APPLICATIONS OF TREND-SURFACE ANALYSIS FOR: INVESTIGATION OF STRUCTURE AND PREDICTION OF GYPSUM OCCURRENCES IN NORTH-EASTERN KANSAS

by

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INTRODUCTION

Location of the Problem Area

The investigation covers an area in Kansas from townships one through thirteen south and ranges one through ten east, approximately 4,680 square miles. This embraces all of Marshall, Washington, and Riley counties and portions of Clay, Pottawatomie, Geary, Dickinson, and Waubunsee counties. The area is shown on the map of Kansas (Fig. 1).

Purpose of the Investigation

In recent years the solution of field problems in geology has been greatly enhanced through the use of trend-surface analysis. This is a tedious process made available to geologists through the use of computers. Programs have been prepared using the least-squares criterion to fit varying degree polynomial equations to a set of data.

Through the use of one such program written by O'Leary, Lippert, and Spitz, it was hoped that the geologic conditions favorable for the formation of gypsum deposits in north-eastern Kansas could be determined. The investigation encompassed two major tasks:- the first, to test the reliability of the trend-surface analysis by comparing it to the known geologic structure of the area; the second, to analyze the maps based on computer data for facts pertinent to locating gypsum deposits not yet discovered.

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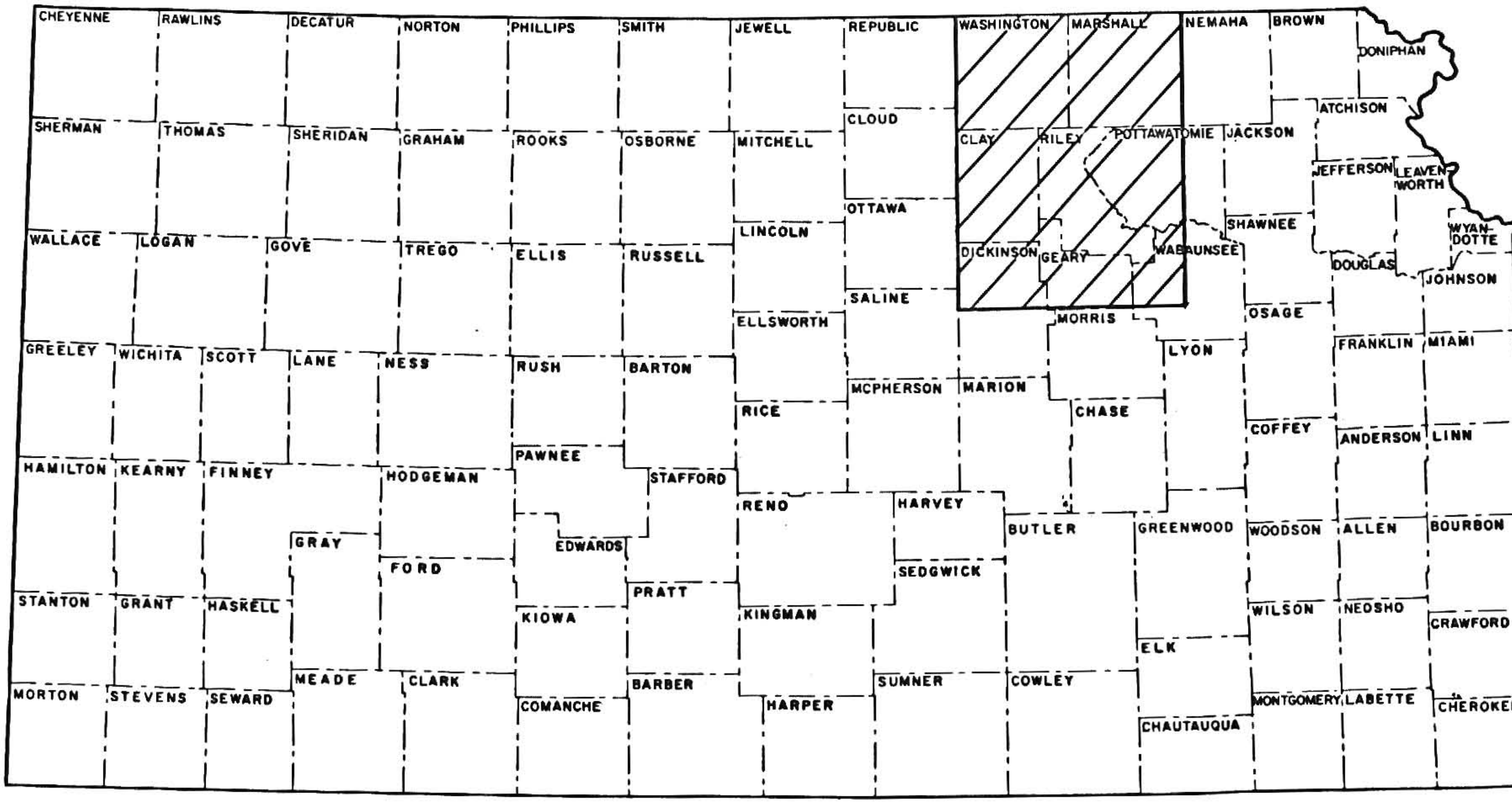


AREA OF STUDY

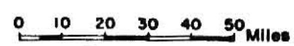


Figure 1

Review of Literature

One of the first investigations dealing with trend-surface analysis was done by Krumbein (1956). His report deals with a number of different methods of preparing trend-surface maps without the aid of computers. These methods make use of orthogonal polynomials and, therefore, require a grid system for interpolation of values at each grid point. This is a lengthy, and tedious process.

In the relatively short period of time that trend-surface analysis has been run on computers, a rather voluminous amount of literature has been published. This has been possible only because of the capabilities of computers for handling large, complex and tedious operations. Most of the work has been done since 1960.

One of the most classical works was written by Allen and Krumbein (1962). They used polynomial trend analysis on zircon sizes, percent staurolite, and percent garnet to try and discern the source area for the Top Ashdown Pebble Bed in England. This was actually a sedimentary facies study using trend-surface analysis. The results helped also to resolve the question of whether the bed was the result of a transgressive or regressive sea.

Merriam and Harbaugh (1964) made an important study of the regional and residual components of trend surfaces in five different sized areas in Kansas. Regional and residual (or local) structural features in the areas of differing size were compared for reproduction of the structure. A second section of the study discussed the relationship of features produced by residuals and known oil fields. The results substantiated the fact that computed trend surfaces represent large-scale regional features while the residuals from these surfaces bring out local features. Because the residuals proved so useful in studying local structures, they could then be used successfully in prospecting for oil.

Thickness relations of six Paleozoic horizons in south-central Kansas were studied by Merriam and Lippert (1964). The results of their study showed the progressive or cumulative structural developments that took place through the Paleozoic Era.

Krumbein (1959) discussed and outlined the method for preparing trend-surface maps with irregular control-point spacing. This was one of the earliest and most successful attempts at writing a program for this type of data. Lithologic characteristics were quantified and used for preparation of sedimentary facies maps. Krumbein (1959, p. 832) concluded:

> experimental polynomial analysis of maps having relatively few irregularly spaced control points showed in a number of instances that fitted linear or quadratic surfaces conveyed an unexpected amount of information about the underlying systematic controls of the phenomenon being studied. Moreover, deviations from these surfaces carried meaningful information about some of the intermediate-scale effects that influence the observational values.

Duff and Walton (1964) mapped sedimentary features of the Modiolaris zone of the East Pennine Coalfield in England using trend-surface analysis. Thickness relations were used as the criteria of the investigation.

> Although much remains to be learned about the method and especially about the geological meaning of the deviations, the results of the two computations of the partial trend surfaces of thickness give a striking illustration that the general variation in sedimentary characters may be obtained from very restricted data (Duff and Walton, 1964, p. 122).

In 1968, Harbaugh and Merriam published the first book devoted entirely to computer applications in geology, specifically stratigraphic analysis. The book covers nearly all aspects of computer applications in geology. An entire chapter devoted to trend analysis discussed the method of the least-squares criterion, its underlying theory, its accuracy, and its advantages and disadvantages.

The Kansas Geological Survey now publishes a special series entitled "Computer Contributions" which is devoted entirely to computer advances in the field of geological sciences. This series, edited by Daniel F. Merriam, is the only known publication dealing strictly with computer uses in geology.

Much more has been written and published on trend analysis that can not possibly be covered here. For a more complete reference listing, the reader is referred to the bibliography at the end of Harbaugh and Merriam (1968, p. 262-276).

The most extensive work on the Easly Creek gypsum was prepared by Kulstad, Fairchild and McGregor (1956). This report is a study of the gypsum in Kansas and deals with the petrography, petrology and origin of the individual deposits of gypsum throughout Kansas.

AVAILABLE MATERIALS

The data required for this study consists of elevations and thicknesses of two formations, the Crouse linestone and the Easly Creek shale. The most important source of information from which over half of the data was obtained came from the files of the State Highway Commission in Topeka, such as records of core drillings and measured sections used in planning the state-road network. The second most important source of information was the well-log library at the Kansas Geological Survey at Kansas University in Lawrence. Three types of logs were used; drillers logs, strip logs and electric logs. For a few of the wells, cuttings were available which were used to verify key horizons on the electric logs. The third source of information was obtained from measured sections published in the county reports of the Kansas Geological Survey bulletins.

The trend surfaces were computed and plotted by a program written in Fortran IV for computation and plotting of trend surfaces of degrees one through six. The program was obtained through the courtesy of the Operations Research Section, Kansas Geological Survey. Written by Mont O'Leary, R. H. Lippert and Owen T. Spitz, the program also includes a list of statistical-error measures and plots of the residuals.

The program was run at the Kansas State University Computing Center on an IBM 360 Model 50 computer. Only a few program alterations were required for operation.

TREND MAPPING AND COMPUTER PROGRAM

A summary of the method of trend analysis is presented as simply and concisely as possible. A more detailed explanation of the method and the mathematics involved can be found in Krumbein and Graybill, (1965) or Krumbein, (1959).

> Essentially, trend-surface analysis may be defined as a precedure by which each map observation is divided into two or more parts: Some associated with the "large-scale" systematic changes that extend from one map edge to the other and others associated with "small-scale" apparently nonsystematic fluctations that are superimposed on the large scale patterns (Krumbein, 1965, p. 321).

Trend-surface analysis involves the fitting of a polynomial equation as a three-dimensional surface to a set of data by the least squares criterion. This simply means that a surface represented by some polynomial involving three variables will pass above and below data points that it is trying to fit. The distance between the observed data point and the point that represents it on the computed surface is known as the deviation or residual. When all residuals are squared and summed, it is called the sum of the squared residuals. The equation of the trend-surface that best fits all the data points will have the smallest sum of squared deviations.

For purposes in this report, the polynomial equations will involve three variables, one independent and two dependent variables. The two dependent variables represent geographical coordinates and the independent variable represents some value at a geographical coordinate such as a bed thickness, an elevation or possibly some grain-size diameter. Actually, trend analysis is the same as any statistical regression method that finds a line that best shows the trend of points, only trend analysis uses three variables to describe a surface. The lower degree polynomial equations describe surfaces of rather regular form such as rolling or undulating topography. The higher degree equations fit more irregular surfaces. For most geological work, the degree of the polynomial seldom exceeds the sixth degree. Figure 2 shows the relation of the types of surfaces to the degree of the equation. The equation of each degree showing the number of terms is also given.

Least Squares Criterion and Calculation of Coefficients

Most of the following discussion may be found in Harbaugh and Merriam (1968) and in Krumbein and Graybill (1965).

The actual contouring of the data requires a grid to be generated. The grid is constructed from irregularly spaced data, although, regularly spaced data also may be used. The process involves fitting a low-degree polynomial to the original data to provide values on a rectangular grid. The grid values are then smoothed by fitting a linear (first-degree) surface on a quadrant-by-quadrant basis moving progressively over the grid (Harbaugh and Merriam, 1968, p. 35).

To derive the polynomial equation of the surface desired, the coefficients of the terms must be computed. Coefficients may be calculated in terms of the three-dimensional coordinates, x, y, and z, where x is the distance along the horizontal axis, y is the distance along the vertical axis, and z is the value

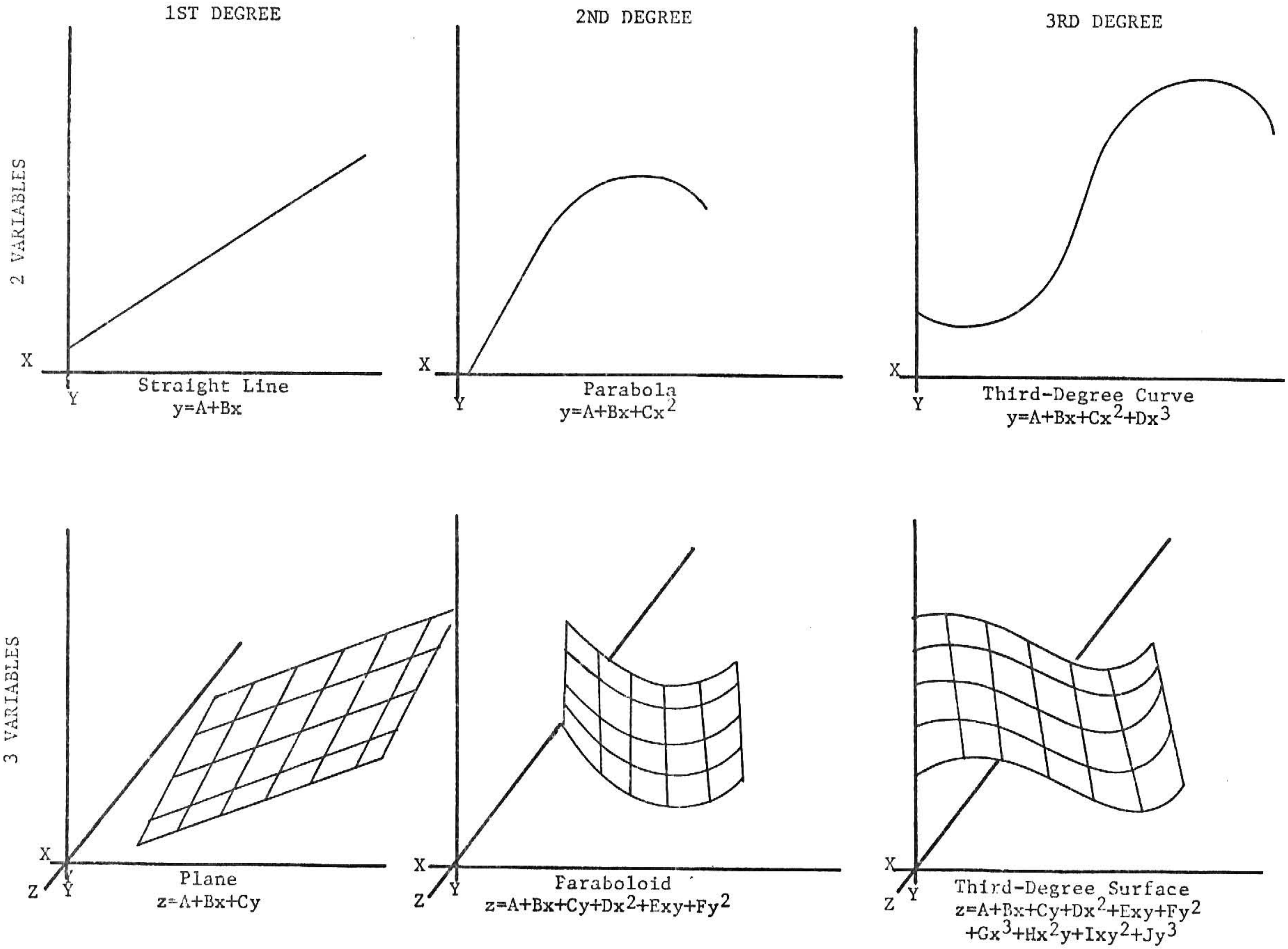


Figure 2 (After Harbaugh and Merriam, 1968)

of the observation. These coordinates now act as the variables for the equation, where z is the independent variable, and x and y are the two dependent variables. The equation is then solved for z in terms of x and y. The first three equations written in terms of x, y, and z are:

linear equation
$$z = A + Bx + Cy,$$

quadratic equation
$$z = A + Bx + Cy + Dx^2 + Exy + Fy^2,$$

cubic equation
$$z = A + Bx + Cy + Dx^2 + Exy + Fy^2 + Gx^3 + Hx^2y + Ixy^2 + Jy^3.$$

The coefficients are calculated so that the sum of the squared deviations are at a minimum. This is called the least-squares criterion and is expressed as:

$$\Sigma(x_{obs} - x_{trend})^2 = \text{minimum}$$

Where x_{obs} equals observed data value,

x_{trend} equals calculated trend-surface value at data point.

This system requires the calculation of three coefficients for the linear equation where each coefficient is represented by an equation. The second-degree polynomial has six coefficients and they may be derived by solving six simultaneous equations. Each higher degree polynomial is solved in the same manner, that is, each coefficient must be expressed as an equation. These equations may then be solved by setting them up as a matrix and evaluated using matrix algebra. The following example is the computation of the linear coefficients for the first-degree surface.

As stated the first-degree polynomial may be expressed as

$z = A + Bx + Cy$

where z is the value of the trend at a given point.

To satisfy the least-squares criterion, the sum of the squared residuals must be at a minimum or,

$\Sigma(z_{obs} - z_{trend})^2 = 0$

Then,

$\Sigma(z_{obs} - A - Bx - Cy)^2 = 0.$

For z_{trend} to be minimized, calculus must be used to find the partial derivatives of the coefficients. This is accomplished by expressing A, B, and C as a function or F(A,B,C). Therefore, to minimize F(A,B,C), the derivatives should equal zero or,

$\partial F/\partial A = \partial F/\partial B = \partial F/\partial C = 0.$

The partial derivatives are written

$\partial F/\partial A = \Sigma 2(z-A-Bx-Cy)(-1) = 0,$

$\partial F/\partial B = \Sigma 2(z-A-Bx-Cy)(-x) = 0,$

$\partial F/\partial C = \Sigma 2(z-A-Bx-Cy)(-y) = 0.$

These may be evaluated as

$-\Sigma z + An + B\Sigma x + C\Sigma y = 0,$

$-\Sigma zx + A\Sigma x + B\Sigma x^2 + C\Sigma xy = 0,$

$-\Sigma zy + A\Sigma y + B\Sigma xy + C\Sigma y^2 = 0,$

where n is the number of data points. These equations may be rewritten as

$An + B\Sigma x + C\Sigma y = \Sigma z,$

$A\Sigma x + B\Sigma x^2 + C\Sigma xy = \Sigma zx,$

$A\Sigma y + B\Sigma xy + C\Sigma y^2 = \Sigma zy.$

The coefficients may then be evaluated using matrix algebra.

Matrix algebra involves long tedious operations and will not be developed here.

After the coefficients have been calculated, the z_{trend} value at each z_{obs} point may be determined along with its associated deviation or residual value. The deviation is given by the following expression

$z_{obs}-z_{trend}$.

The higher degree polynomial surfaces are computed in the same way. Each coefficient is expressed as an equation, the derivative of each equation is found, the derivatives are expressed as normal equations and solved using matrix algebra and finally, each z_{trend} term and its deviation are determined. The surfaces are then ready for plotting.

Computer Output and Statistical Measures

It is essential that a number of statistical measures be incorporated into the computations of trend surfaces when the least-squares criterion is used.

One such measure, known as the goodness of fit, expresses how well a trend surface fits the data. A second measure, known as the F test, can be incorporated to test whether a trend function is actually significant or was produced merely by chance. A third measure, known as confidence surfaces or confidence levels, may be used. However, this measure was not used as part of the investigation and so will not be elaborated here.

The computer program calculates and lists a number of measures by which the goodness of fit may be calculated directly.

The first is entitled the "Total Variation" and is given by the equation

$$V = \Sigma(z_{obs}-\bar{z}_{obs})^2,$$

where $\bar{z}_{obs}$ is the arithmetic mean of observed values of z. V gives an indication of the total variation within the data set.

A second measure, "Variation Not Explained By Surface", is given by the following equation

$$S = \Sigma(z_{obs}-z_{trend})^2.$$

This is simply the total sum of squares due to deviations and "... is a reflection of the failure of the trend values to coincide with the observed values (Harbaugh and Merriam, 1968, p. 67)."

Another measure called the "Variation Explained By The Surface" is given by

$$E = V-S \text{ or,}$$

$$E = \Sigma(z_{obs}- \bar{z}_{obs})^2 - \Sigma(z_{obs} - z_{trend})^2 \text{ or,}$$

$$E = \Sigma(z_{trend} - \bar{z}_{obs})^2.$$

E is the sum of squares contributed by the trend function (Harbaugh and Merriam, 1968).

The actual goodness of fit is referred to as "Coefficient of Determination". It is in whole-number form and may be converted to a percentage simply by multiplying by 100. "Coefficient of Determination" is given by

$$T = E/V.$$

where $E = V-S$ and,

$$V = \Sigma(z_{obs} -\bar{z}_{obs})^2.$$

"Coefficient of Determination" or percent total sum of squares may also be found by this equation

$100\ [1-S/V]$ or,

$100\ \left[1-\left[\Sigma(z_{obs}-z_{trend})^2/\ \Sigma(z_{obs}-\bar{z}_{obs})^2\right]\right]$.

In short, this measure expresses by percent how well the trend surface comes to lying on or near the data points.

Also included in the program output are two other measures, the "Standard Deviation" and the "Coefficient of Correlation". The "Coefficient of Correlation" is expressed as a percent and is given by the equation

$L = T^{\frac{1}{2}}.$

where $T = E/V$.

"Standard Deviation" is given by

$D = (S/N)^{\frac{1}{2}}.$

where N equals the number of data points and,

$S = \Sigma(z_{obs}-z_{trend})^2.$

The second actual statistical error measure is a form of analysis of variance. Here the trend function is tested for the level of significance at which it will be statistically sound. Trend-function components of the regression equations can be tested as a group or individually. They are evaluated to see if they are real or due merely to chance. This is expressed as a significance level and is given in a percent. The test is called the F test or F ratio.

F is a ratio of the mean square associated with the variation due to the trend function compared to the mean square

Table I:

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	Ratio of Mean Square
Trend Function Regression	m	$S_{tr}=\Sigma(z_{trend}-\bar{z}_{obs})^2$	$M_1=S_{tr}/m$	$F=M_1/M_2$
Deviations	n-m-1	$S_d=\Sigma(z_{obs}-z_{trend})^2$	$M_2=S_d/n-m-1$	
Total	n-1	$S_{t1}=\Sigma(z_{obs}-\bar{z}_{obs})^2$		

m equals number of terms in trend component,

n equals number of data points,

S_{tr} equals E equals sum of squares due to regression or trend function,

S_d equals S equals sum of squares due to deviations,

S_{t1} equals V equals sum of squares due to total variation,

z_{trend} equals value predicted by trend function,

z_{obs} equals observed data point,

$\bar{z}_{obs}$ equals arithmetic mean of observed data values,

M_1 equals mean square associated with regression,

M_2 equals mean square associated with deviations,

F equals ratio of mean square,

(after Harbaugh and Merriam, 1968).

associated with the variation due to the residuals. The general set of equations needed for computation of the F test are given in Table I.

Analysis of variance covers many different types of tests of which the F test is only one. For purposes in this paper, only a brief discussion of the F test and its underlying assumptions will be given. The reader is referred to Krumbein and Graybill, p. 365, 1965; Griffiths, p. 321, 1968; or Harbaugh and Merriam, 1968, p. 69-70 for a more detailed explanation of the subject.

Analysis of variance is a method to test the manner in which a statistical population is likely to vary. For this it is essential to know the degrees of freedom or the number of ways in which variation can occur. Degrees of freedom is defined mathematically as n-1, where n equals the number of observations.

> The degrees of freedom associated with the trend components are equivalent to the number of terms in a trend equation, excepting the base or zeroth-degree term. The degrees of freedom associated with the deviations from a trend function represent the difference between n-1 degrees of freedom and the number associated with the trend equation components (Harbaugh and Merriam, 1968, p. 68).

From Table I, it can be seen that the sum of squares are divided by the degrees of freedom to obtain a mean square and the mean squares are compared as a ratio called the F ratio. The F value has a known probability distribution associated with two different degrees of freedom. Tables of F values with their associated degrees of freedom and their levels of probability have been prepared and are listed in the appendix of Krumbein and Graybill, 1965, p. 422-440, and in most other books on statistics.

> The significance level obtained from the F tests is commonly expressed as a percentage. In applying this test the hypothesis to be tested is that the coefficients of the regression components to be tested are equal to zero, or, in other words, that there is no regression. If the computed value of F exceeds the tabulated value of F, the hypothesis is rejected and the alternative hypothesis that the coefficients of the regression components are not equal to zero is accepted. If such an hypothesis is to be tested, it is essential that the desired level of significance be stated by the investigator before the test is made; then he may accept or reject according to results of the F test (Harbaugh and Merriam, 1968, p. 70).

Any portion of a trend function may be tested for its significance if the sum of squares and the degrees of freedom are known. This program only gives the total sum of squares associated with the complete polynomial equation. Some other programs, however, have been written which give the sum of squares contributed by each set of terms. The cubic equations, for instance, could be divided into the sums of squares contributed by the linear, by the quadratic or by the cubic terms, and each evaluated separately. This program handles each equation as a whole unit. The smaller the equations are broken down, the more tedious becomes the task. The extra expense this would create for evaluation on the computer is not justifiable on the basis of significance of the results.

The percent of total sums of squares and the maximum significance levels for the thickness maps of the Crouse lime-

Table II:

	Degree	Crouse Thickness	Easly Creek Thickness	Structure on Easly Creek
No. of Data Points		35	30	39
Cumulative Percent of Total Sum of Squares by Each Surface (%)	1^o	26.3	56.4	94.6
	2^o	35.0	62.0	95.2
	3^o	40.5	73.6	97.0
	4^o	46.6	77.3	98.3
	5^o	59.0	80.0	99.1
Maximum Significance Levels (%)	1^o	97.5	99.9	99.9
	2^o	95.0	99.9	99.9
	3^o	75.0	99.9	99.9
	4^o	50.0	97.5	99.9
	5^o	25.0	50.0	99.9

stone, the Easly Creek shale, and the structure map of the Easly Creek shale are tabulated in Table II.

The output from the computer program lists for each x and y coordinate, its z value, its calculated z value (z_{trend}) and the residual value for each trend surface. The equation for each degree polynomial requested and the error measures described previously are part of the output. Finally, contour maps of each fitted surface, a plot of the original z values and plots of the residuals for each degree equation are incorporated as part of the program output.

STRATIGRAPHY

The Easly Creek Shale along with the Crouse Limestone and the Bader Limestone, comprise a small portion of the Council Grove Group of the Lower Permian System.

The rocks of Permian age crop out over most of the area of study and several of the flint bearing formations form persistent benchs or escarpments known as the Flint Hills. The Flint Hills extend as a belt from Nemaha County on the northern Kansas border to Chautaqua County at the southern Kansas border.

Upper Permian strata known as the Ochoan Series consist mainly of shale and sandstone. There are, however, no known Ochoan rocks in Kansas.

The middle Permian strata known as the Cimarron series also consist of shale, sandstone and some thick deposits of salt, but these occur to the west of the area of investigation.

The Lower Permian consists mainly of even beds of marine shale and limestone. The shale units are varicolored and separate the light gray and yellowish-brown colored limestones. The total outcrop thickness of Permian rocks in Kansas is approximately 3,000 feet.

Only three formations are actually involved in this study. From the oldest to the youngest, they include the Bader Limestone, the Easly Creek Shale, and the Crouse Limestone.

The following description is taken from Walters's (1954) report on Marshall County.

Bader Limestone

> The Bader Limestone is divided into three members, which in ascending order are: the Eiss Limestone Member, the Hooser Shale Member and the Middleburg Limestone Member. The thickness of the formation in Marshall County ranges from 17 to 22 feet.
>
> At the base of the Eiss Limestone Member is a massive, argillaceous, light-gray limestone about 2.5 feet thick. This bed is nonresistent to weathering and is well exposed in a few places. The middle part of the member is composed of fossiliferous gray shale generally about 2.5 feet thick. The upper part of the Eiss Limestone Member is composed of a very massive limestone about 4 feet thick.
>
> In weathered outcrops this upper bed is commonly pitted and has solution channels. A very conspicuous bench is formed by the upper part of the Eiss Limestone Member.
>
> The Hooser Shale Member consists of 8 to 11 feet of sparsely fossiliferous shale. A large part of the shale is green and gray, but bands of pink and maroon are common near the center of the member.

> At the base of the Middleburg Limestone Member is a limestone bed about 2 feet thick, dark gray at the top and yellowish-brown below, and containing many fossils. About 1 foot of dark-gray calcareous shale separates the lower limestone bed and an upper limestone bed just about a foot thick. The upper bed of the Middleburg limestone member is fossiliferous and weathers pitted. The Middleburg Limestone Member does not form a conspicuous bench ...
>
> Easly Creek Shale
>
> A massive bed of gypsum 8 to 9 feet thick occurs at the base of the Easly Creek Shale in the area around Blue Rapids. This gypsum bed is readily leached away when exposed to weathering and is not generally present in natural outcrops, but it is exposed in mine workings and has been penetrated in many wells in the area. The gypsum is overlain by out 10 feet of gray, green and red shale....
>
> Crouse Limestone
>
> The Crouse Limestone, typically a platy, thin-bedded, argillaceous, gray limestone, has a bed of gray calcareous shale about 2.5 feet thick near the middle of the formation. The upper limestone bed is more massive and crystalline than the lower bed. Fossil fragments are common, but well-preserved specimens are rare. The total thickness of the formation is about 7.5 feet...

Gypsum of The Easly Creek Shale

Located at Blue Rapids in Marshall County is the only mining operation in the Easly Creek gypsum. The mine is owned by Georgia and Pacific Enterprises, but had previously been owned by a number of other firms.

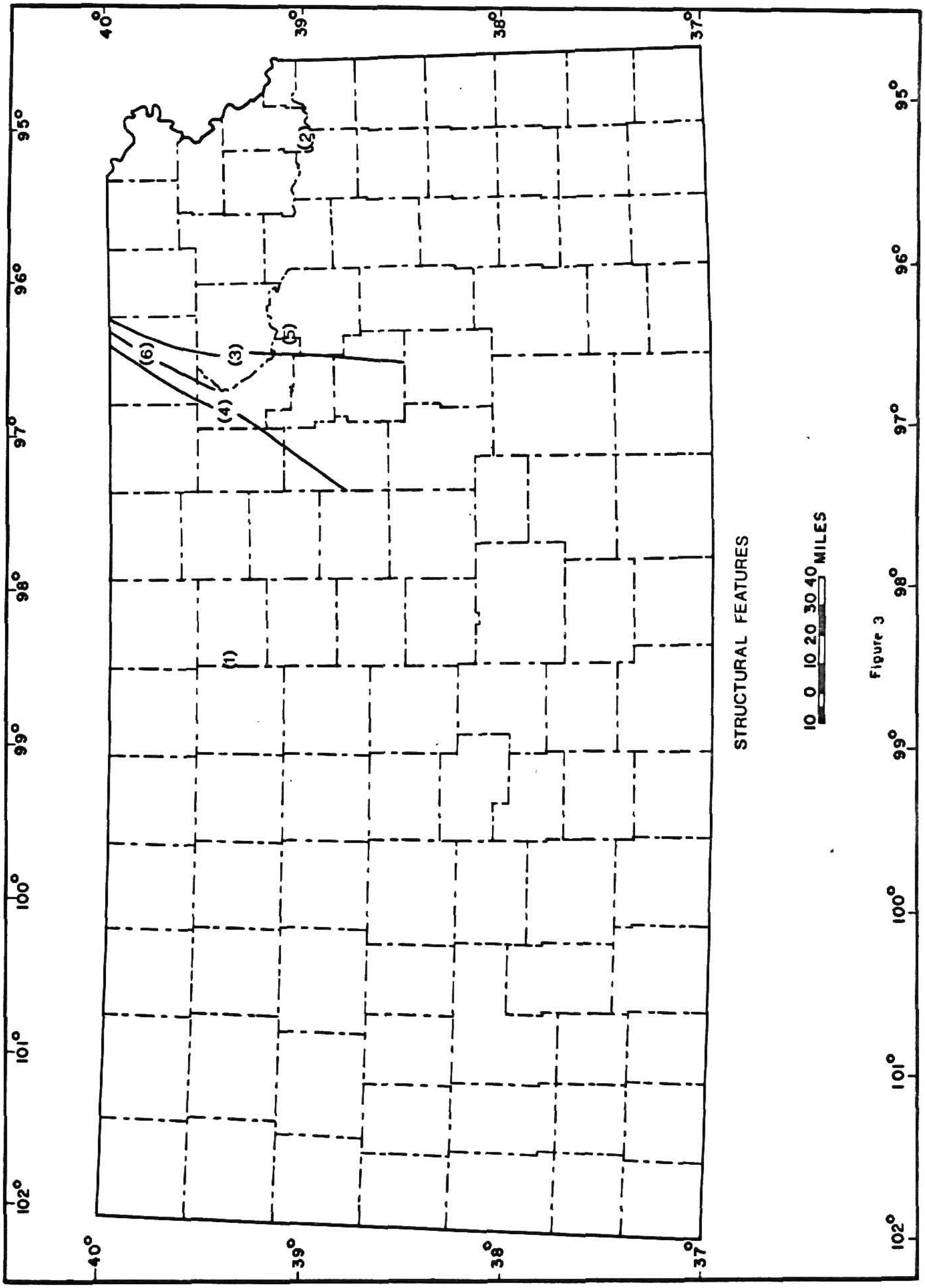
The gypsum ranges from eight to ten feet thick and is overlain by approximately 100 feet of overburden. The gypsum occurs at the base of the Easly Creek Shale. It exists in three different forms in the mine, massive gypsum, satin spar and selenite. The massive or rock gypsum is white and comprises most of the mined gypsum. Satin spar exists as stringers one-quarter to one-half inch thick at the upper and lower contacts of the gypsum bed. Selenite forms crystals interspersed throughout the rock gypsum.

Ten to twenty miles south in a stream-cut at the lower end of North Otter Creek the gypsum averages about four feet thick, but the color has changed to a light red or pink. Satin spar occurs as stringers. The outcrop shows much solution, but probably grades back from the outcrop to massive gypsum. A few miles farther east, at the Randolph Bridge, core records show a solid mass of gypsum four to five feet thick. Other drillings by the Highway Department near Junction City, Geary County, found massive gypsum occurring in five foot thicknesses. There also have been some cobble-sized pieces of red gypsum found in stream beds in Marshall County just south of Marysville.

PALEOZOIC GEOLOGIC HISTORY AND STRUCTURE OF THE REGION

This section is divided by structures of the area under study and include a description of the feature and a short discussion of its formation during Paleozoic time. The descriptions are based primarily on work by Jewett (1951) and supplemented by Merriam (1963), Gasaway (1959), and Lee (1943) and (1956).

Figures 3 and 4 indicate the approximate location of the features in Kansas. The numbers on the map correspond with those in this section.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STRUCTURAL FEATURES
10 0 10 20 30 40 MILES

Figure 3

Salina Basin (1)

The Salina basin lies between the Nemaha uplift on the east and the Central Kansas uplift on the west. To the south, lies the saddle between the Chautauqua arch and the Central Kansas uplift.

Prior to the development of the Nemaha anticline, the Salina basin did not really exist. The Nemaha anticline separated a large basin, North Kansas basin. This in turn created two smaller basins, Salina on the west and the Forest City basin to the east. The basin is post-Mississippian and is a depressed area or syncline trending northwest and plunging northward where the basin deepens. Permian rocks cover the entire basin and crop out in the eastern half. Cretaceous rocks are exposed in the western half. The sequence ranges from Cambrian to Tertiary with a maximum thickness of 4,500 feet. During Mississippian time the area went through a stage of erosion until middle Pennsylvanian time when more sediments were deposited on this peneplained surface of Mississippian limestone. There were five periods of folding in the Salina basin that Lee (1956) described: 1. Late Cambrian to early Ordovician, 2. St. Peter to Mississippian, 3. Mississippian to Permian, 4. Post-Permian and pre-Cretaceous, 5. Post-Cretaceous. A minor structural feature called the Abilene anticline in the basin is economically important. Also developed within the basin are the Voshell anticline and the Wilson-Burns element.

Forest City Basin (2)

The Forest City basin lies east of the Nemaha anticline in northeastern Kansas and in parts of Iowa, Missouri and Nebraska. It is bounded on the southwest by the Bourbon arch. The Forest City basin, like the Salina basin, is part of an older and larger pre-Mississippian basin called the North Kansas basin. The Forest City basin was formed as a result of the uplift of the Nemaha anticline along with other positive features and the downwarping of the basin itself. The North Kansas basin has deposits of rocks as old as Ordovician which are, therefore, also in the Forest City basin. The basin itself is a depositional area for pre-Pennsylvanian sediments.

The southern edge is bounded by the Prairie Plains homocline and has Pennsylvanian and Permian strata exposed. The northern edge is covered by Pleistocene glacial deposits. The western edge has many faults and structural features which have been covered by Pennsylvanian deposits. The deepest section of the basin lies along the western edge containing sedimentary thicknesses of approximately 4,000 feet.

The basin had a relatively brief existence because it was joined over the Bourbon arch by early Pennsylvanian sediments with the Cherokee basin.

Nemaha Anticline (3)

The Nemaha anticline is the largest structure of its kind in Kansas extending from Nemaha County in the north to Sumner County in the south. It also extends into parts of Oklahoma and Nebraska. It is a post-Mississippian structure recogniza-ble in the surface rocks of Permian and Pennsylvanian ages. The axis strikes approximately N20°E and plunges to the south. The anticline is truncated with steeper dips on the east flank than on the west.

In the subsurface, the Nemaha Anticline is probably cut by a fault zone along its entire eastern flank, but in Potta-watomie and Nemaha Counties, and northward into Nebraska, a surface expression occurs, known as the Humboldt Fault. The underlying Precambrian granite along the axis of the anticline plunges from a level within 600 feet of the surface in Nebraska to 4,000 feet below the surface in Oklahoma. The granite sur-face has "knob-like" irregularities that are expressed as sur-face structures in the overlying sediments probably because of differential compaction during sedimentation. One such struc-ture is the Zeandale dome. Some geologists believe the Nema-ha anticline is a horst-like block over which the post-Mississippian sediments have been draped, Koons (1955). Local-ly, Pennsylvanian rocks rest directly on the Precambrain gran-ite due to a period of erosion which peneplained the area during late or post-Mississippian times.

A rather large but more local structure, the Abilene anti-cline, developed to the west of the Nemaha, and at about the same time.

Abilene Anticline and Barneston Anticline (4)

The Abilene anticline trending northeast extends through Clay, Riley and Marshall Counties. North of Marshall County it is known as the Barneston anticline.

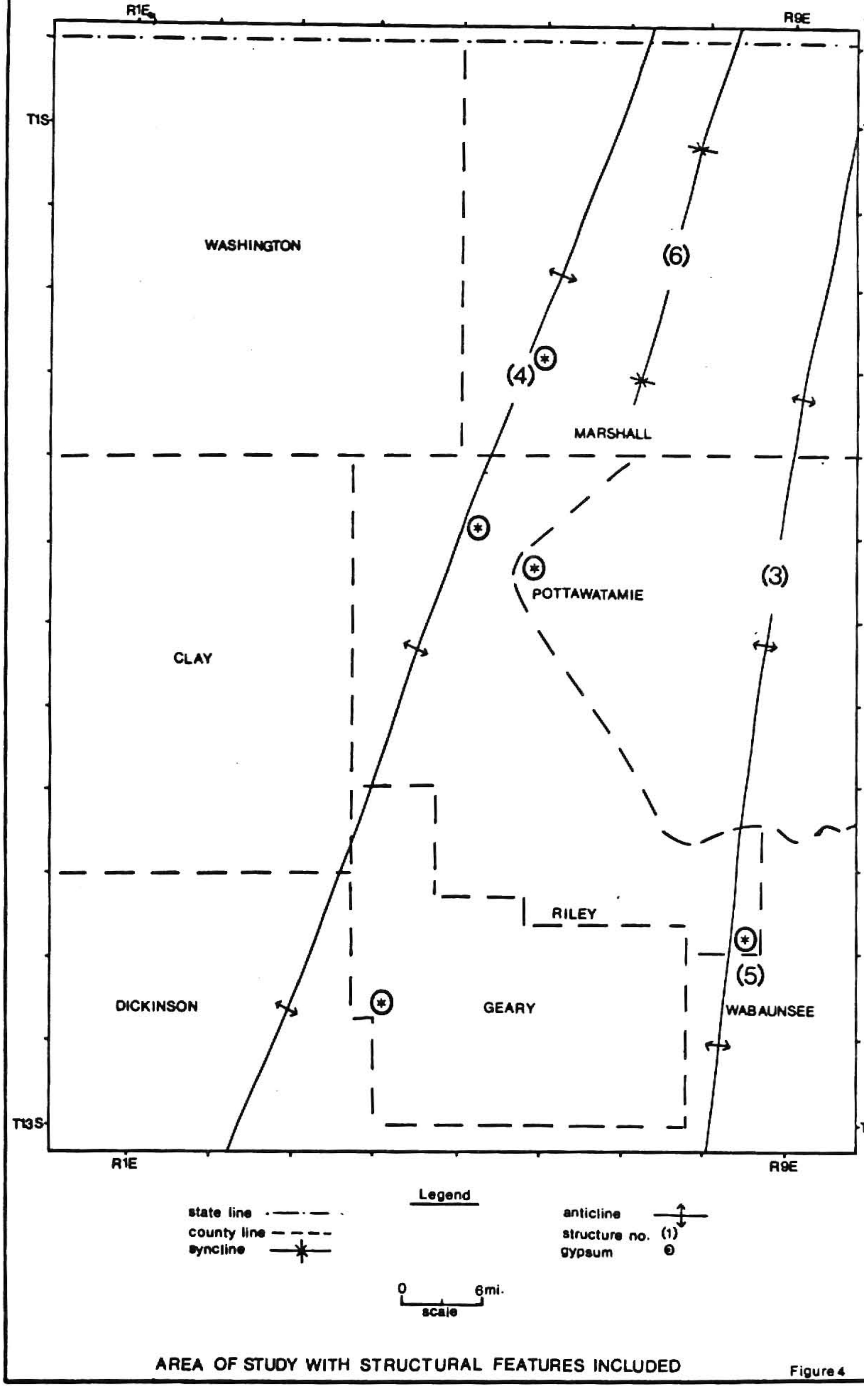
The anticline resembles the Nemaha in its direction of strike, its asymmetry (the western slope is more gentle than the eastern slope), and general configuration. The anticline may be the result of sursurface hinge faulting according to Koons (1955), with 400 feet of displacement upward to the west in Marshall County and disappearing completely in Clay County.

> Nelson (1952) described it as a normal fault with oblique slip movement. The strike element was minor and affected a clockwise rotation of the joint pattern of the area. Rieb (1954) who proposed the fault be named the Big Blue fault, called it a rotational fault, the west side being elevated to the north and depressed to the south (Merryman, 1957, p. 18).

The structure of the Abilene anticline is expressed on the surface rocks of Permian age and probably formed contemporaneously with the Nemaha anticline or during post-Mississippian times. Some slight folds have been reported by Lee (1956) in the Permian strata indicating some further activity during or just after this time.

Zeandale Dome (5)

The crest of the Zeandale dome is located in township ten south and range nine east. It reflects one of the many small granite knobs on the crest of the Nemaha anticline. Rieb (1955,



AREA OF STUDY WITH STRUCTURAL FEATURES INCLUDED

Figure 4

pp. 12-13) reports that it

> ... appears as a northwest southeast elongated dome with a closure of about 600 feet. The dome was originally elongated parallel to the Nemaha fault, but a short fault cuts the northern half giving an appearance of elongation in northwest-southeast direction. The flanks dip gently forty feet per mile to the south and steepen to 200 feet per mile to the west. Truncation on the north and east give the dome a "chopped" appearance.

Irving Syncline (6)

> A synclinal fold east of the Barneston or Abilene anticline and west of the Table Rock or Nemaha anticline in northern Kansas is called Irving.
>
> The Irving syncline was named by Condra and Upp (1931, p. 10); "The narrow trough between the Barneston arch and the Table Rock arch is herein named the Irving syncline from Irving, Kansas." Irving is in southern Marshall County. The axis of the syncline is shown extending from about the Riley-Marshall County line near Big Blue River northward a short distance into Nebraska (Jewett, 1951, p. 141).

The syncline is not apparent in the Precambrian rocks. The syncline is, therefore, probably due to thickening and thinning and to changes in the regional dip in rocks above the Precambrian granite (Koons, 1955).

TREND ANALYSIS

Each trend map and each corresponding third-degree residual map in this section will be covered with a discussion and evaluation of the analysis of variance and a comparison with known structural features.

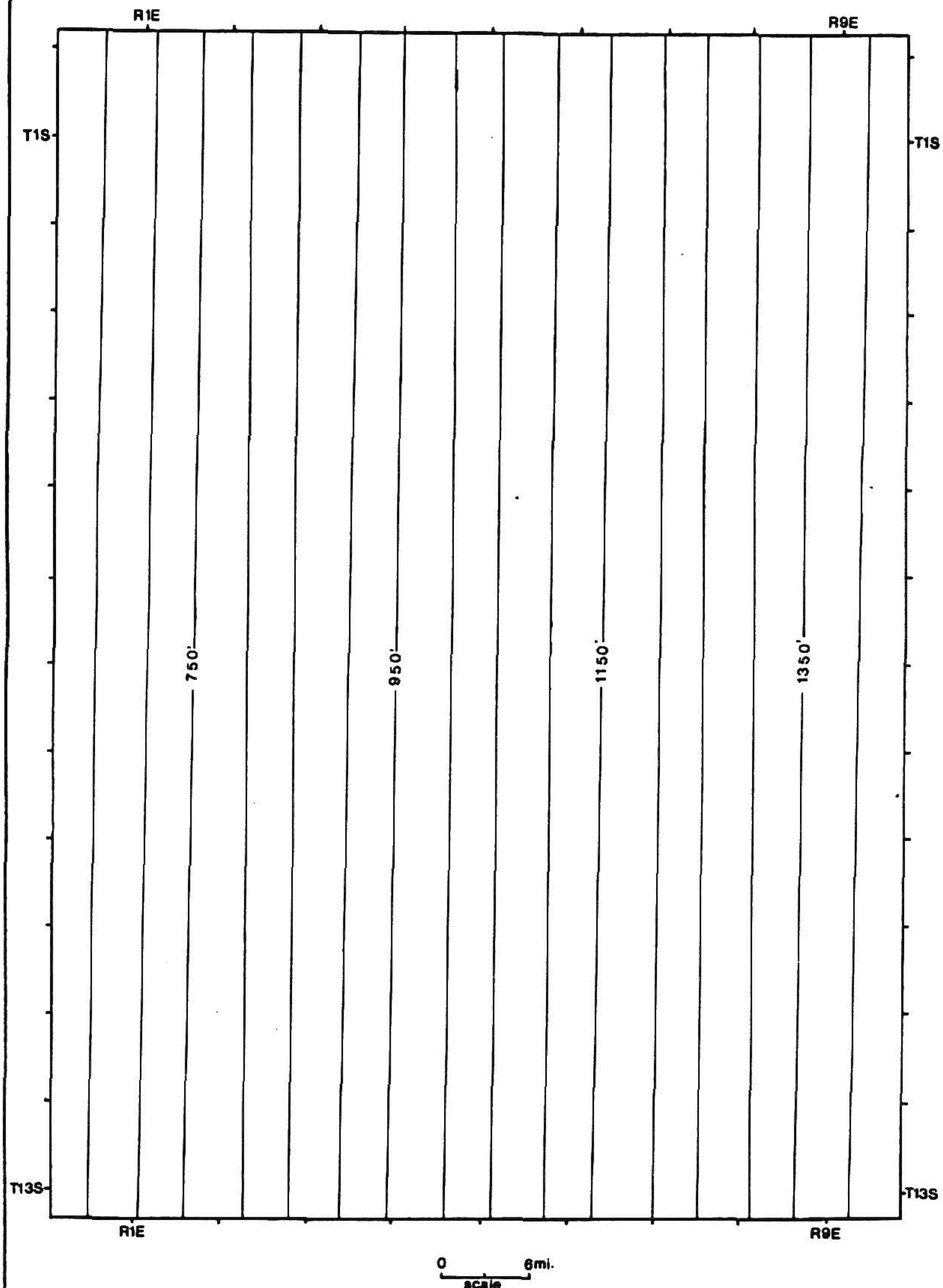
The error measures computed by the program and essential to this discussion are found in the appendix.

Structure on Top of The Easly Creek Shale

The percent total sum of squares for the structure on top of the Easly Creek Shale ranges from 94.6 percent for the first degree to 99.1 percent for the fifth degree trend-surface. A maximum significance level of 99.9 percent given by the F test occurs at all levels of the trend functions. The largest jump in percent total sum of squares, 1.8 percent, occurs at the third degree. Most of the trend-surface is accounted for by the linear component 94.6 percent total sum of squares, but with a substantial gain at the third degree, it is most probable that the third-degree surface represents the best fit to the real surface.

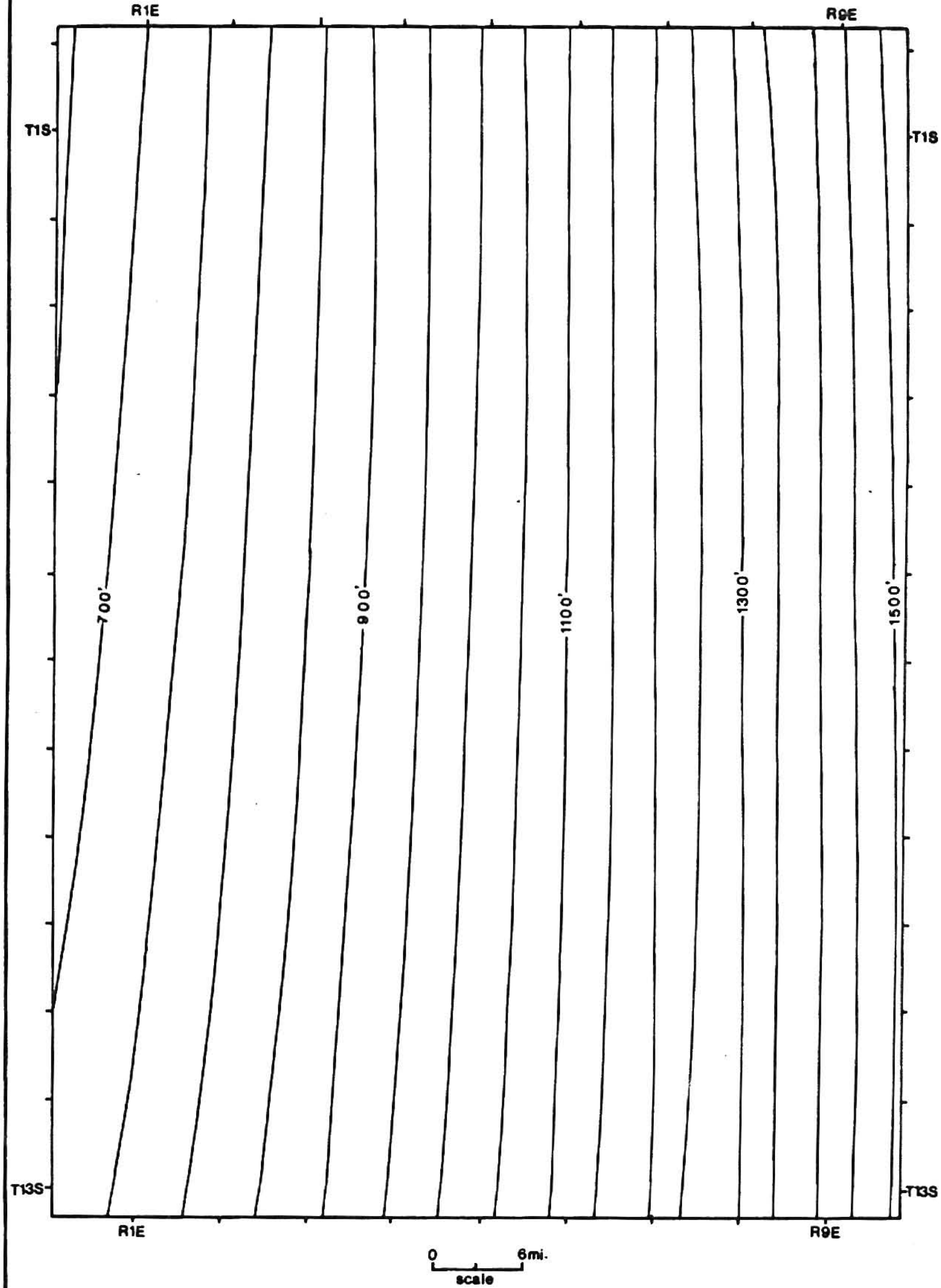
The first-degree surface (Fig. 5) indicates an almost north-south strike tending slightly to the east between one and five degrees. The dip ranges from about 13 to 14 feet per mile on the eastern edge of the map to 10 or 11 feet per mile on the western side. The dip is slightly west of north. The slight gain in dip to the east is most likely a result of the influence from the crest of the Abilene anticline.

As a whole, the third-degree structural map (Fig. 7) on top of the Easly Creek Shale parallels the approximate known strike and dip of the Abilene and Nemaha anticlines. The trends begin to bend slightly in a northwest-southeast direction in the lower southeast corner probably as a result of the influence of the Zeandale dome. The map fails in one respect,



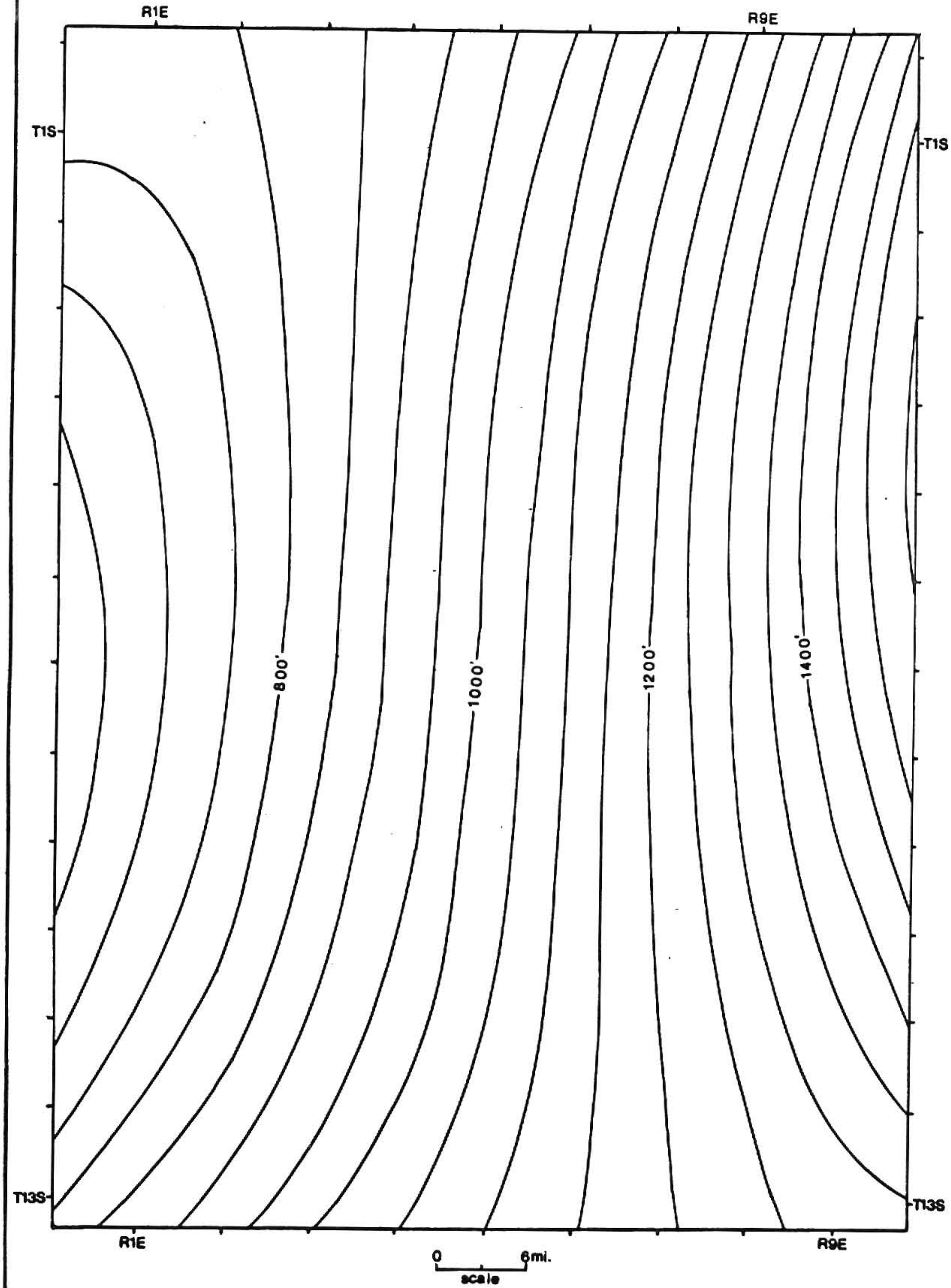
FIRST-DEGREE TREND SURFACE ON TOP OF EASLY CREEK SHALE

Figure 5



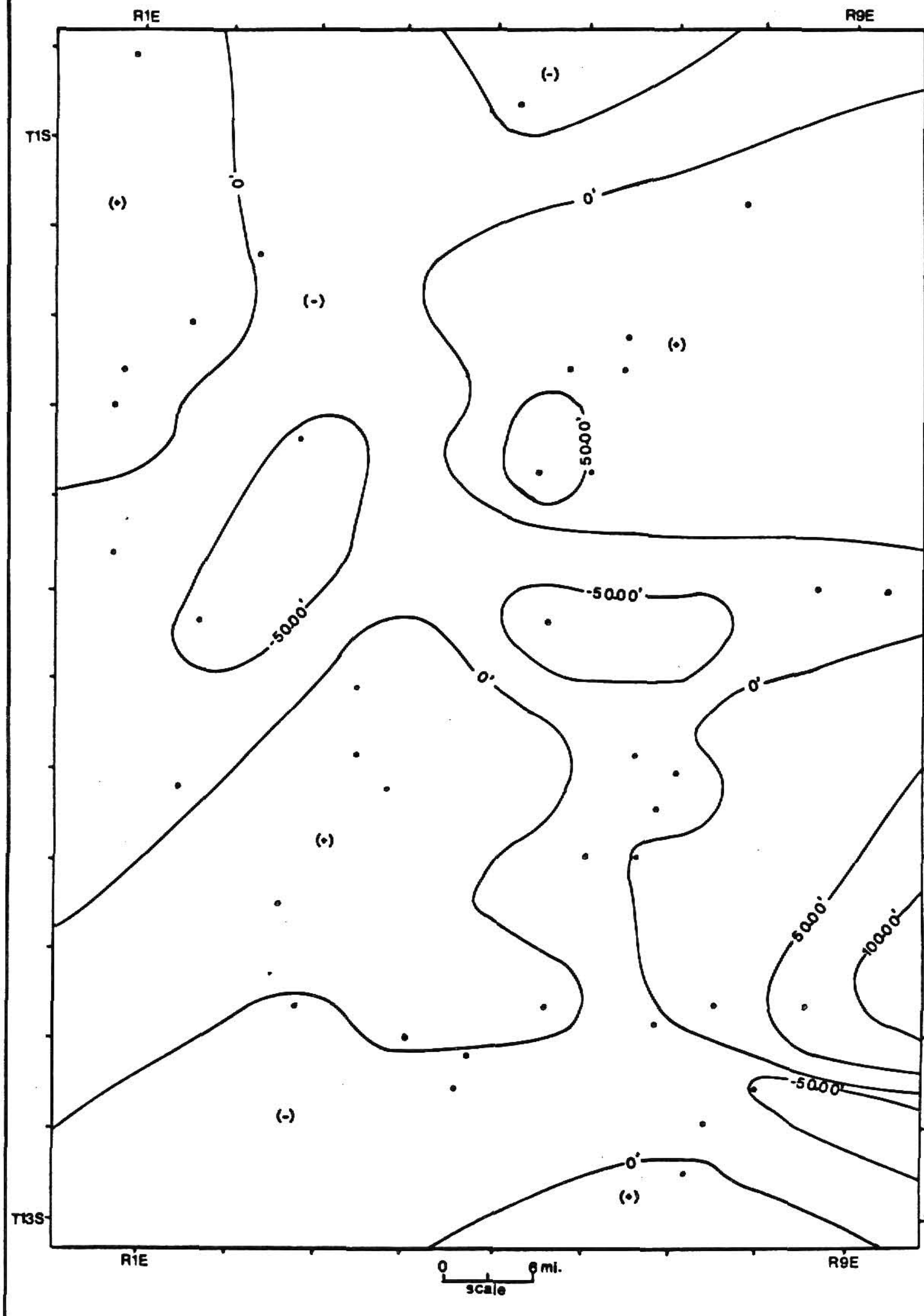
SECOND-DEGREE TREND SURFACE ON TOP OF EASLY CREEK SHALE

Figure 6



THIRD-DEGREE TREND SURFACE ON TOP OF EASLY CREEK SHALE

Figure 7



THIRD-DEGREE TREND SURFACE RESIDUALS ON TOP OF EASLY CREEK SHALE

Figure 8

to show any indication of the Irving syncline. This may be because the syncline does not have fifty feet of closure, the contour interval size used. There was no indication of the depth of the syncline given anywhere in the literature. The absence of the Irving also may be caused by a paucity of control in this area.

For standardization, the residuals from each of the plots from the third-degree trend surfaces (Figs. 8, 12, and 16) were contoured. Trend-surfaces higher than the third degree tend to lose the effect of the regional influence and assume the effect of the local influence.

The residuals from the structure on top of the Easly Creek (Fig. 8) closely approximate the local structure in the area. Both the Abilene and Nemaha anticlines are formed by a series of highs and lows running along their crests. The positive areas on the residual maps correspond with structural highs and the negative areas correspond to structural lows. The section of the Abilene anticline investigated appeared essentially as two highs separated by a low on the residual map.

The crest of the Nemaha anticline passes over two areas, a rather well pronounced high and a definite low. The high coincides with the location of the Zeandale dome. The strike of the dome due to a fault appears to be northwest-southeast (Koon, 1955). There is a general trend in this direction in the area of the dome, Sec. 34, T.10S, R.9E.

The only feature that is not brought out by the third-degree residuals is the Irving syncline in the northern portion of the map between the Abilene and Nemaha anticlines. This is again most likely due to the lack of control in this area.

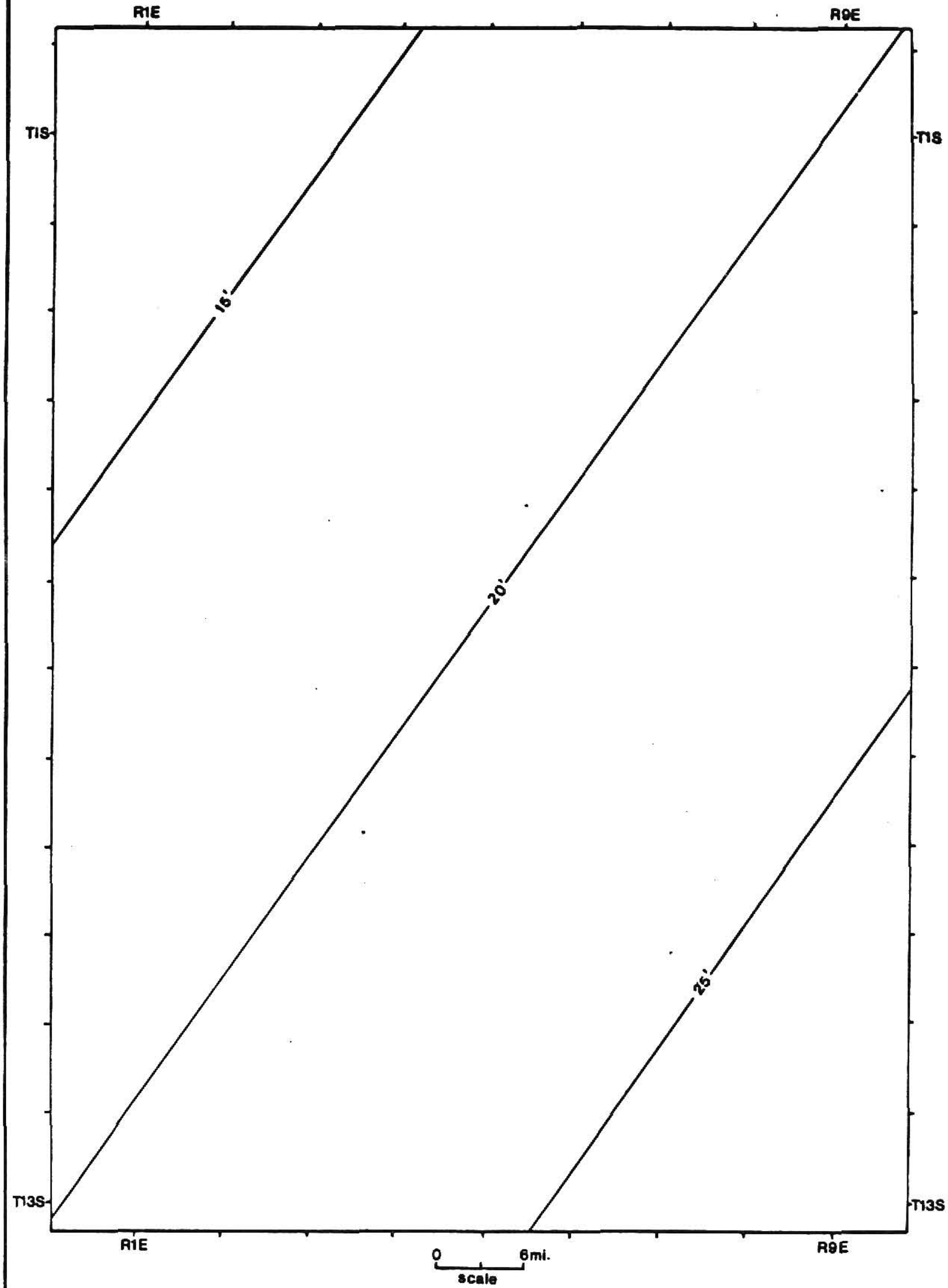
What is most striking about the residuals are the locations of the thickest known deposits of gypsum. The thickest deposit is a very pronounced high in the vicinity of the gypsum mine at Blue Rapids. Southwest of Blue Rapids along the anticlinal axis near Randolph lies another substantial thickness of gypsum. However, this deposit coincides with a structural low. A third area of gypsum lies even further southwest near Junction City and just southeast of the anticlinal axis in another structural high. Although these deposits fall on both structural highs and lows, there still is a correspondence to the axis of the Abilene anticline.

A very thin deposit, one foot thick, occurs very near the crest of the Nemaha anticline in the area of the Zeandale dome.

In summary then, the trend maps of the structure on top of the Easly Creek Shale and the third-degree residual seem to fit the structural trends and features with a high goodness of fit, and with a high degree of significance. The gypsum seems also to be following a pattern by its placement along the crest of the Abilene anticline and localized thicker deposits at or near the center of structural highs or lows.

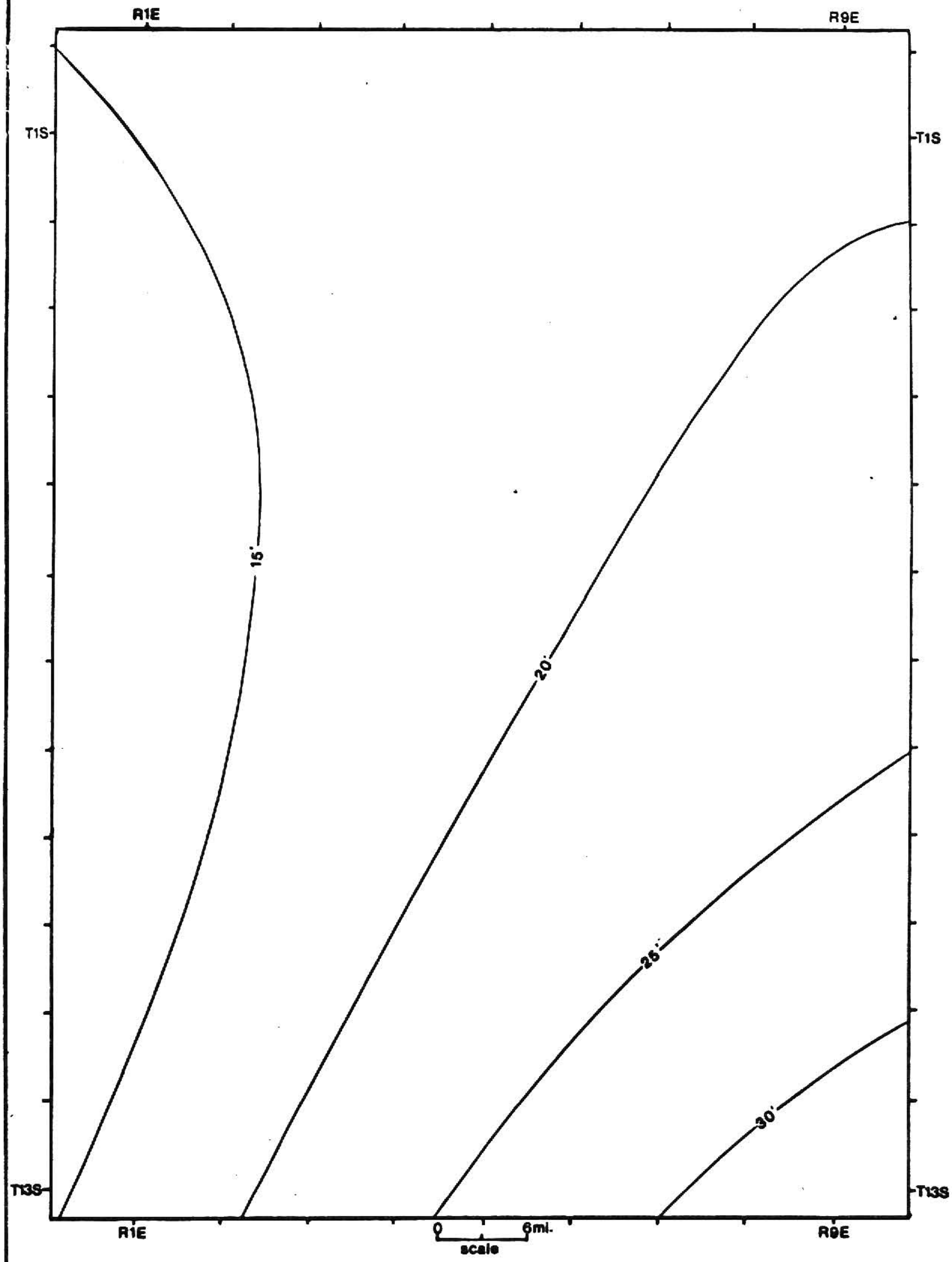
Thickness Map of The Easly Creek Shale

Trend surfaces from thickness data on the Easly Creek Shale (Figs. 9, 10, and 11) gave goodness of fit values ranging from 56.4 percent for the first degree to 80.5 percent total sum



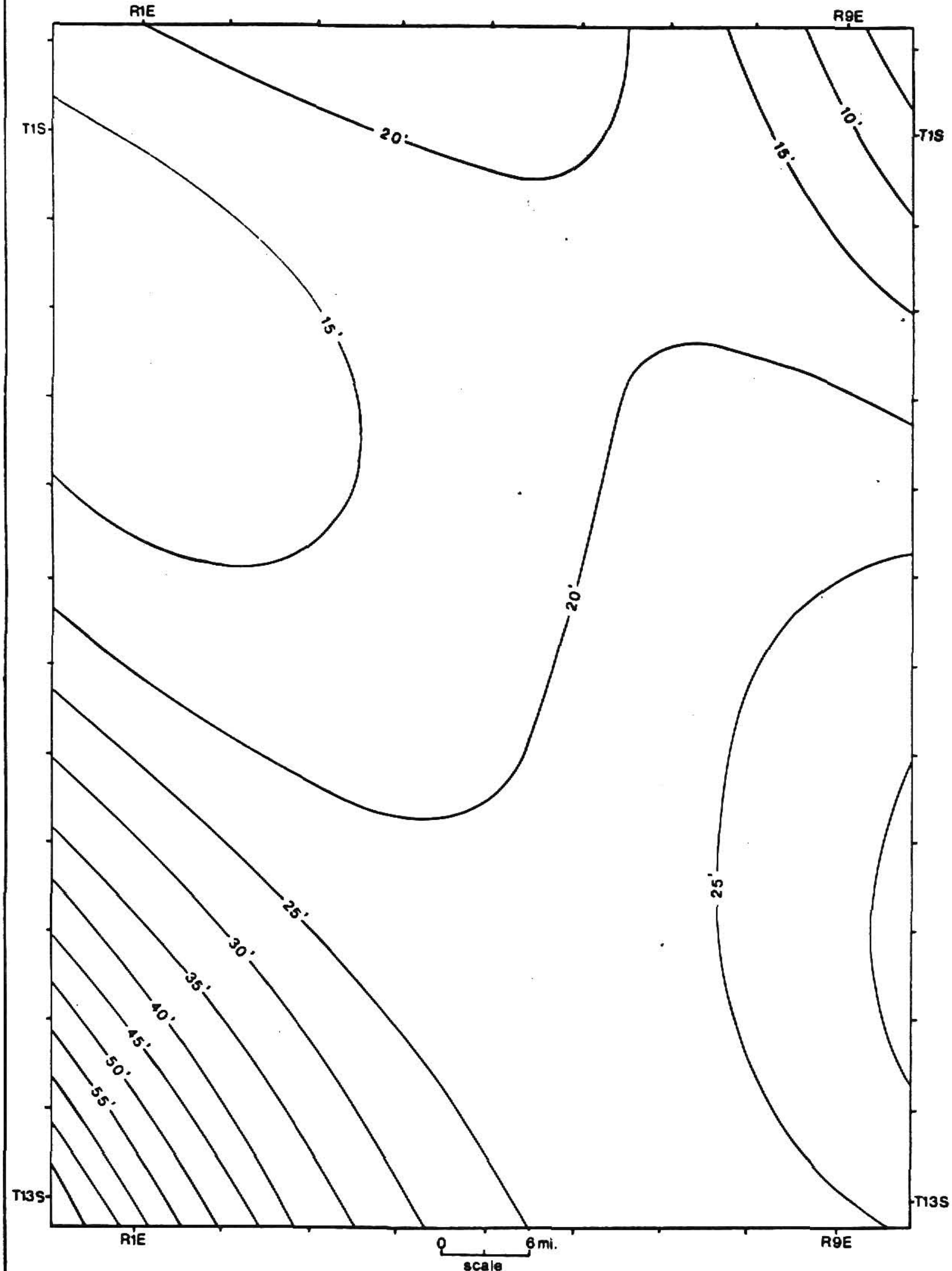
FIRST-DEGREE TREND SURFACE OF THICKNESS OF EASLY CREEK SHALE

Figure 9



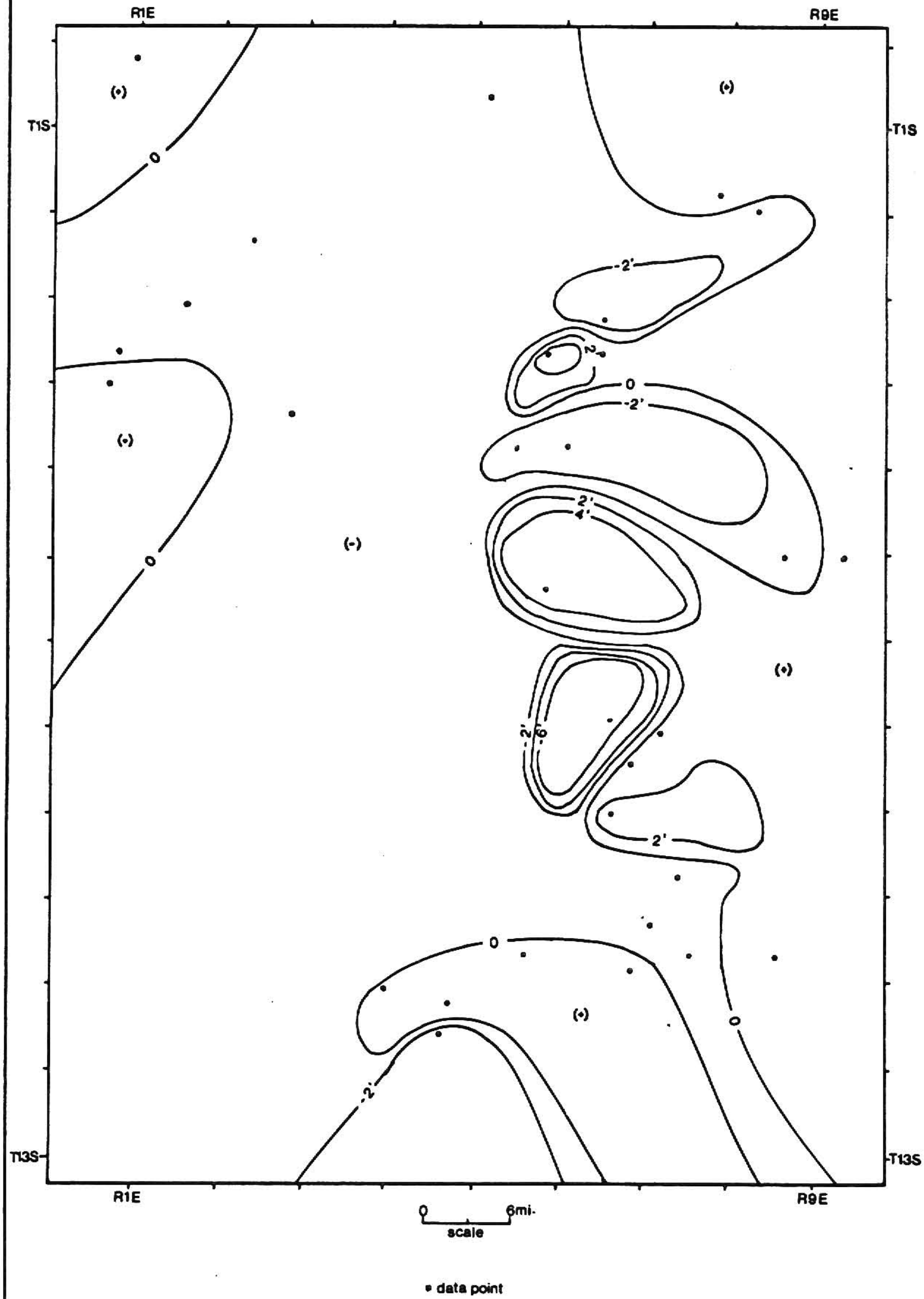
SECOND-DEGREE TREND SURFACE OF THICKNESS OF EASLY CREEK SHALE

Figure 10



THIRD-DEGREE TREND SURFACE OF THICKNESS OF EASLY CREEK SHALE

Figure 11



THIRD-DEGREE TREND SURFACE RESIDUALS FROM THICKNESS OF EASLY CREEK SHALE

Figure 12

of squares for the fifth degree. The third-degree surface showed the largest gain in goodness of fit, 11.6 percent. Maximum significance levels varied from 99.9 percent for the first degree to 50.0 percent at the fifth degree. The third degree trend surface, therefore, statistically represents the best fit. It not only accounts for 73.6 percent total sum of squares and a very substantial gain in percent total sum of squares, 14.9 percnet, but it also attains a maximum significance level of 99.9 percent.

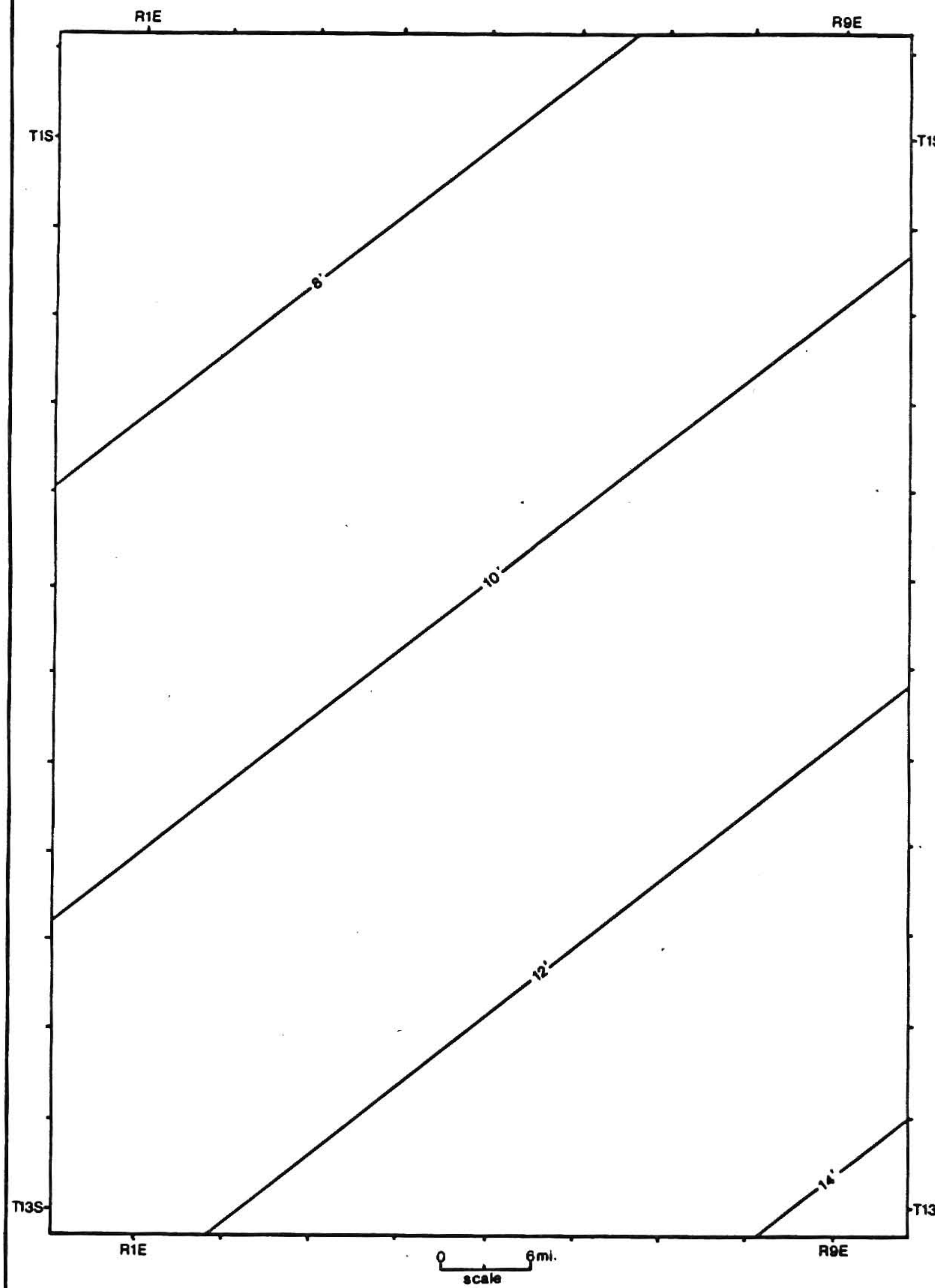
The trend on the linear surface shows a thinning to the northwest at approximately an angle parallel to that of the strike of the Abilene anticline. Overall, the total amount of thickening or thinning is very small plus or minus five feet. Therefore, the regional effect shown by the trend surfaces only indicate the major direction of thinning while the residual component points out the more important local variations in thickness.

Although the percent total sum of squares is quite substantial for these trend surfaces, the local features produced by the residuals (Fig. 12) create some confusion as to their interpretation. The axis of the Abilene anticline passes over three positive highs (areas of thickening) which are separated by negatives (areas of thinning). The region between the Abilene and Nemaha anticlines is a series of minuses and pluses running parallel to the strike of the anticlines. There is no real indication of a syncline between the anticlines, however, the Zeandale dome is associated with a definite thinning of the Easly Creek. This confusing pattern of positive and negative residuals is difficult to comprehend. It may in part be due to differing rates of sedimentation. With near shore or littoral deposits like the Easly Creek, (Kulstand, Fairchild and McGregor, 1956) rates of sedimentation, for all practical purposes, are impossible to evaluate. They are altered by marine, terrestrial and climatic factors all acting together. "...measurements in shallow water environments have only local significance (Kuenen, 1950, p. 385)." The irregularities may also be accounted for by differential compaction. Differential compaction is thought by many, (Kulstad, and others, 1956; Gasaway, 1959; and Koons, 1950) to be prevalent over the Nemaha anticline. Errors in well-log or core interpretations also may create the irregularities.

Although the map interpretations are somewhat confusing, the relation between the Easly Creek Shale thickness and the occurrence of gypsum is distinct. All three areas of the thickest deposits of gypsum fall very near or on the crest of definite positive areas or areas of thickenings. So it would seem that the gypsum is tending not only to fall along the axis of the Abilene anticline, but also in areas where the Easly Creek Shale is the thickest.

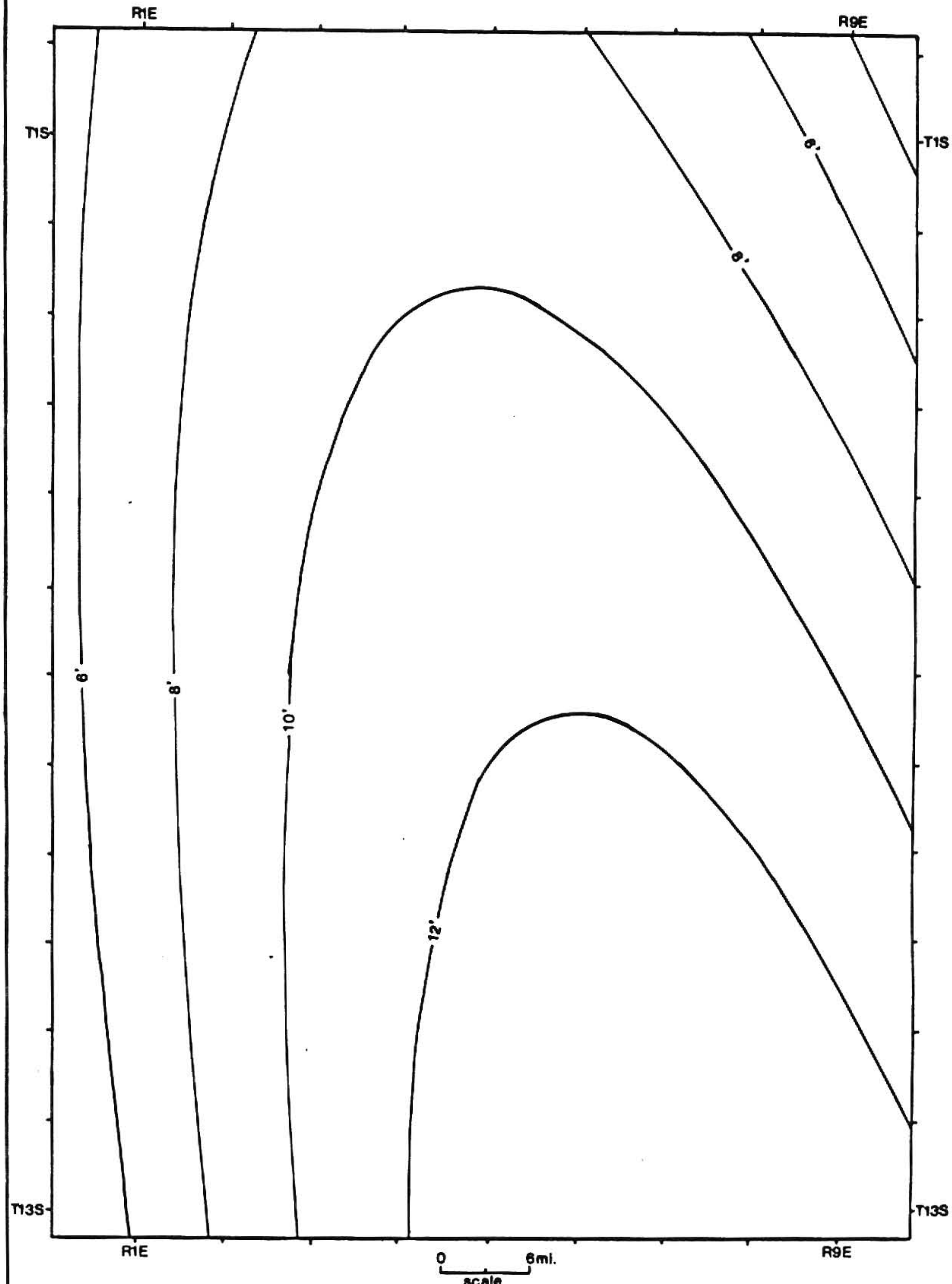
Thickness Maps of The Crouse Limestone

The Crouse Limestone, (Figs. 13, 14, and 15) as one would imagine, has similar trends to those of the Easly Creek Shale. The error measures, however, show a poor fit and a lower level of significance. The goodness of fit ranges from 26.3 percent



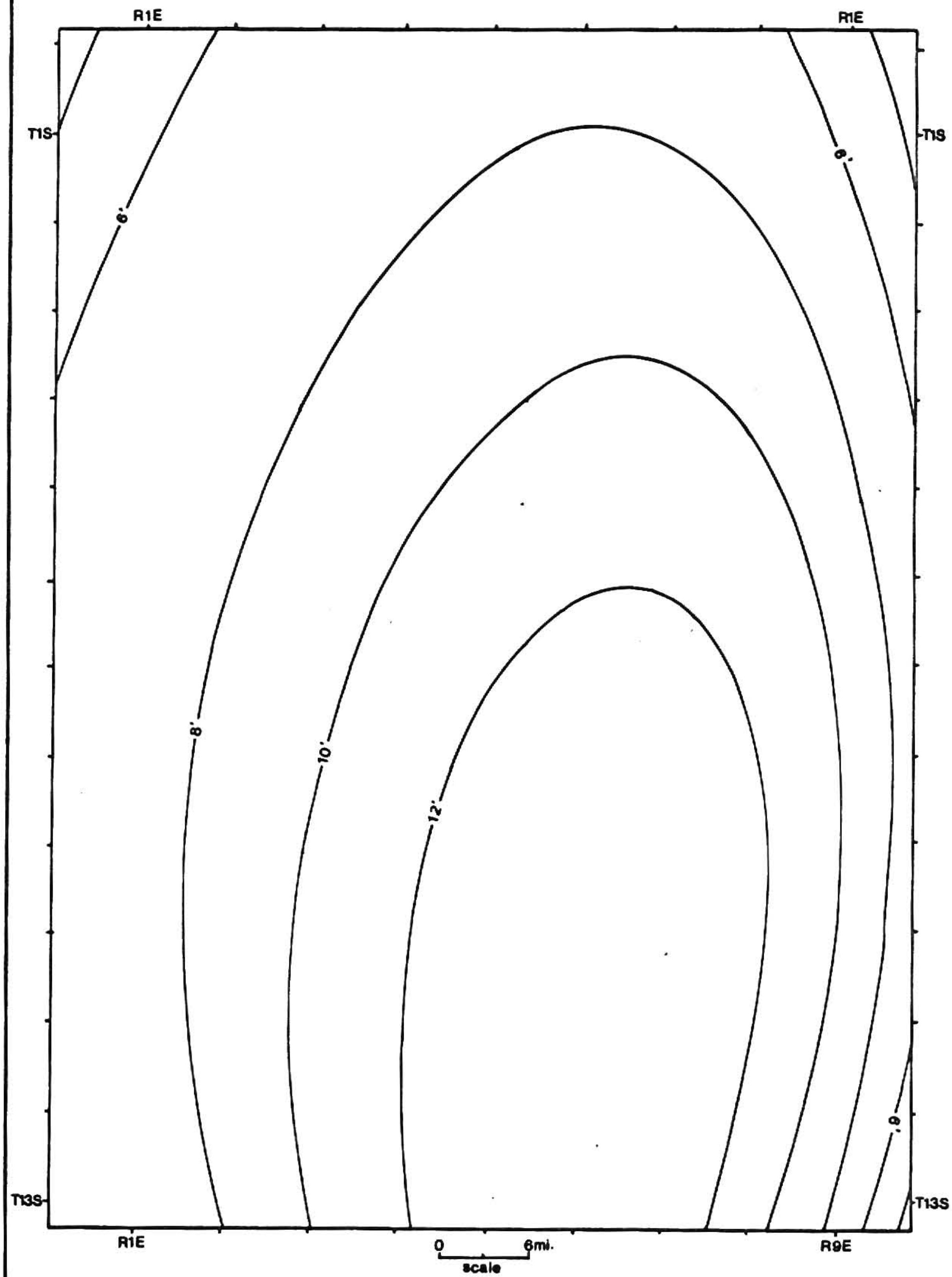
FIRST-DEGREE TREND SURFACE OF THICKNESS OF CROUSE LIMESTONE

Figure 13



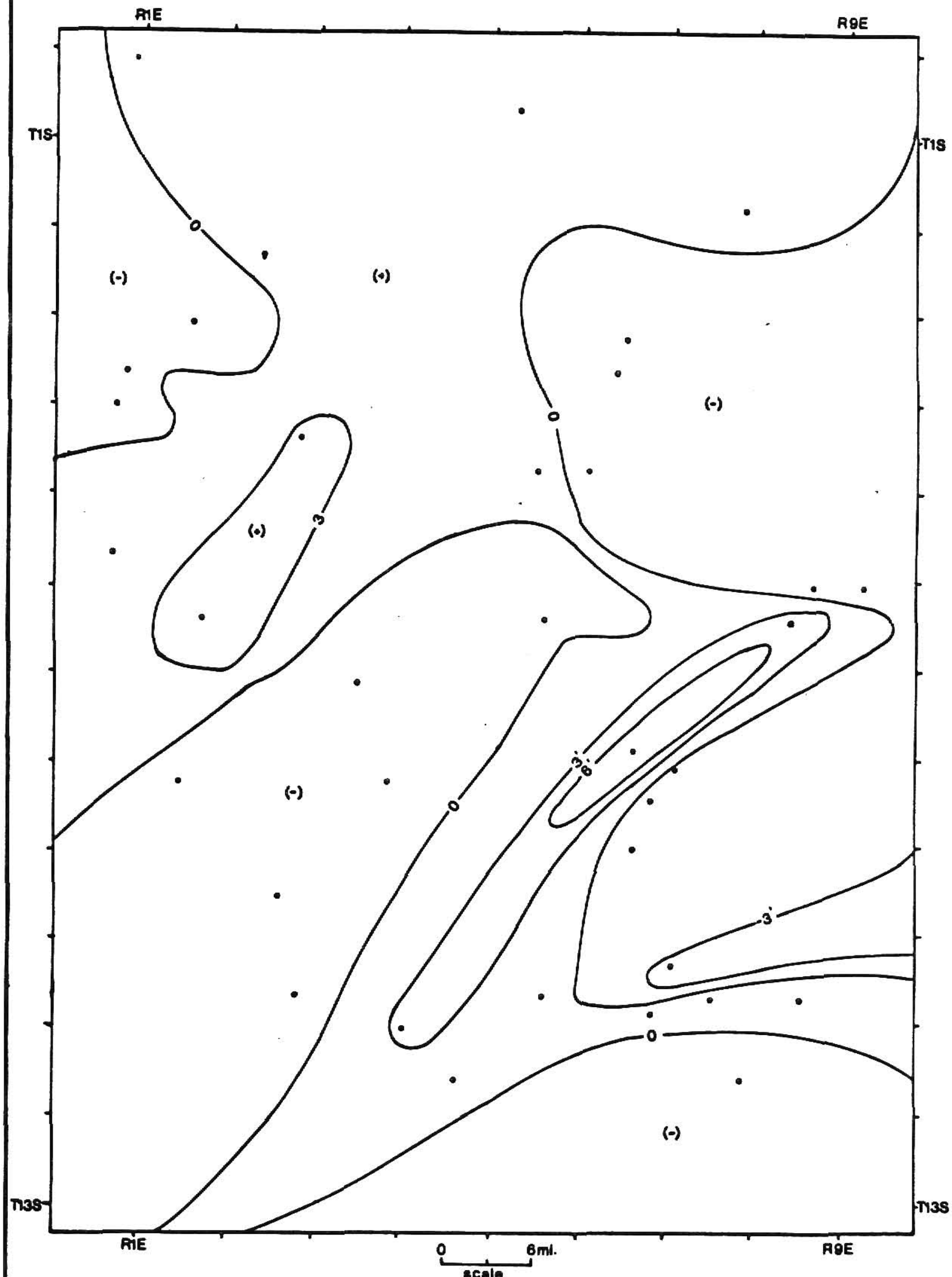
SECOND-DEGREE TREND SURFACE OF THICKNESS OF CROUSE LIMESTONE

Figure 14



THIRD-DEGREE TREND SURFACE OF THICKNESS OF CROUSE LIMESTONE

Figure 15



• data point

THIRD-DEGREE TREND SURFACE RESIDUALS FROM THICKNESS OF CROUSE LIMESTONE

Figure 16

total sum of squares for the first degree to 59.0 percent for the fifth degree. It, therefore, can be assumed that most of the surface is accounted for in the residuals. The significance levels indicate little reliability in the regression functions being reproducable. They ranged from 97.5 percent for the linear surface down to 25.0 percent for the quintic surface. The third-degree trend-surface accounts for only 40.5 percent total sum of squares, but still has a 75.0 percent maximum level of significance and so probably represents the nearest fit to the true surface.

As to why the statistical measures on these two formations should differ so widely when their trends are so similar lies not only in the fact that there is a lack of control for both maps, but also in fact that the thickness data for the Easly Creek Shale was very poorly distributed over the region.

The Crouse Limestone has an almost identical northwest thinning trend as the Easly Creek Shale. The cubic surface (Fig. 15) shows a rather steady thickness over the crest of the Abilene anticline, which also holds true for the Easly Creek Shale cubic surface.

Residuals from the third degree surface (Fig. 16) shows a band of minuses and pluses running between the Nemaha and Abilene anticlines similar to that of the Easly Creek Shale. The points of thinning and thickening do not coincide between the two formations. This most likely is due to a combination of a small amount of regional tilt and differing rates of sedimentation.

Since an isopach may be thought of as ...the structure on a lower surface at the time the upper surface was flat and horizontal (Lee, 1954), then the thinning of both the Crouse Limestone and the Easly Creek Shale indicate a definite tilting from the northwest, striking almost parallel to the axis of the Abilene and Nemaha anticlines. The irregularities between the two beds is local and due in all probability to a slight regional tilt accompanied by differing types and rates of sedimentation.

SUMMARY

Trend-surface mapping has proven to be an excellent means for discerning important facts from seemingly scant amounts of information. The trend surfaces and the residuals from the thickness and structure data of the Easly Creek Shale and Crouse Limestone represent a very close fit to the physical relationships in northeastern Kansas.

The trend surfaces computed from the structure on top of the Easly Creek Shale not only indicate a strong fit statistically, but also approximate the major regional trends and features. The contours drawn on the residual values have brought out all the local structural components except the Irving Syncline. The absence of the syncline is undoubtedly due to the large contour interval and the lack of data in the area.

The trend surfaces of the Easly Creek Shale thickness data have a very substantial statistical fit. The somewhat confusing pattern of thickening and thinning on the residual map is likely if the small contour interval is considered along with the number of possible factors that could create the situation, such as, differing rates of sedimentation, differential compaction and errors in data collection.

The trend surfaces of the Crouse Limestone are weak statistically, but the northwest thinning shown by the contours substantiate the trends of the Easly Creek Shale. The plots of the deviations also give confusing patterns as do the Easly Creek residuals. Reasons for the local patterns are similar to those of the Easly Creek Shale. They are probably due to some regional tilting affecting the rate of sedimentation, but may also be a result of differing climatic factors.

Even with the dissimilarities pointed out in the local features of the two formations, which are to be expected, the overall regional trends coincide.

What is most interesting to note from this study is the placement of gypsum along the axis of the Abilene anticline. The structure on top of the Easly Creek Shale shows deposits of gypsum at or near the center of residual highs or lows, and finally, the residuals from the isopachous map of the Easly Creek Shale suggest the largest deposits are associated with the thickest accumulations of the shale.

ACKNOWLEDGMENTS

No piece of research is ever really completed alone and it is with the greatest of pleasure and honor that I take in thanking all my committee members, Dr. J. Chelikowsky, Dr. P. Twiss, Mr. L. Riseman, and Dr. O. Bidwell, for their help in preparing this paper. I especially want to thank Drs. Chelikowsky and Twiss for their very kind concern and patience in seeing the degree completed.

To my wife, Kathy, without whose love, understanding, encouragement, patience and invaluable help none of this would ever be possible, I would like to express my love and thanks.

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APPENDIX

ILLEGIBLE DOCUMENT

THE FOLLOWING DOCUMENT(S) IS OF POOR LEGIBILITY IN THE ORIGINAL

THIS IS THE BEST COPY AVAILABLE

STRUCTURE ON TOP OF THE EASLY CREEK SHALE

Coefficients Of First-Degree Equation.

$$Z = 616.94667 + 14.20991x - 0.09955y$$

Coefficients Of Second-Degree Equation

$$Z = 717.01325 + 7.93167x - 1.49116y + 0.09323x^2 + 0.02274xy + 0.00641y^2$$

Coefficients Of Third-Degree Equation

$$Z = 794.96152 + 10.60053x - 11.01420y - 0.00245x^2 + 0.12395xy + 0.19480y^2 - 0.00053x^3 + 0.00357x^2y - 0.00383xy^2 - 0.00068y^3$$

Coefficients Of Fourth-Degree Equation

$$Z = -53.12780 + 66.51400x + 50.08308y - 1.509966x^2 - 1.79428xy - 1.77170y^2 + 0.01143x^3 + 0.04358x^2y + 0.01571xy^2 + 0.02930y^3 + 0.00005x^4 - 0.00041x^3y - 0.00001x^2y^2 - 0.00014xy^3 - 0.00016y^4$$

Coefficients Of Fifth-Degree Equation

$$Z = -4300.37008 + 393.71639x + 409.05222y - 9.79049x^2 - 24.90421xy - 12.22921y^2 + 0.07576x^3 + 0.50407x^2y + 0.59224xy^2 + 0.14000y^3 + 0.00063x^4 - 0.00467x^3y - 0.00671x^2y^2 - 0.00653xy^3 - 0.00017y^4 - 0.00001x^5 + 0.00003x^4y + 0.00001x^3y^2 + 0.00005x^2y^3 + 0.00002xy^4 - 0.00000y^5$$

ERROR MEASURES

Surface	First-Degree	Second-Degree	Third-Degree	Fourth-Degree	Fifth-Degree
D=	51.15	48.20	38.19	28.69	20.59
E=	1764107.0	1775229.0	1808100.0	1832232.0	1847[illegible]10.0
S=	99413.000	88290.875	55419.672	31287.336	16109.336
V=	1863520.0	1863520.0	1863520.0	1863520.0	1863520.0
T=	0.94665307	0.95262134	0.97026056	0.98321027	0.99135506
L=	0.97296101	0.97602326	0.98501807	0.99156958	0.99566817

D = Standard Deviation, E = Variation Explained By Surface, S = Variation Not Explained By Surface, V = Total Variation, T = Coefficient Of Determination, L = Coefficient Of Correlation.

ISOPACH MAP OF THE EASLY CREEK SHALE

Coefficients of First-Degree Equation

$$z = 19.87496 + 0.14993x + 0.10852y$$

Coefficients Of Second-Degree Equation

$$z = 14.37637 + 0.44379x + 0.17803y - 0.00194x^2 - 0.00319xy + 0.00238y^2$$

Coefficients Of Third-Degree Equation

$$z = 73.86727 - 2.85008x - 1.85003y + 0.04714x^2 + 0.07289xy + 0.01079y^2 - 0.00021x^3 - 0.00057x^2y - 0.00042xy^2 + 0.00005y^3$$

Coefficients Of Fourth-Degree Equation

$$z = -65.41947 + 6.33908x + 4.83755y - 0.14855x^2 - 0.20688xy - 0.012787y^2 + 0.00038x^3 + 0.00493x^2y + 0.00175xy^2 + 0.00161y^3 + 0.00001x^4 - 0.00004x^3y - 0.00001x^2y^2 - 0.00001xy^3 - 0.00001y^4$$

Coefficients Of Fifth-Degree Equation

$$z = -586.48009 + 49.14290x + 39.28323y - 1.37576x^2 - 2.47096xy - 0.83233y^2 + 0.01288x^3 + 0.05088x^2y + 0.05221xy^2 + 0.00111y^3 + 0.00010x^4 - 0.00067x^3y - 0.00039x^2y^2 - 0.00061xy^3 + 0.00015y^4 - 0.00000x^5$$

ERROR MEASURES

Surface	First-Degree	Second-Degree	Third-Degree	Fourth-Degree	Fifth-Degree
D=	3.29	3.07	2.56	2.37	2.20
E=	407.71533	448.26050	531.79443	558.90576	582.00024
S=	314.52686	273.98169	190.44766	163.3364	140.24174
V=	722.24219	722.24219	722.24219	722.24219	722.24219
T=	0.56451327	0.62065119	0.73631036	0.77384812	0.80582416
L=	0.75134099	0.78781420	0.85808527	0.87968636	0.89767706

D= Standard Deviation, E= Variation Explained By Surface, S= Variation Not Explained By Surface, V= Total Variation, T= Coefficients of Determination, L= Coefficients of Correlation.

ISOPACH MAP OF THE CROUSE LIMESTONE

Coefficients of First-Degree Equation

$$z = 11.28537 + 0.05240x - 0.06713y$$

Coefficients of Second-Degree Equation

$$z = 3.70183 + 0.46896x + 0.06338y - 0.00543x^2 - 0.00250xy - 0.00054y^2$$

Coefficients of Third-Degree Equation

$$z = 5.05378 + 0.21699x + 0.11025y + 0.00705x^2 - 0.00452xy - 0.00237y^2 - 0.00019x^3 + 0.00011x^2y - 0.00005xy^2 - 0.00002y^3$$

Coefficients of Fourth-Degree Equation

$$z = 22.81815 + 0.82212x - 2.67112y - 0.05764x^2 + 0.02884xy + 0.10841y^2 + 0.00142x^3 + 0.00025x^2y - 0.00106xy^2 - 0.00168y^3 - 0.00001x^4 - 0.00000x^3y$$

Coefficients of Fifth-Degree Equation

$$z = -242.07183 + 22.58903x + 18.72797y - 0.69687x^2 - 1.30976xy - 0.57649y^2 + 0.00305x^3 + 0.03312x^2y + 0.02573xy^2 + 0.00999y^3 - 0.00001x^4 - 0.00031x^3y - 0.00047x^2y^2 - 0.00020xy^3 - 0.00010y^4$$

ERROR MEASURES

Surface	First-Degree	Second-Degree	Third-Degree	Fourth-Degree	Fifth-Degree
D=	2.99	2.81	2.69	2.54	2.23
E=	108.56348	144.51025	167.12668	192.24591	243.40843
S=	303.83667	267.88989	245.27347	220.15424	168.99171
V=	412.40015	412.40015	412.40015	412.40015	412.40015
T=	0.26324791	0.35041267	0.40525365	0.46616352	0.59022391
L=	0.51307690	0.59195632	0.63659537	0.68276167	0.76826030

D= Standard Deviation, E= Variation Explained by Surface, S= Variation Not Explained by Surface, V= Total Variation, T= Coefficients of Determination, L= Coefficient of Correlation.

APPLICATIONS OF TREND-SURFACE ANALYSIS FOR: INVESTIGATION OF STRUCTURE AND PREDICTION OF GYPSUM OCCURRENCES IN NORTH-EASTERN KANSAS

by

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B.S., Bowling Green University, 1967

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ABSTRACT

A study of northeastern Kansas has been undertaken in an attempt to ascertain some meaningful relationships between the structure and the gypsum in the Easly Creek Shale. Maps have been prepared by trend-surface analysis using a computer program for computation and plotting of trend surfaces of degrees one through six. Trend maps of thicknesses and structural horizons of the Easly Creek Shale and Crouse Limestone have been computed. Contour maps of the third-degree residuals have also been prepared.

The structure in northeastern Kansas is controlled by the Nemaha anticline and the smaller, but contemporaneous Abilene anticline. Results from the trend analysis show a good response to these structural features and their trends. The trend surfaces, therefore, seem reliable for study.

Known gypsum deposits in the area are related to the structure. The third-degree residuals point to gypsum development in or near structural highs or lows along the axis of the Abilene anticline. The residuals from the isopachous map of the Easly Creek Shale suggest gypsum development in areas where the Easly Creek Shale is the thickest.

The trend surfaces of the thickness data of the Crouse Limestone and the Easly Creek Shale agree quite well. They both indicate thinning to the northwest. The residuals, however, from these two formations do differ. Their differences are local and are probably the result of three factors: distribution of data points, regional tilt and rates of sedimentation.