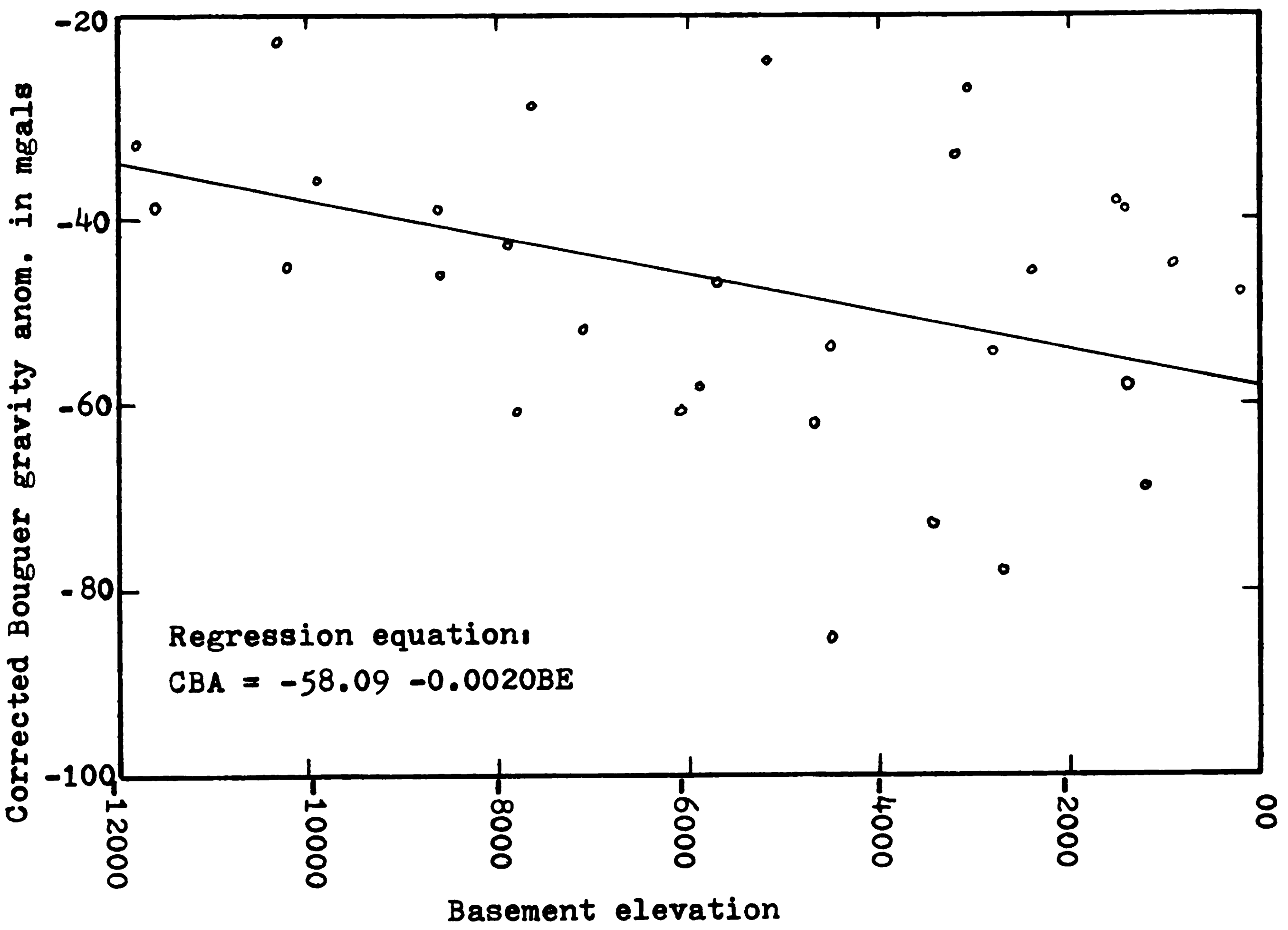


Figure 33. Corrected Bouguer anomaly-basement elevation relationship (Williston Basin; 1° x 1°)

In contrast to the Bouguer gravity anomaly basement elevation relationship of the Williston Basin which shows no correlation (Figure 27c), the corrected Bouguer gravity anomaly-basement elevation relationship indicates an inverse linear relationship (Figure 33). This relationship should be significant as it has a confidence leval of 98 percent and a correlation coefficient of -0.42. The least square line representing this relationship is given by equation CBA = -58.09 - 0.0020BE.

Application of the geological correction to the Bouguer gravity anomalies of other basins of the Midcontinent does not alter the previous conclusion that no observable correlation exists between Bouguer gravity anomaly and basement elevation.

Summary

1. There is no obvious relationship between Bouguer gravity anomaly and basement elevation for the Midcontinent area between the Appalachian Basin and the Rocky Mountains and for the portions of Midcontinent west of 96°W meridian. However, there is a definitely significant inverse relationship between Bouguer gravity anomaly and basement elevation, considering both 1^{o}x 1^{o} and 2^{o}x 2^{o} quadrangles in the area east of 96°W longitude west of the Appalachian Basin.

2. In the eastern portion of the Midcontinent there is a direct relationship between surface elevation

and basement elevation. As a result of this relationship and the general correlation between Bouguer gravity anomaly and surface elevation, the inverse relationship between Bouguer gravity anomaly and basement elevation can be explained atleast in part. A direct relationship between surface elevation and basement elevation is also possible in the western portion of the Midcontinent.

3. There is no obvious correlation between Free-air gravity anomaly and basement elevation for either $1^{o}x\ 1^{o}$ or $2^{o}x\ 2^{o}$ quadrangles in the Midcontinent except for a probable inverse relationship observed for $2^{o}x\ 2^{o}$ quadrangles in the eastern Midcontinent.

4. Considering only the sedimentary basins of the Midcontinent area there is a highly significant inverse relationship between Bouguer gravity anomaly and basement elevation in the eastern portion and a possible inverse correlation in the western portion. Only a possible inverse relationship exists between Free-air gravity anomaly and basement elevation for sedimentary basins within the Midcontinent. No correlation exists between surface elevation and basement elevation.

5. Within the Michigan Basin, there is a probably significant inverse relationship between Bouguer gravity anomaly and basement elevation and a highly significant inverse relationship between Free-air gravity anomaly and basement elevation considering $1^{o}x\ 1^{o}$ area. There is a definitely significant relationship between

surface and basement elevations.

6. The Illinois Basin has a highly significant inverse relationship between Bouguer gravity anomaly and basement elevation and a probably significant relationship between Free-air gravity anomaly and basement elevation considering $1^o x\ 1^o$ quadrangles. The surface elevation varies directly with basement elevation and the relationship is highly significant.

7. Within the Williston Basin, there is no obvious correlation between Bouguer gravity anomaly and basement elevation. However, the Bouguer gravity anomaly, geologically corrected for low density sedimentary rocks, shows a significant inverse relationship to the basement elevation. The Free-air gravity anomaly and surface elevation also exhibit an inverse relationship with the basement elevation.

8. No obvious correlation exists between the Bouguer gravity anomaly, Free-air gravity anomaly and surface elevation with basement elevation for the basins in the Midcontinent other than Michigan Basin, Illinois Basin and Williston Basin.

9.The slope of the line best representing the relationship between Bouguer gravity anomaly and basement elevation is increased by a factor of 0.0019 milligals per foot of basement elevation assumig a density contrast of 0.15 gm/cc between the sediments and the enclosing basement rocks.

TABLE 2. Regression equations, confidence levels and correlation coefficients.

Related parameters	Area	Regr. equation	Conf.level	Cor.coef.
Boug.anom.-Base.elev.	East.Midcont. 1°x 1°	BA = - 46.60-0.0034BE	Over 99.9	-0.62
	East.Midcont. 2°x 2°	BA = - 43.55-0.0025BE	Over 99.9	-0.66
	East. Basins 2°x 2°	BA = - 55.21-0.0041BE	Over 99.9	-0.78
	West. Basins 2°x 2°	BA = -145.46-0.0088BE	Over 90.0	-0.60
	Mich. Basin 1°x 1°	BA = - 37.05-0.0017BE	Over 95.0	-0.51
	Ill. Basin 1°x 1°	BA = - 41.45-0.0027BE	Over 99.0	-0.57
Surf. el. -Base.elev.	East.Midcont. 2°x2°	SE = 927 +0.0380BE	Over 98.0	0.47
	Mich. Basin 1°x 1°	SE = 281.5 -0.0626BE	Over 99.0	-0.71
	Ill. Basin 1°x 1°	SE = 784.5 +0.0292BE	Over 99.9	0.72
	Will. Basin 1°x 1°	SE = 1784 -0.0617BE	Over 98.0	-0.44
Boug.anom.-Base.elev. (calculated)	East.Midcont. 2°x 2°	BA = - 34.0 -0.0016BE		
Free-air-Base. elev.	East.Midcont. 2°x 2°	FA = - 11.82-0.0013BE	Over 95.0	-0.44
	Basins 2°x 2°	FA = - 6.17-0.0015BE	Over 90.0	-0.33
	Mich. Basin 1°x 1°	FA = - 24.28-0.0034BE	Over 99.9	-0.76
	Ill. Basin 1°x 1°	FA = - 15.08-0.0018BE	Over 95.0	-0.45
	Will. Basin 1°x 1°	FA = 6.35-0.0014BE	Over 98.0	-0.43
Res.Boug.-Base elev.	East.Midcont. 2°x 2°	RBA= - 11.25-0.0013BE	Over 95.0	-0.42
Corr.Boug.-Base.elev	Mich. Basin 1°x 1°	CBA= - 37.00-0.0036BE	Over 99.9	-0.78
	Ill. Basin 1°x 1°	CBA= - 41.35-0.0046BE	Over 99.9	-0.76
	Will. Basin 1°x 1°	CBA= - 58.09-0.0020BE	Over 98.0	-0.42

The regression equations, confidence levels and correlation coefficients for the established linear relationships between geological and geophysical parameters are summarized in Table 2.

Discussion of Results

Midcontinent Area

The relationship between Bouguer gravity anomalies and basement elevations in the Midcontinent (Figure 2) is not a simple inverse relationship as has been previously suggested, but is a complex one and varies within the study area. Within the western Midcontinent (Figure 4) area between 96°W longitude and the Rocky Mountain front, there is no obvious correlation between these parameters. This is not unexpected because of the wide range of elevation within the area which will distort the Bouguer gravity anomalies and possible effect of diastrophism associated with the Cordilleran mountain systems. Even in the stable eastern Midcontinent (Figure 3) east of 96°W longitude and west of the Appalachian Basin, the relationship between Bouguer gravity anomalies and basement elevations is not simple. In areas where basement surface is above sea level there is no correlation between the parameters and the areas adjacent to the Appalachian Basin. However, in the eastern area, where basement elevations are less than sea level and excluding areas involved in Paleozoic activities, there is an inverse correlation between Bouguer anomalies and basement elevations (Figures 3 and 5). This relationship can be at least partially explained by the observed direct relationship between surface and basement elevations (Figures 8 and 9) using the surface elevation-Bouguer gravity anomaly relationship (Figure 6 and 7). The direct relationship between surface and basement elevations observed in the eastern Midcontinent, where basement elevations are less than sea level, reflects the regional decrease in elevation from cratonic areas where the basement is at higher elevations. This may be due to continued relative vertical movements of Paleozoic basins and arches to the present day and more resistance to erosion of Precambrian and early Paleozoic sediments of the arches.

Assuming that the observed inverse relationship between Bouguer gravity anomalies and basement elevations is completely due to surface elevation effect, the regional Free-air anomaly should show no relationship to basement elevation. However, this is not true in the case of $2^{o}x\ 2^{o}$ quadrangle averages of Free-air gravity anomaly in the eastern Midcontinent where basement elevations are below sea level. These Free-air gravity anomalies show an inverse correlation with basement elevations (Figure 14) and the residual Bouguer gravity anomalies have a similar relationship. Therefore, the inverse correlation between Bouguer gravity anomalies and basement elevations observed in the eastern Midcontinent, although partially due to surface elevation, is also a result of mass differences within the geological section. The regional Free-air gravity anomalies (Figure 14) indicate that areas of lowest basement elevation are undercompensated in relation to the areas where the basement is near sea level, i.e., areas of maximum basin development are areas of greater mass. In contrast to this it appears (Figure 14) that the cratonic areas, where basement elevations are above sea level, are also undercompensated. Thus both the highest and lowest basement elevations of the eastern Midcontinent are associated with excess mass areas.

Lyons (1959), Hinze (1963) and McGinnis (1966) have individually suggested that the inverse relationship of Bouguer gravity anomalies to basement elevations within various basins of the eastern Midcontinent may be the result of elastic deformation of the basement in response to the additional mass of the basic rocks extruded onto or intruded into the basement comlex. This hypothesis is not valid when considering broad areas such as eastern Midcontinent because average Bouguer gravity anomalies equivalent to those obtained over the deepest basins are observed in cratonic areas (Figures 3 and 5). Furthermore, as pointed out, above, both the deepest basin areas and cratonic areas are undercompensated indicating a mass excess.

Basins

Better relationships of gravity anomalies with basement elevations are exhibited when considering the basins only, although no single correlation exists between Bouguer gravity anomaly and basement elevation. The basins in the eastern and western portions of the Midcontinent show similar inverse but independent relationships (Figure 21). Lack of any single correlation between Bouguer gravity anomaly and basement elevation may be due to the complicating effect of the surface elevation on the Bouguer gravity anomaly. However, a possible inverse relationship occurs between Free-air gravity anomaly and basement elevation of sedimentary basins (Figure 24)

The relationships between gravity anomalies and basement elevations are clarified by considering individual basins. The Free-air gravity anomalies of the Michigan, Illinois and Williston Basins (Figures 25, 26 and 27) show a distinct inverse correlation with basement elevations. Similarly , an inverse correlation exists between Bouguer gravity anomalies and basement elevations of the Michigan and Illinois Basins (Figure 25 and 26) which are increased or decreased respectively by the effect of surface elevation . Parts of Anadarko Basin also exhibits the inverse relationship of Bouguer gravity anomaly with basement elevation. The Bouguer gravity anomalies of the Williston Basin only exhibit an inverse correlation with basement elevations after correcting for the gravitational effect of the sediments (Figure 33). The other basins of the Midcontinent do not exhibit definable relationships between gravity anomalies and basement elevations. This may be a result of a different origin of the basins or subsequent deformation and the limited basement elevation range within some basins which makes it impossible to define the relationship.

The Free-air gravity anomalies of the Michigan, Illinois and Williston Basins indicate a relative undercompensation over the center and deepest parts of the basins and an overcompensation along margins. Considering the entire basin, the Michigan and Illinois Basins are essentially in isostatic equilibrium and the Williston Basin is undercompensated perhaps reflecting the higher surface elevations and its proximity to the Cordilleran mountain systems.

Recognition of this inverse relationship between Bouguer gravity anomalies and basement elevations in the Michigan and Illinois Basins have led Hinze (1963) and McGinnis (1966) respectively to hypothesize a cause and effect relationship between the source of gravity anomalies and the development of basins. They have suggested, as Lyons (1959) did for basins along the Midcontinent gravity high, that the basins originated

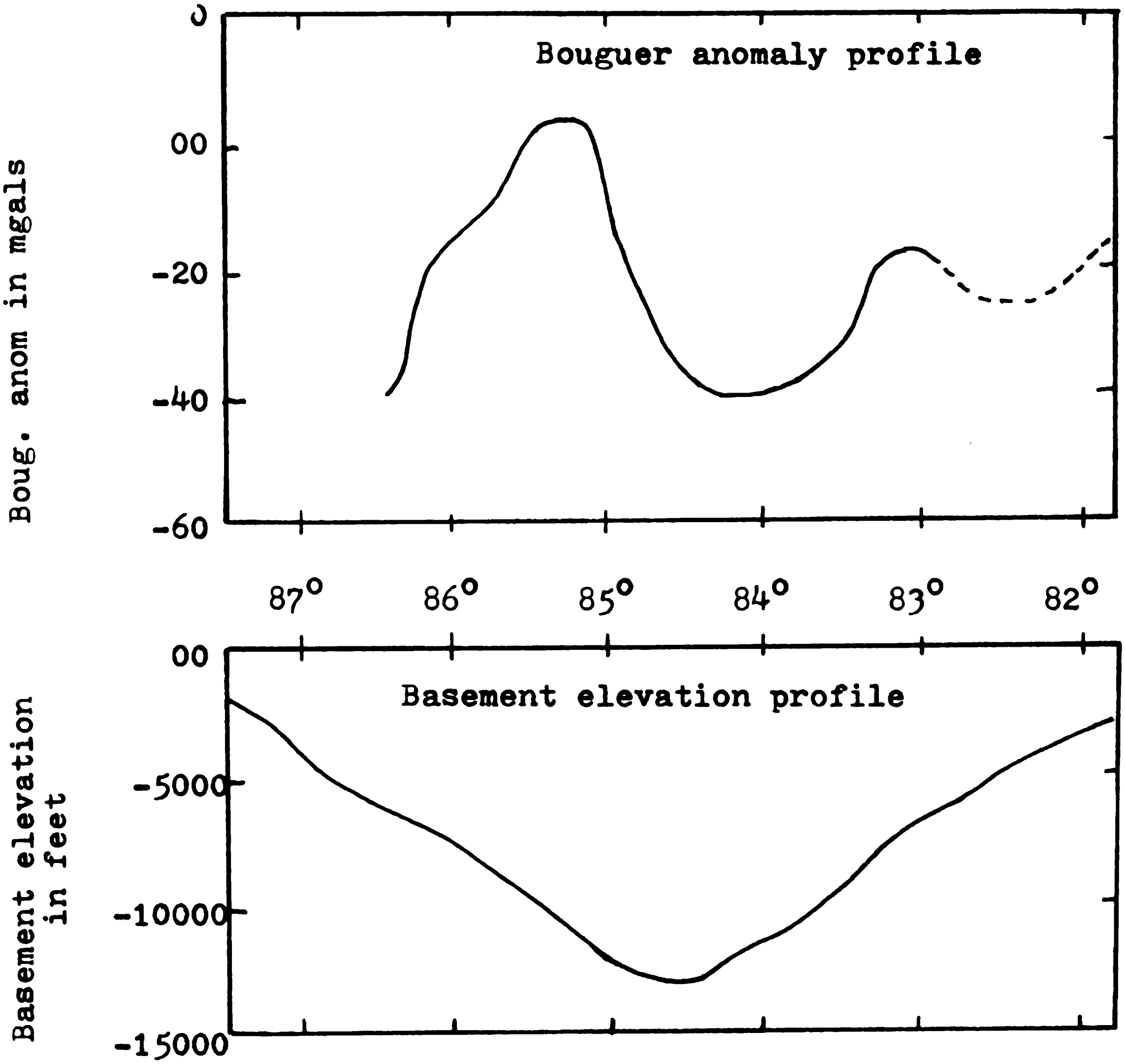


Figure 34. Bouguer anomaly and basement profiles for Michigan Basin, along 44th parallel

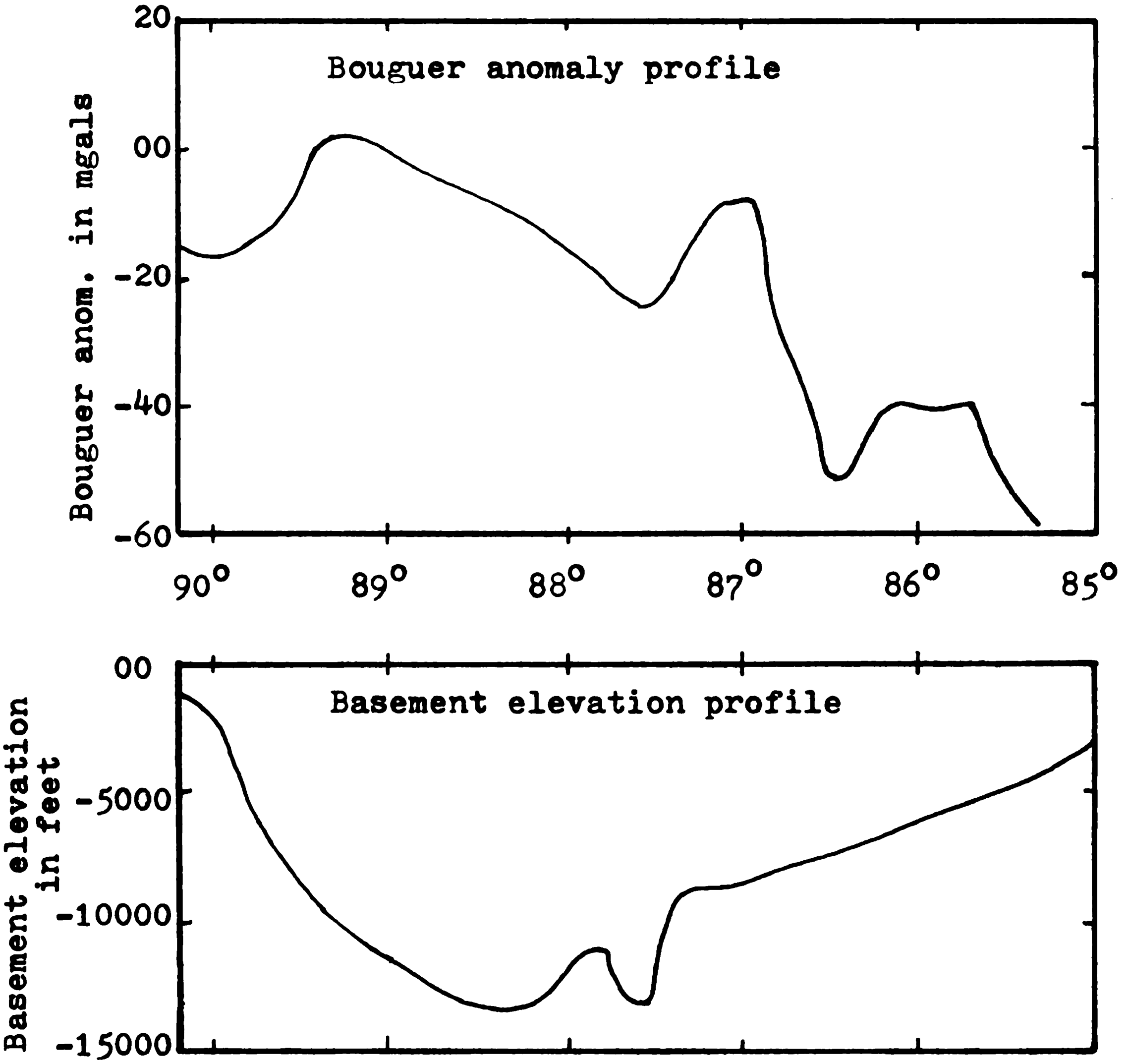


Figure 35. Bouguer anomaly and basement profile for Illinois Basin, along 38th parallel

from elastic deforamation in response to the added mass of basic rocks emplaced in the basement complex in late Precambrian time. McGinnis has expanded on this idea, relating the basins to elastic deformation due to basic intrusives and extrusives emplaced along a Keweenawan rift zone. This theory suggests that similar relationship between Bouguer gravity anomalies and basement elevations should be observed over all the basins of the Midcontinent area. Furthermore, if basins originated by regional elastic deformation associated with crustal loading, there should be a direct correspondence between gravity anomalies and basement elevations. However, gravity and basement profiles of the Michigan Basin (Figure 34), Illinois Basin (Figure 35), Williston Basin (Figure 36) and Forest City Basin (Figure 37) do not confirm to this conclusion.

Recently Hinze, Davidson and Roy (1971) have suggested an alternate theory for the origin of some Midcontinent basins associated with Paleo-rift zones. They point out that the elastic deformation theory of the origin of basins previously suggested encounters serious difficulties in timing. The basins filled with shallow water sediments devloped over long period of time, into late Paleozoic time, while the masses associated with rift zones were added to the crust near the end of Precambrian time. The isostatic relaxation time as determined by McConnell (1968) is too short for the

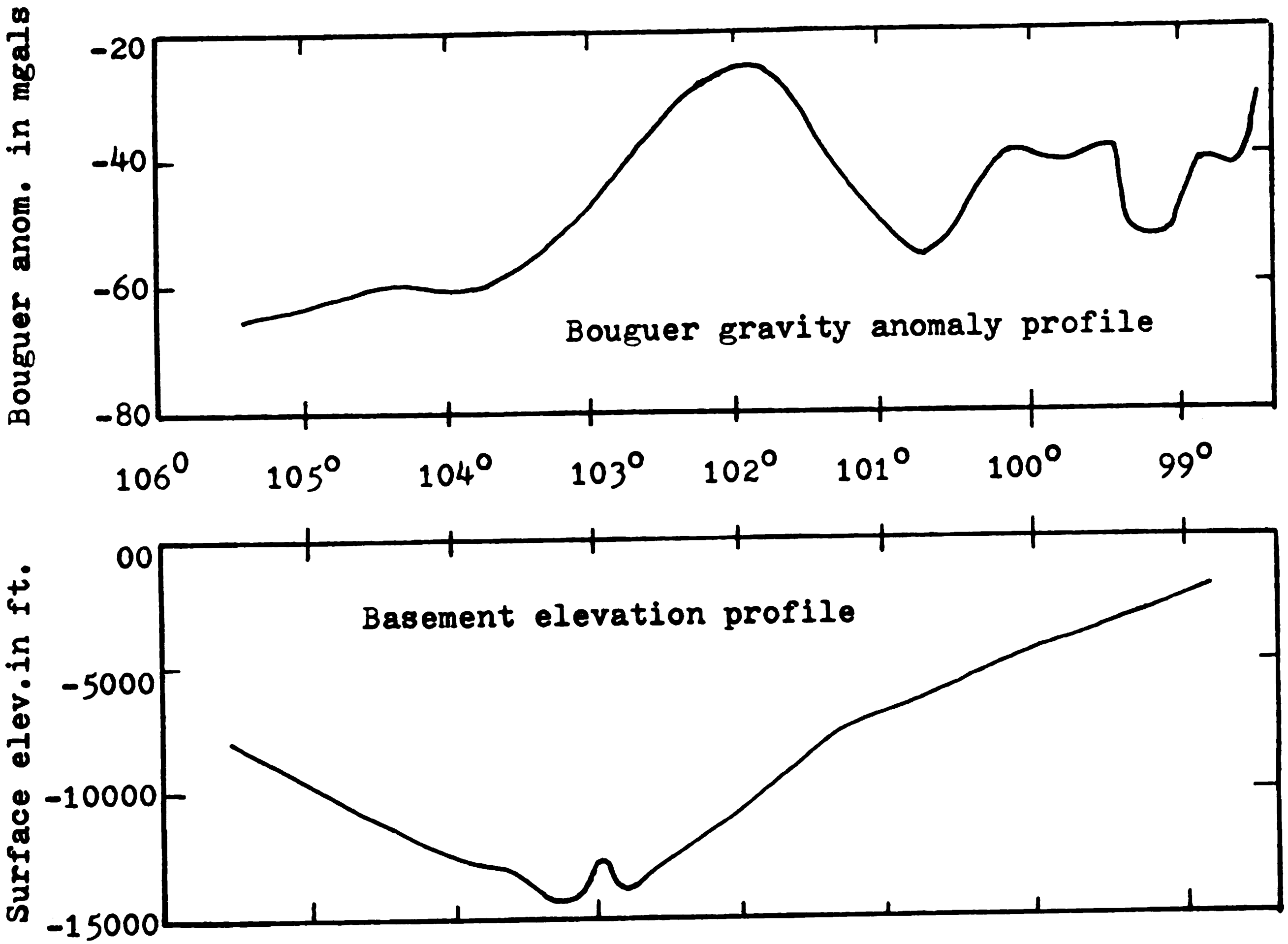


Figure 36. Bouguer anomaly and Basement profiles for Williston Basin, along 48th parallel.

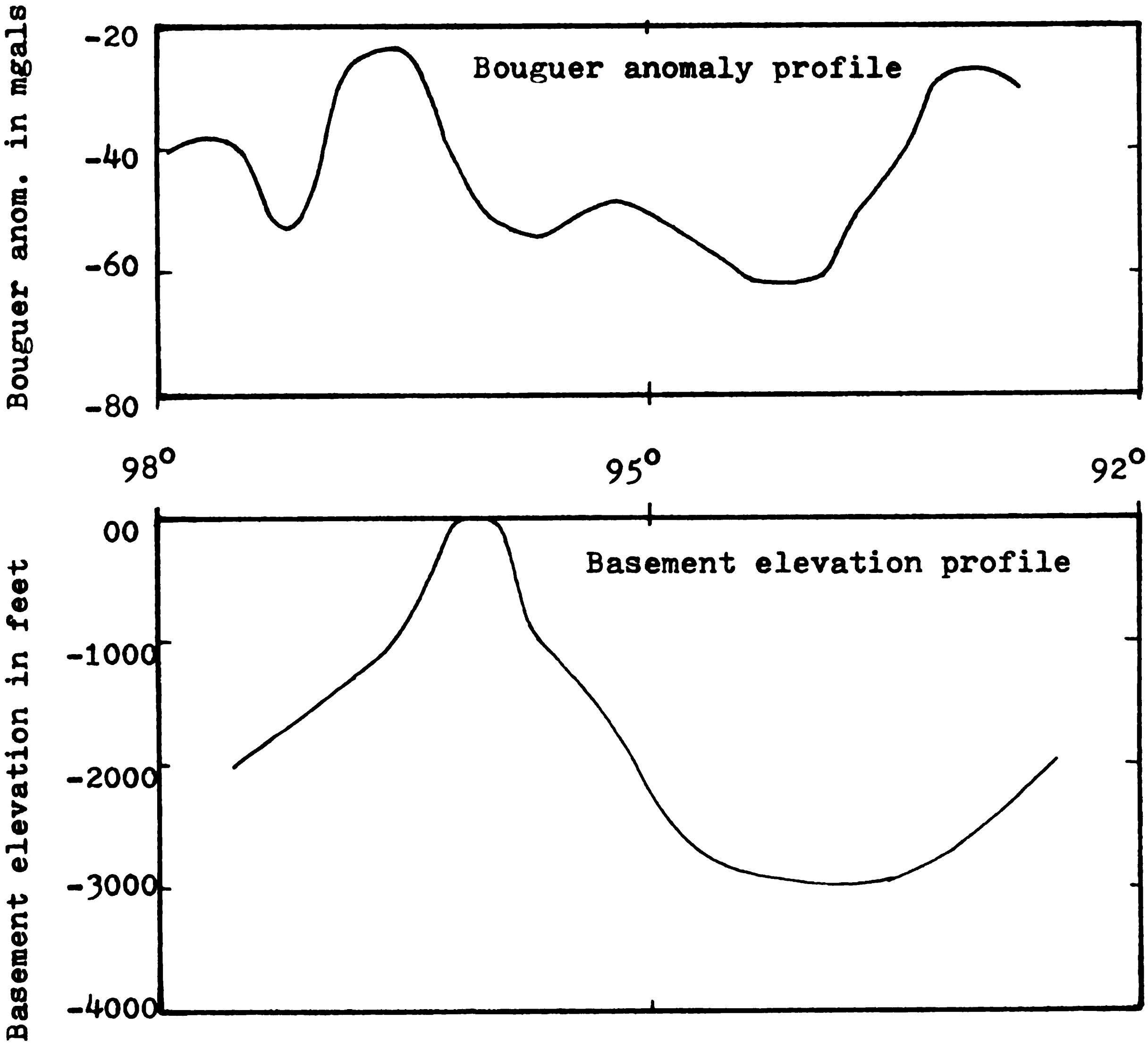


Figure 37. Bouguer anomaly and basement profiles for Forest City Basin along 40th parallel

elastic deformation to continue for hundreds of millions of years as observed. Therefore, they suggest that the possible final stage of the continental rifting process involves compression of the crust and slow development of a basin over a paleo-rift zone. According to this theory there is no cause and effect relationship between gravity anomalies and basement elevations, but rather they are both a result of complex continental rifting process where late basin development is centered over a paleo-rift zone which due to basic intrusives and extrusives shows up as a gravity high. As a result of this theory there is no necessity for a constant inverse correlation between gravity anomalies and basement elevations but only a general correlation of gravity anomalies with basement elevations where basins developed as a last stage of the rifting process. Thus the lack of correlation along the Midcontinent gravity high where it traverses the Forest City Basin can be explained by variations in the final stage of the rifting process and variations between other relationships detailed in this study can be explained similarily. Furthermore, not all of the basins of the Midcontinent developed as final stages of a continental rifting process, other origins are quite likely for many basins. Therefore other relationships between gravity anomalies and basement elevations as observed in this study are expected. However, the similarity between the relationships of the Michigan and Illinois and perhaps the Williston Basins suggest a similar origin for the basins, although according to this theory there is no cause and effect relationship between gravity anomalies and basement elevations.

CONCLUSION

In conclusion, the results of this study substantiate the previous observation that in general basement elevations in the eastern Midcontinent are inversely related to gravity anomalies, both Bouguer and Free-air, and a similar relationship is indicated for the Williston Basin of the western Midcontinent. The Anadarko Basin in part, exhibits this relationship for Bouguer gravity anomaly only. The inverse relationship are particularly well illustrated in the Michigan, Illinois and Williston Basins. Other basins of the Midcontinent do not have definable relationships. This fact together with the equivalence of average gravity anomalies in the center of the basins and in some cratonic areas suggest that the basins were not developed by elastic deformation in response to the added mass of basic rocks, in the basement complex. Thus the relationship is not related by cause and effect, but rather it is suggested that both the increased mass of the basement complex in the center of the basins which produce the gravity anomalies and development of the basins result from stages of the same complex process, perhaps late Precambrian crustal rifting.

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APPENDIX

APPENDIX

Data

Quadrangle		Base. el.	Free-air anom.	Boug. anom.	Surf. el.
Lat.	Long.	in feet	in mgals	in mgals	in feet
49	105	- 10208	+ 011	- 064	2201
49	104	- 11830	+ 019	- 055	2169
49	103	- 10313	+ 031	- 043	2172
49	101	- 05178	+ 021	- 033	1578
49	100	- 03083	+ 023	- 032	1617
49	99	- 01509	+ 011	- 041	1539
49	98	- 00052	- 001	- 033	0941
49	97	+ 00988	+ 003	- 031	0988
49	96	+ 01161	+ 016	- 024	1161
49	95	+ 01158	+ 013	- 027	1158
49	94	+ 01175	+ 002	- 038	1175
49	93	+ 01276	- 008	- 052	1276
49	92	+ 01414	+ 009	- 093	1414
49	90	+ 01214	- 015	- 056	1214
49	89	+ 00643	- 024	- 046	0643
49	88	+ 00393	- 004	- 017	0393
49	87	+ 00545	- 000	- 019	0545
48	105	- 09877	+ 027	- 055	2405
48	104	- 11603	+ 020	- 061	2379
48	103	- 12409		- 037	2250
48	102	- 08634	+ 014	- 055	2014

The latitude and longitude values are given for the north-western corner of the 1°x 1° quadrangle.

Quadrangle Lat.	Long.	Base el. in feet	Free-air anom. in mgals	Boug. anom. in mgals	Surf. el. in feet
48	101	- 05688	+ 006	- 058	1880
48	100	- 03177	+ 019	- 039	1699
48	99	- 01367	+ 009	- 042	1486
48	98	+ 00258	- 001	- 039	1125
48	97	+ 00978	+ 003	- 030	0978
48	96	+ 01381	+ 006	- 041	1381
48	95	+ 01355	+ 008	- 038	1355
48	94	+ 01348	- 001	- 047	1348
48	93	+ 01411	- 007	- 055	1411
48	92	+ 01362	+ 043	- 003	1362
48	91	+ 00751	+ 030	+ 004	0751
48	90	+ 00318	- 003	- 014	0318
48	89	+ 00400	+ 004	- 010	0400
48	87	+ 00194	- 008	- 015	0194
48	86	+ 00427	- 021	- 036	0427
47	105	- 07794	+ 023	- 076	2890
47	104	- 07897	+ 038	- 058	2825
47	103	- 08591	+ 025	- 062	2549
47	102	- 07123	+ 007	- 066	2146
47	101	- 04528	+ 000	- 063	1854
47	100	- 02383	+ 016	- 051	1965
47	99	- 00905	+ 005	- 047	1512
47	98	+ 00570	- 004	- 043	1148
47	97	+ 01056	- 004	- 040	1056
47	96	+ 01407	+ 012	- 036	1407
47	95	+ 01309	+ 009	- 036	1309
47	94	+ 01266	+ 012	- 031	1266
47	93	+ 01161	+ 033	- 007	1161
47	92	+ 01007	+ 030	- 004	1007
47	91	+ 01050	000	- 036	1050
47	90	+ 01237	+ 029	-013	1237
47	89	+ 01345	+ 013	- 033	1345
47	87	+ 00328	000	- 020	0594

Quadrangle Lat.	 Long.	Base. el. in feet	Free-air anom. in mgals	Boug. anom. in mgals	Surf. el. in feet
47	86	+ 00087	- 003	- 025	0656
47	85	+ 00432	- 003	- 029	0751
46	106	- 06525	+ 015	- 101	3396
46	105	- 04494	+ 023	- 094	3419
46	104	- 05934	+ 036	- 069	3064
46	103	- 06072	+ 017	- 073	2628
46	102	- 04723	+ 006	- 071	2247
46	101	- 02839	+ 006	- 059	1869
46	100	- 01364	+ 013	- 051	1873
46	99	- 00167	- 001	- 048	1381
46	98	+ 01640	+ 009	- 047	1640
46	97	+ 01142	+ 001	- 038	1142
46	96	+ 01207	+ 015	- 026	1207
46	95	+ 01165	+ 016	- 024	1165
46	94	+ 01004	+ 002	- 032	1004
46	93	+ 01040	+ 025	- 010	1040
46	92	+ 01197	- 001	- 042	1197
46	91	+ 01447	+ 021	- 028	1447
46	90	+ 01549	+ 007	- 046	1549
46	89	+ 01306	- 007	- 052	1306
46	88	+ 00353	- 026	- 051	0735
46	87	- 02197	- 014	- 030	0456
46	86	- 04622	- 002	- 020	0535
46	85	- 04688	- 003	- 029	0751
46	84	- 03169	- 028	- 046	0531
45	106	- 07125	+ 021	- 125	4272
45	105	+ 00550	+ 042	- 108	4386
45	104	+ 00403	+ 034	- -93	3714
45	103	- 03456	+ 009	- 081	2648
45	102	- 02692	- 007	- 083	2228
45	101	- 01195	- 009	- 071	1831
45	100	- 00252	+ 005	- 055	1768
45	99	+ 00163	+ 002	- 046	1411

Quadrangle Lat.	Long.	Base. el. in feet	Free-air anom. in mgals	Boug. anom. in mgals	Surf. el. in feet
45	98	+ 00559	+ 011	- 045	1654
45	97	+ 01086	+ 015	- 040	1617
45	96	+ 01178	+ 001	- 039	1178
45	95	+ 01040	+ 001	- 034	1040
45	94	+ 00700	+ 027	- 007	1010
45	93	+ 00644	- 012	- 047	1040
45	92	+ 00958	+ 005	- 028	0958
45	91	+ 01102	- 020	- 057	1089
45	90	+ 00814	- 041	- 079	1102
45	89	+ 00713	- 032	- 060	0814
45	88	- 01097	- 024	- 043	0545
45	87	- 05200	- 020	- 032	0361
45	86	- 08608	+ 019	- 015	1003
45	85	- 10133	+ 001	- 038	1138
45	84	- 07541	- 007	- 031	0692
45	83	- 04236	- 005	- 020	0427
44	105	- 06417	+ 037	- 109	4288
44	104	+ 02006	+ 046	- 093	4088
44	103	- 00969	+ 013	- 089	2995
44	102	- 01703	- 001	- 094	2713
44	101	- 00827	- 031	- 109	2280
44	100	- 00053	- 031	- 095	1873
44	99	+ 00579	- 021	- 074	1555
44	98	+ 01041	- 003	- 052	1430
44	97	+ 01309	+ 002	- 048	1470
44	96	+ 01307	+ 006	- 045	1503
44	95	+ 00656	+ 004	- 038	1217
44	94	- 00380	+ 004	- 037	1211
44	93	- 00428	- 002	- 044	1227
44	92	- 00256	+ 015	- 020	1020
44	91	+ 00434	- 025	- 059	1004
44	90	+ 00854	- 028	- 061	0978
44	89	+ 00398	- 013	- 044	0919

Quadrangle Lat.	Long.	Base. el. in feet	Free-air anom. in mgals	Boug. anom. in mgals	Surf. el. in feet
44	88	- 01697	- 021	- 038	0486
44	87	- 06064	- 007	- 025	0535
44	86	- 09628	+ 021	- 010	0922
44	85	- 11594	+ 008	- 017	0745
44	84	- 08536	- 001	- 024	0686
44	83	- 05061	- 001	- 022	0604
43	105	+ 00877	+ 028	- 136	4806
43	104	- 01806	+ 022	- 143	4249
43	104	- 01806	+ 002	- 143	4249
43	103	- 00217	+ 023	- 108	3832
43	102	- 00709	+ 026	- 091	3419
43	101	- 00830	+ 018	- 079	2831
43	100	- 00411	+ 015	- 065	2349
43	99	- 00291	+ 002	- 061	1860
43	98	- 00192	+ 012	- 042	1572
43	97	- 00134	+ 022	- 022	1286
43	96	- 00611	- 008	- 054	1362
43	95	- 01078	+ 002	- 039	1191
43	94	- 01131	+ 034	- 004	1125
43	93	- 01103	- 021	- 055	0991
43	92	- 01360	+ 008	- 025	0974
43	91	- 01399	- 005	- 036	0896
43	90	- 00958	- 006	- 036	0883
43	89	- 01958	- 006	- 035	0860
43	88	- 03198	- 018	- 034	0472
43	87	- 05406	+ 001	- 016	0495
43	86	- 06663	+ 005	- 023	0823
43	85	- 07272	- 002	- 033	0915
43	84	- 05319	+ 003	- 025	0820
43	83	- 03583	- 007	- 028	0610
42	105	- 04013	- 002	- 184	5348
42	104	- 03572	- 009	- 161	4452
42	103	- 02173	+ 004	- 128	3875

Quadrangle		Base. el.	Free-air anom.	Boug. anom.	Surf. el.
Lat.	Long.	in feet	in mgals	in mgals	in feet
42	102	- 01228	+ 014	- 104	3451
42	101	- 00922	+ 012	- 089	2963
42	100	- 01178	+ 016	- 068	2467
42	99	- 01406	+ 006	- 062	2005
42	98	- 01027	+ 019	- 037	1640
42	97	- 00881	+ 011	- 032	1273
42	96	- 01667	- 004	- 046	1230
42	95	- 02130	+ 015	- 026	1214
42	94	- 01805	- 024	- 056	0935
42	93	- 01653	- 016	- 045	0843
42	92	- 02070	- 015	- 040	0735
42	91	- 02773	- 008	- 032	0699
42	90	- 03356	- 006	-030	0712
42	89	- 03547	+ 001	- 022	0682
42	88	- 04080	- 004	- 026	0640
42	87	- 03548	- 010	- 035	0732
42	86	- 03250	+ 009	- 021	0883
42	85	- 03617	- 008	- 036	0833
42	84	- 02556	- 028	- 051	0666
42	83	- 03244	- 018	- 041	0669
42	82	- 05270	- 002	- 030	0833
41	105	- 05234	- 016	- 186	4990
41	104	- 03872	+ 005	- 148	4475
41	103	- 02569	+ 006	- 127	3911
41	102	- 01798	- 004	- 114	2338
41	101	- 01094	- 001	- 093	2710
41	100	- 01655	000	- 078	2300
41	99	- 02173	+ 004	- 062	1932
41	98	- 01589	- 013	- 067	1585
41	97	- 00694	+ 028	- 016	1293
41	96	- 02463	- 022	- 057	1033
41	95	- 02891	- 021	- 058	1083
41	94	- 02420	- 009	- 042	0974

Quadrangle		Base. el.	Free-air anom.	Boug. anom.	Surf. el.
Lat.	Long.	in feet	in mgals	in mgals	in feet
41	93	- 02013	- 016	- 045	0863
41	92	- 02313	- 020	- 042	0646
41	91	- 03209	- 019	- 040	0630
41	90	- 04577	- 007	- 029	0633
41	89	- 05255	+ 011	- 014	0728
41	88	- 05123	- 006	- 029	0686
41	87	- 03771	- 020	- 045	0774
41	86	- 02814	- 017	- 047	0873
41	85	- 02425	+ 003	- 028	0919
41	84	- 02258	- 014	- 047	0981
41	83	- 04127	000	- 037	1079
41	82	- 07666	+ 006	- 030	1047
40	105	- 04867	+ 005	- 199	5968
40	104	- 03138	+ 008	- 167	5118
40	103	- 02139	- 005	- 149	4219
40	102	- 02177	- 009	- 126	3419
40	101	- 02050	- 007	- 100	2736
40	100	- 01859	- 001	- 074	2126
40	99	- 02758	000	- 057	1683
40	98	- 02266	+ 017	- 031	1417
40	97	- 00900	- 020	- 063	1253
40	96	- 02278	- 020	- 056	1050
40	95	- 02013	- 029	- 060	0922
40	94	- 01880	- 021	- 047	0768
40	93	- 01581	- 009	- 036	0781
40	92	- 01377	- 013	- 036	0676
40	91	- 02792	- 011	- 031	0587
40	90	- 05300	- 005	- 026	0620
40	89	- 07453	- 006	- 028	0640
40	88	- 07173	- 005	- 026	0604
40	87	- 05386	- 005	- 031	0774
40	86	- 03570	- 020	- 051	0899
40	85	- 02722	- 009	- 039	0886

Quadrangle		Base. el.	Free-air anom.	Boug. anom.	Surf. el.
Lat.	Long.	in feet	in mgals	in mgals	in feet
40	84	- 02756	+ 011	- 022	0961
40	83	- 05245	- 019	- 048	0860
40	82	- 09827	- 021	- 051	0886
39	105	- 01047	- 007	- 199	5633
39	104	- 02567	- 013	- 171	4646
39	103	- 02138	- 003	- 141	4055
39	102	- 02719	- 004	- 119	3383
39	101	- 03034	- 005	- 098	2723
39	100	- 02831	- 004	- 078	2175
39	99	- 02259	+ 011	- 050	1775
39	98	- 02600	- 004	- 052	1417
39	97	- 01509	- 021	- 067	1342
39	96	- 01631	- 022	- 058	1060
39	95	- 01170	- 024	- 055	0919
39	94	- 00900	- 024	- 052	0817
39	93	- 00952	- 023	- 050	0784
39	92	- 00903	- 009	- 035	0764
39	91	- 01828	- 001	- 021	0577
39	99	- 06344	+ 001	- 016	0486
39	89	- 11078	- 004	- 020	0472
39	88	- 10145	- 003	- 019	0459
39	87	- 06971	- 016	- 038	0636
39	86	- 04692	- 019	- 042	0689
39	85	- 03027	- 026	- 053	0801
39	84	- 03397	- 002	- 032	0879
39	83	- 07291	- 011	- 037	0774
39	82	- 13409	- 017	- 052	1020
38	105	+ 01931	+ 007	- 205	6204
38	104	+ 01452	+ 006	- 164	4974
38	103	- 01907	000	- 141	4134
38	102	- 04088	- 015	- 125	3212
38	101	- 04870	- 010	- 102	2687
38	100	- 04630	- 003	- 077	2178

Quadrangle Lat.	Long.	Base. el. in feet	Free-air anom. in mgals	Boug. anom. in mgals	Surf. el. in feet
38	99	- 03975	- 007	- 065	1693
38	98	- 03684	- 004	- 049	1322
38	97	- 02388		- 062	1150
38	96	- 01411	- 016	- 048	0932
38	95	- 00791	- 013	- 045	0928
38	94	- 00703	- 002	- 039	1089
38	93	- 00847	+ 002	- 039	1204
38	92	- 00333	- 007	- 044	1083
38	91	- 00305	+ 008	- 020	0807
38	90	- 06378	+ 017	+ 001	0546
38	89	- 11134	+ 011	- 004	0443
38	88	- 10753	+ 003	- 012	0443
38	87	- 07909	- 005	- 025	0584
38	86	- 05238	- 021	- 051	0876
38	85	- 05859	+ 003	- 031	1004
38	84	- 08536	- 003	- 041	1115
38	83	- 12641	- 002	- 048	1358
38	82	- 19581	+ 015	- 058	2149
37	105	+ 02459	+ 034	- 193	6653
37	104	+ 01997	+ 022	- 165	5472
37	103	- 02853	- 008	- 148	4091
37	102	- 05191	- 020	- 130	3222
37	101	- 09248	- 021	- 112	2661
37	100	- 10828	- 020	- 090	2054
37	99	- 08795	- 006	- 054	1407
37	98	- 06372	- 009	- 046	1079
37	97	- 03058	+ 003	- 029	0928
37	96	- 01519	- 008	- 033	0735
37	95	- 00441	+ 009	- 028	1093
37	94	- 00694	+ 008	- 035	1273
37	93	- 01622	+ 008	- 023	0912
37	92	- 02614	- 007	- 032	0728
37	91	- 03581	- 003	- 016	0371

Quadrangle Lat.	Long.	Base. el. in feet	Free-air anom. in mgals	Boug. anom. in mgals	Surf. el. in feet
37	90	- 05466	+ 005	- 005	0302
37	89	- 08373	+ 010	- 005	0440
37	88	- 07577	- 001	- 021	0577
37	87	- 05281	+ 003	- 019	0653
37	86	- 05178	- 005	- 038	0961
37	85	- 07345	+ 026	- 020	1342
37	84	- 11103	- 007	- 056	1450
37	83	- 13000	- 002	- 071	2018
37	82	+ 02638	+ 001	- 089	2638
36	105	+ 01613	+ 005	- 177	1331
36	104	+ 00092	- 001	- 149	4334
36	103	- 03266	- 004	- 134	3809
36	102	- 02959	- 011	- 123	3297
36	101	- 08397		- 085	2750
36	100	- 18775	- 010	- 077	1955
36	99	- 20128	+ 003	- 048	1499
36	98	- 10825	+ 001	- 038	1135
36	97	- 05753	- 002	- 032	0879
36	96	- 05884	- 020	- 043	0666
36	95	- 08422	- 020	- 049	0843
36	94	- 11247		- 040	1000
36	93	- 08562	+ 016	- 012	0810
36	92	- 06975	+ 008	- 004	0358
36	91	- 06727	+ 004	- 004	0236
36	90	- 06305	+ 008	- 004	0338
36	89	- 05941	+ 003	- 013	0479
36	88	- 05253	+ 008	- 018	0751
36	87	- 05009	+ 013	- 016	0856
36	86	- 09175	+ 009	- 037	1348
36	85	- 08801	- 014	- 055	1207
36	84	+ 02546	+ 023	- 064	2546
36	83	+ 02402	+ 004	- 078	2402
36	82	+ 01070	- 020	- 056	1070