Trend-Surface Analysis of Regional and Residual Components of Geologic Structure in Kansas

```
STRUCTURE TOP MISSISSIPPIAN RCCKS IN WESTERN KANSAS - CI = 10C FEET

CONTOURS CF LINEAR + QUACRATIC + CUBIC TRENC SURFACE
X VALUE LEFT EDGE OF MAP =          .0       X VALUE RIGHT EDGE OF MAP =    171.0
Y VALUE BOTTOM EDGE OF MAP =     184.0       REFERENCE CONTCUR VALUE =   -1500.C
Y VALUE TOP EDGE OF MAP   =         .0       CONTOUR INTERVAL =            100.0
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SPECIAL DISTRIBUTION PUBLICATION 11

1864 - 1964
1889-1964

State Geological Survey
The University of Kansas, Lawrence, Kansas
1964

COMPUTER CONTRIBUTIONS

In 1963, the Kansas Geological Survey issued the first in a series of reports on computer applications in geology and related sciences. In addition to publishing the computer programs, it was planned that results of research using these new techniques be made available when completed. Several programs have been published and additional ones will be released as they become available. Because computer programs are obviously timely, a special editorial procedure has been set up for handling the manuscripts in order to make them available as rapidly as possible. A list of these publications and other computer contributions of interest are listed at the end of this Special Distribution Publication.

This paper reports the results of research based on a computer program developed earlier by J. W. Harbaugh ("BALGOL program for trend-surface mapping using an IBM 7090 computer", Special Distribution Publication 3 of the Kansas Geological Survey). Inasmuch as the program is economical to use and the technique already developed and available, it is suggested by the authors of the present paper that trend-surface analysis be carried out routinely by oil-exploration geologists.

The Kansas Geological Survey is making results of research in computer applications in the earth sciences available because of its continued role as a service to industry and the state. Every effort has been made to make the programs and results as usable as possible. Therefore, any comments or suggestions are welcomed and should be addressed to the editor.

The Editor

TREND-SURFACE ANALYSIS OF REGIONAL AND RESIDUAL COMPONENTS OF GEOLOGIC STRUCTURE IN KANSAS

by

Daniel F. Merriam and John W. Harbaugh

INTRODUCTION

This paper reports a study of the relationship between large-scale "regional" structural features and small-scale "residual" structural features. In areas of gently dipping strata, as in Kansas and surrounding states, small-scale structural features may have such small structural relief that they tend to be partly masked by structural features of regional magnitude. One method of accentuating the small-scale structural features is to subtract the regional component, leaving the residual component. In doing so, however, a problem arises in deciding how much of the structure is regional and how much is residual. Both the size of the area mapped and the density of control points affect the shape of the regional and residual surfaces.

Five areas (Fig. 1) of different geographic extent were studied in Kansas: (I) the entire state, (II) the northwestern part of the state, (III) an area in the southeastern part of the state, (IV) an area embracing Pratt County and parts of three adjacent counties in south-central Kansas, and (V) an area surrounding the Lost Springs oil-producing area in parts of Dickinson, Marion, and Morris Counties. The principal purpose was to compare regional and residual features in areas of different size and a second purpose was to study the relationship between residual features and oil fields. All basic data were obtained from well logs.

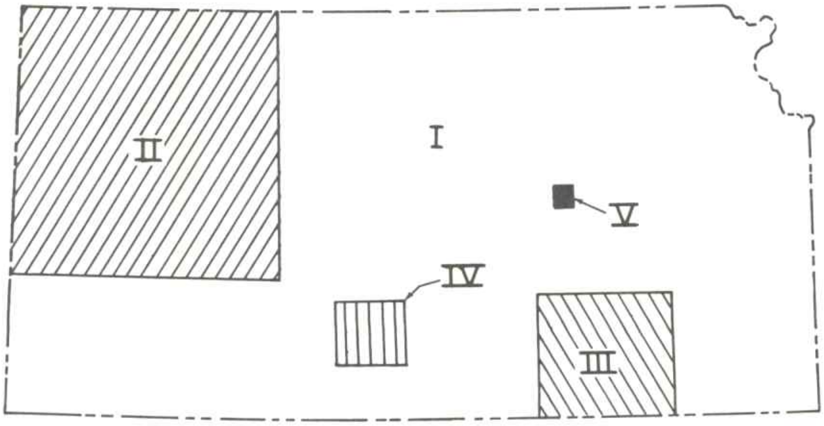

Figure 1.--Index map of Kansas showing location of five areas in which trend-surface analyses of geologic structure were made.

The practice of subtracting regional surfaces is not new. Geophysicists have done it for years, but geologists have made surprisingly little use of the method, although papers outlining its value have been published by Griswold and Munn (1907), Corbett (1919), Levorsen (1927), Rich (1935a, 1935b), and Lee and Payne (1944).

Until recently, regional dip was subtracted simply by fitting a homoclinal surface by eye. Now, however, regional dip may be represented by trend surfaces fitted by least-squares methods, which provide a much greater degree of rigor.

A number of papers have appeared which deal with application of trend surfaces to geologic and geochemical data (Allen and Krumbein, 1962; Baird, McIntyre, and Welday, 1963; Cain, 1964; Chayes and Suzuki, 1963; Connor and Miesch, 1964a, 1964b; Dawson and Whitten, 1962; Harbaugh, 1962; Jenness, 1963; Kofoed and Gorsline, 1963; Krumbein, 1956, 1958, 1959a, 1959b, 1960, 1962a, 1962b, 1963; Krumbein and Imbrie, 1963; Lippitt, 1959; Miesch and Connor, 1964; Miller, 1956, 1964; Nordeng, Ensign, and Volin, 1964; Peikert, 1962; Whitten, 1959, 1960a, 1960b, 1961a, 1961b, 1961c, 1961d, 1962a, 1962b, 1962c, 1963a, 1963b, 1963c). Most of these papers deal with trend surfaces applied to petrologic data or facies data. However, Forgotson (1963), Harbaugh (in press) Merriam (1964), Merriam and Harbaugh (1963), Merriam and Lippert (in press), and Wolfe (1962) suggest that trend surfaces fitted to structural data might aid in mineral exploration. Trend-surface computer programs available to the public have been written by Harbaugh (1963, 1964, in press), McIntyre (1963), Peikert (1963), and Whitten (1963d).

Equations and Degree of Trend Surfaces

Trend surfaces are described by equations in which a dependent variable is a function of two independent variables. The mathematical operations of trend-surface fitting consist of finding the constants (A, B, . . .,J in Table 1) such that the least-squares criterion is satisfied. In fitting a trend surface to structural data, the dependent variable, z, represents elevation and the independent variables, x and y, represent map coordinates measured from some arbitrary origin. The map coordinates may be in miles, feet, inches, or any arbitrary unit. We have found tenths of an inch scaled directly from maps to be convenient.

Table 1. General classification of trend-surface equations in which components are grouped according to degree. Letters A through J represent constants of equations, and x and y represent independent variables; z is dependent variable.

Surface	Dependent variable, elevation	Linear component	Quadratic component	Cubic component
First degree (plane)	$z =$	$A + Bx + Cy$		
Second degree (paraboloid)	$z =$	$A + Bx + Cy$	$+ Dx^2 + Exy + Fy^2$	
Third degree	$z =$	$A + Bx + Cy$	$+ Dx^2 + Exy + Fy^2$	$+ Gx^3 + Hx^2y + Ixy^2 + Jy^3$

Trend surfaces may be classified according to degree. In this study, first-, second-, and third-degree surfaces were fitted. Terms in the generalized equations of these surfaces are classified in Table 1. A first-degree surface is a plane and contains only linear terms, whereas generalized second-degree surfaces, containing both quadratic and linear terms, are either bowl-shaped or saddle-shaped paraboloids. Generalized third-degree surfaces are more complex and contain cubic, quadratic, and linear terms.

Criterion of Least Squares

In the least-squares method, the objective is to make the sum of the squared residual values the least possible. If a trend surface of given order is fitted in this manner, its shape and position are unique in that no other configuration will satisfy the least-squares criterion. A trend surface fitted by least squares passes below some data points and above others. Each residual value is the difference, positive or negative, between the trend surface and the actual surface at each data point.

Quality of Fit of Trend Surfaces

The goodness of fit of a trend surface may be expressed as the percentage reduction in the total sum of squares, which is given by the expression:

$$100 \times \frac{\Sigma x_{trend}^{2} - \frac{(\Sigma x_{trend})^{2}}{n}}{\Sigma x_{obs}^{2} - \frac{(\Sigma x_{obs})^{2}}{n}},$$

where

x_{trend} = values on trend surface at location of data points,
x_{obs} = observed data values, and
n = number of data values.

The percent of total sum of squares is automatically calculated by the computer program used (Table 2). A perfect fit of the trend surface to the data points would be 100 percent of the total sum of squares. For example, in the application in south-central Kansas, the linear surface accounts for about 94.4 percent of total sum of squares, and the improvement gained by incorporating the quadratic and cubic components in the second- and third-degree surfaces is 0.7 and 2.3 respectively (Table 3). Although the improvement in fit is small, the quadratic and cubic components have confidence levels about 98 and 95 percent respectively (Table 3). Stated differently, we can be about 98 percent confident that the improvement in fit offered by the quadratic component is due to a real effect and not to chance alone, and 95 percent confident in the case of the cubic component.

Selection of Data Points

In fitting trend surfaces, it is desirable that the data points be more or less evenly distributed within the mapped area. They should not be clustered in some places and spread far apart elsewhere, because clustered data points give undue influence to the areas containing them relative to areas in which the points are far apart. Of course, spacing of wells is usually extremely uneven, being close together in oil fields and far apart between fields. In this study,

Table 2.--Example of actual computer printout using Harbaugh (1963) program, listing: (1) matrix and column vector values, (2) equation coefficients, (3) statistical properties, (4) volumes, mean, and spatially weighted average values, and (5) original and calculated data values. Data are for top of Arbuckle over entire state.

```
STRUCTURE TOP ARBUCKLE (CAMBRO-ORDOVICIAN) ROCKS IN KANSAS  CI = 500 FT

10 X 10 (X,Y) MATRIX VALUES

   2.000, 02   4.686, 03   2.873, 03   1.444, 05   7.096, 04   5.121, 04   5.040, 06   2.249, 06   1.289, 06   1.001, 06

   4.686, 03   1.444, 05   7.096, 04   5.040, 06   2.249, 06   1.289, 06   1.902, 08   7.994, 07   4.147, 07   2.545, 07

   2.873, 03   7.096, 04   5.121, 04   2.249, 06   1.289, 06   1.001, 06   7.994, 07   4.147, 07   2.545, 07   2.068, 07

   1.444, 05   5.040, 06   2.249, 06   1.902, 08   7.994, 07   4.147, 07   7.589, 09   3.059, 09   1.492, 09   8.272, 08

   7.096, 04   2.249, 06   1.289, 06   7.994, 07   4.147, 07   2.545, 07   3.059, 09   1.492, 09   8.272, 08   5.289, 08

   5.121, 04   1.289, 06   1.001, 06   4.147, 07   2.545, 07   2.068, 07   1.492, 09   8.272, 08   5.289, 08   4.443, 08

   5.040, 06   1.902, 08   7.994, 07   7.589, 09   3.059, 09   1.492, 09   3.157, 11   1.236, 11   5.768, 10   3.005, 10

   2.249, 06   7.994, 07   4.147, 07   3.059, 09   1.492, 09   8.272, 08   1.236, 11   5.768, 10   3.005, 10   1.734, 10

   1.289, 06   4.147, 07   2.545, 07   1.492, 09   8.272, 08   5.289, 08   5.768, 10   3.005, 10   1.734, 10   1.141, 10

   1.001, 06   2.545, 07   2.068, 07   8.272, 08   5.289, 08   4.443, 08   3.005, 10   1.734, 10   1.141, 10   9.833, 09
1 X 10 COLUMN VECTOR VALUES


  -4.177, 05  -8.622, 06  -6.399, 06  -2.330, 08  -1.325, 08  -1.198, 08  -7.091, 09  -3.528, 09  -2.465, 09  -2.436, 09

EQUATION COEFFICIENTS
LINEAR, Z =  -2225.52916+    39.37789X +   -54.68865Y

LIN   + QUAD, Z =  -1050.78693+  -104.38976X +    18.30625Y +      1.72457X2 +      4.09030XY +     -6.05900Y2

LIN + QUAD + CUB, Z = -1669.44869+     11.64578X +    -29.99471Y +      -.85848X2 +     -3.54274XY +      3.92624Y2
         +      .00090X3   +       .16755X2Y +     -.01050XY2 +      -.24554Y3

ERROR MEASURE LINEAR TREND SURFACE =                        533444.44

ERROR MEASURE QUADRATIC TREND SURFACE =                     212633.24

ERROR MEASURE CUBIC TREND SURFACE =                         159194.43

PERCENT TOTAL SUM SQUARES LINEAR SURFACE =                      37.37

PERCENT TOTAL SUM SQUARES QUADRATIC SURFACE =                   75.04

PERCENT TOTAL SUM SQUARES CUBIC SURFACE =                       81.31


SUM OF SQUARES DUE LINEAR COMPONENT =                   940015770.00

SUM OF SQUARED DEVIATIONS FROM LINEAR =                 106155445.00

SUM OF SQUARES DUE LINEAR + QUADRATIC COMPONENT =      1003857640.00

SUM OF SQUARES DUE TO QUADRATIC ALONE =                  63841880.10

SUM OF SQUARED DEVIATIONS FROM LINEAR + QUADRATIC =      42314014.50

SUM OF SQUARES DUE LINEAR+QUADRATIC+CUBIC =            1014491670.00

SUM OF SQUARED DEVIATIONS FROM LINEAR+QUADRATIC+CUBIC =  31679692.40

SUM OF SQUARES DUE CUBIC ALONE =                         10634031.90


VOLUME BENEATH LINEAR SURFACE =          -2613253.74

VOLUME BENEATH LIN+QUAD SURFACE =        -2675637.68

VOLUME BENEATH LIN+QUAD+CUB SURFACE =    -2722376.32

ARITH. MEAN Z, = SUM OF Z VALUES/ N   =       -2088.41

AVERAGE Z VALUE, LINEAR SURFACE =           -1918.13

AVERAGE Z VALUE, LIN+QUAD SURFACE =         -1963.91

AVERAGE Z VALUE, LIN+QUAD+CUB SURFACE =     -1998.22

AREA OF MAP IN SQUARED UNITS                 1362.40

    XCOORD  YCOORD Z-VALUE 1ST-TRD 1ST-RSD 2ND-TRD 2ND-RSD 3RD-TRD 3RD-RSD

5     16.7      8.7 -1709.0 -2039.6   330.6 -2018.0   309.0 -1955.8   246.8
5     12.1     18.0 -2934.0 -2733.4  -200.6 -2806.8  -127.2 -2726.8  -207.2
5     23.4     22.1 -2951.0 -2514.3  -446.7 -2991.3    30.3 -3178.3   217.3
5     29.8     10.6 -2240.0 -1630.7  -609.3 -1825.0  -415.0 -1807.4  -432.6
5     13.2      3.9 -1478.0 -1920.9   442.9 -1937.1   459.1 -1806.1   328.1
5     22.2     16.2 -1872.0 -2240.3   368.3 -2345.1   473.1 -2325.9   453.9
5     12.3      4.8 -1826.0 -2002.7   176.7 -1885.7    59.7 -1826.1      .0
5     22.0      3.4 -2584.0 -1542.6 -1041.4 -2217.4  -366.6 -1877.1  -706.9
5     14.2     17.1 -2810.0 -2604.0  -206.0 -2655.1  -154.9 -2597.5  -212.5
5     10.8      1.3 -1477.0 -1870.5   393.5 -1908.2   431.2 -1701.2   224.2
```

Table 3.--Number of control points, percent of total sum of squares, and confidence limits of components, of all trend surfaces in this study.

		I Entire state of Kansas				II Northwestern Kansas						III South-eastern Kansas	IV Pratt County Kansas	V Lost Springs Area Kansas
Geologic horizon mapped		Top Lansing Group	Top Mississippian	Top Arbuckle Group	Top Precambrian	Top Dakota Group	Top Stone Corral Formation	Top Lansing Group	Top Mississippian	Top Arbuckle Group	Top Precambrian	Top Mississippian	Top Lansing Group	Top Pennsylvanian Conglomerate
Number of control points		200	200	200	214	131	122	120	110	117	51	125	90	48
Percent of total sum of squares represented by each surface	First degree	41.3	51.4	37.4	23.1	85.0	76.7	76.6	25.0	75.3	56.8	88.6	94.4	91.0
	Second degree	83.6	89.6	75.0	44.2	95.3	93.1	92.6	69.7	85.8	62.9	95.9	95.1	92.0
	Third degree	96.1	95.4	81.3	53.8	97.3	96.7	94.2	76.2	86.7	73.8	97.1	96.7	92.5
Confidence levels in percent	Linear component	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9
	Quadratic component	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	90.0	99.9	98.0	80.0
	Cubic component	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	85.0	99.5	99.9	95.0	50.0

a specified number of wells in each township was selected. Within each township, however, individual wells were selected by using pairs of coordinate values taken from random number tables and then choosing the well closest to the location specified by each coordinate pair.

Computation of Trend Surfaces

The trend-surface program, written in ALGOL-58 (BALGOL), was developed by Harbaugh (1963) and Peter Carah at the Computation Center at Stanford University. The program may be used on IBM 7090 and 7094 computers. On an IBM 7090, the program compiles from the original source program in about 18 seconds, and requires about 30 seconds to perform all calculations in a typical application involving 200 data points. For about $3.00 in computer costs, computations can be made that would require perhaps one hundred hours of labor by a skilled desk-calculator operator.

```
STRUCTURE TOP ARBUCKLE (CAMBRO-ORDOVICIAN) ROCKS IN KANSAS  CI = 500 FT

CONTOURS OF LINEAR TREND SURFACE
X VALUE LEFT EDGE OF MAP =         .0       X VALUE RIGHT EDGE OF MAP =    52.0       Y VALUE TOP EDGE OF MAP  =        .0
Y VALUE BOTTOM EDGE OF MAP =    26.2        REFERENCE CONTOUR VALUE =   -2000.0       CONTOUR INTERVAL =               500.0
```

```
STRUCTURE TOP ARBUCKLE (CAMBRO-ORDOVICIAN) ROCKS IN KANSAS  CI = 500 FT

CONTOURS OF LINEAR + QUADRATIC TREND SURFACE
X VALUE LEFT EDGE OF MAP =         .0       X VALUE RIGHT EDGE OF MAP =    52.0       Y VALUE TOP EDGE OF MAP  =        .0
Y VALUE BOTTOM EDGE OF MAP =    26.2        REFERENCE CONTOUR VALUE =   -2000.0       CONTOUR INTERVAL =               500.0
```

```
STRUCTURE TOP ARBUCKLE (CAMBRO-ORDOVICIAN) ROCKS IN KANSAS  CI = 500 FT

CONTOURS OF LINEAR + QUADRATIC + CUBIC TREND SURFACE
X VALUE LEFT EDGE OF MAP =         .0       X VALUE RIGHT EDGE OF MAP =    52.0       Y VALUE TOP EDGE OF MAP  =        .0
Y VALUE BOTTOM EDGE OF MAP =    26.2        REFERENCE CONTOUR VALUE =   -2000.0       CONTOUR INTERVAL =               500.0
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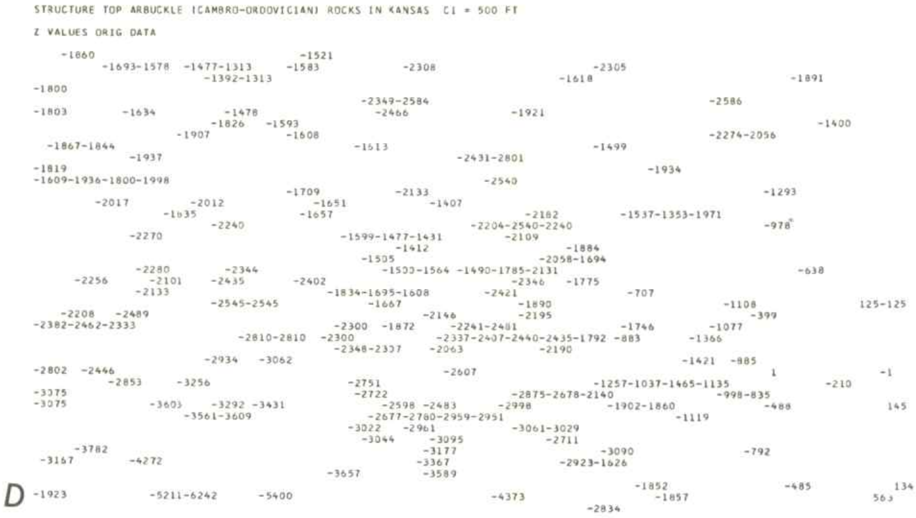
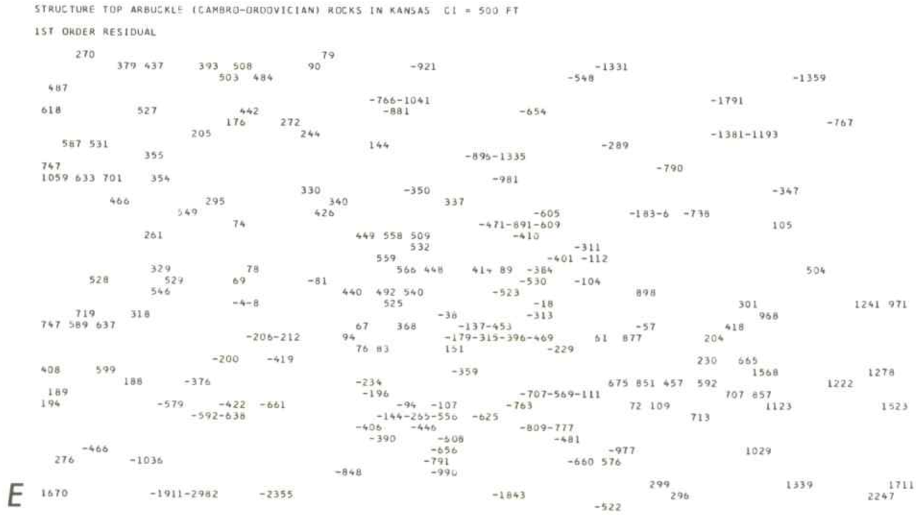
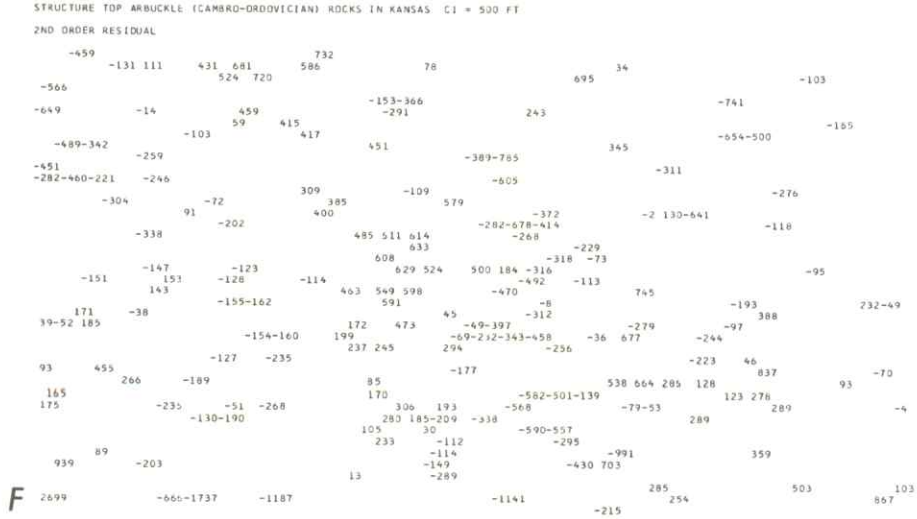
Figure 2. -- Example of maps made by computer: (A) first-degree trend surface in Kansas; (B) second-degree trend surface; (C) third-degree trend values of first-degree trend surface; (F) second-degree residuals;







fitted to structure on top of Arbuckle (Cambrian-Ordovician) rocks surface; (D) plot of original data values; (E) plot of residual third-degree residuals not shown.

The program is versatile in that it will accept irregularly spaced data points. The program (Table 2) fits first-, second-, and third-degree trend surfaces and (1) prints out the equation of each trend surface, (2) calculates statistical properties of each surface, and (3) lists the original data as well as the residual values. The program then (4) contours the trend surfaces and (5) plots original data and residual values (Fig. 2). A complete listing of the program, as well as instructions for its use, are given by Harbaugh (1963).

Acknowledgments.--The authors thank the Computation Center of Stanford University and acknowledge support of Stanford's Computation Center by the National Science Foundation through Grant NSF-GP948. The manuscript was read by E. D. Goebel, W. C. Pearn, F. W. Preston, and G. F. Stewart.

ENTIRE STATE - AREA I

General Statement

Trend surfaces were fitted to structure as interpreted on top of the Lansing Group (Pennsylvanian), Mississippian rocks, Arbuckle Group (Cambrian-Ordovician), and Precambrian rocks over the entire state of Kansas, an area of slightly more than 82,000 square miles. Approximately 200 randomly located control points were used for each trend map (Table 3); as an example, location of points for the Lansing map are shown in Figure 3B. First-, second-, and third-degree trend surfaces were fitted to the data, and second-degree residuals were contoured by hand for comparison with the actual structure (Fig. 3). Data on goodness of fit and confidence levels of components are given in Table 3.

The major late Paleozoic structural features of Kansas (Fig. 3A) include the Nemaha Anticline, which separates the Forest City and Cherokee Basins on the east from the Salina and Sedgwick Basins on the west, and the Central Kansas Uplift and Pratt Anticline, which separate the Salina and Sedgwick Basins to the east from the Hugoton Embayment to the west. The Cambridge Arch lies northwest of the Central Kansas Uplift. These features developed mainly in the late Paleozoic and have remained essentially unchanged except for subsequent tilting and gentle warping (Merriam, 1963).

Trend-Surface Analysis

First-degree surfaces.--First-degree trend surfaces fitted to the four horizons all slope toward the southwest (Fig. 3). The slope of each horizon, except for the Precambrian, becomes successively greater with increasing geologic age (Table 4), reflecting increased structural complexity with depth. The lesser slope of the Precambrian results from the paucity of deep wells which penetrate the Precambrian in the southwestern part of the state. The range of elevations for each horizon is also given in Table 4. If more data were available, the range for the Precambrian would be approximately 7,500 feet (interpreted from Cole, 1962) rather than 4,960 feet. Accordingly, the slope of the Precambrian first-degree trend surface would be greater than that of the Arbuckle. The percent of total sum of squares of the first-degree surfaces ranges from about 23 to 51 (Table 3).

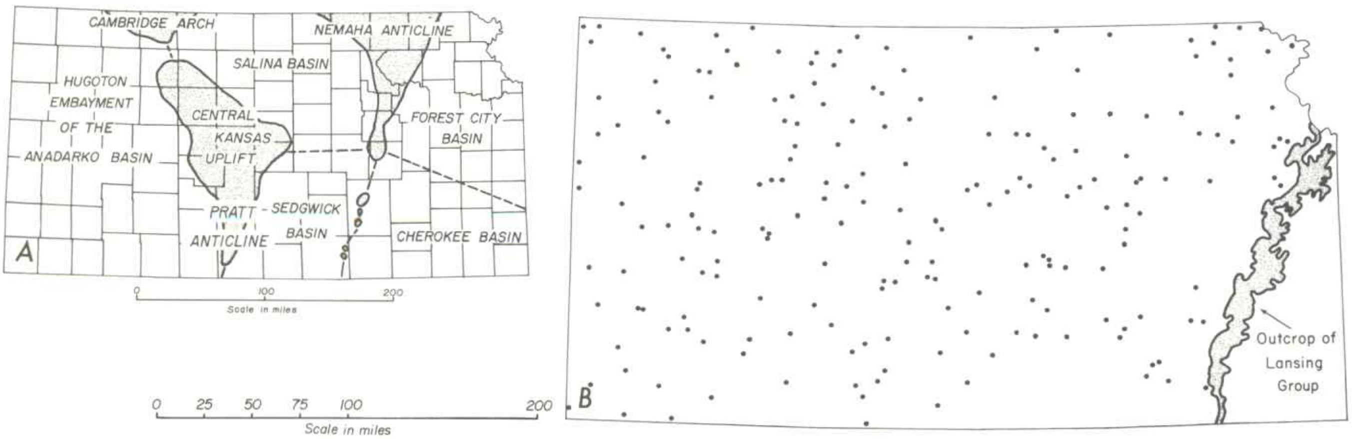
Second-degree surfaces.--Second-degree trend surfaces provide substantial improvement in percent of total sum of squares which ranges from about 44 to 90 (Table 3). With exception of the Nemaha Anticline, the state's major structural features are somewhat discernible on the second-degree trend surfaces (Fig. 3).

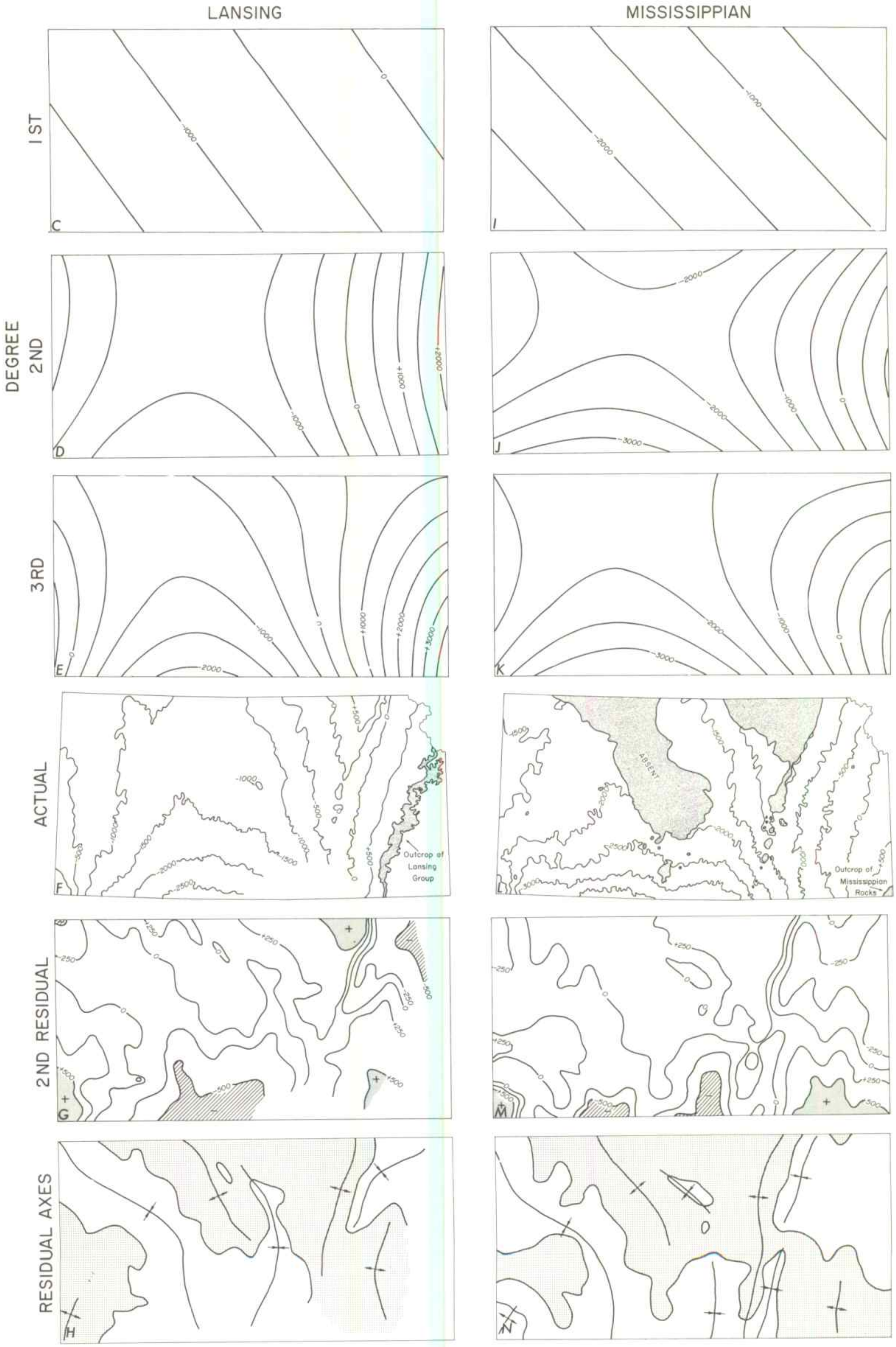
Third-degree surfaces.--The third-degree trend surfaces provide still better fit to the data, as reflected in the percent of total sum of squares ranging from about 54 to 96.

Table 4.--Slope of first-degree trend surfaces and range of data elevation values used in fitting trend surfaces over entire state (area I).

Map horizon	Slope in feet per mile	Range of data elevation values in feet
Lansing Group	5.3	3,738
Mississippian rocks	7.1	4,714
Arbuckle Group	9.1	6,805
Precambrian rocks	6.7	4,960

Figure 3.--Comparison of trend, actual, and residual maps of four structural horizons over entire state: (A) index map; (B) locations of control points used for Lansing map; (C) first-degree trend surface fitted to structure top Lansing (Pennsylvanian) rocks; (D) second-degree Lansing trend surface; (E) third-degree Lansing trend surface; (F) actual Lansing structure (generalized from Merriam, Winchell, and Atkinson, 1958); (G) second-degree Lansing residuals; (H) axes of principal Lansing residual "highs" and "lows"; (I) first-degree Mississippian trend surface; (J) second-degree Mississippian trend surface; (K) third-degree Mississippian trend surface; (L) actual Mississippian structure (generalized from Merriam, 1960); (M) second-degree Mississippian residuals; (N) Mississippian residual axes; (O) first-degree Arbuckle trend surface; (P) second-degree Arbuckle trend surface; (Q) third-degree Arbuckle trend surface; (R) actual Arbuckle structure (generalized from Merriam and Smith, 1961); (S) second-degree Arbuckle residuals; (T) Arbuckle residual axes; (U) first-degree trend surface for top Precambrian rocks; (V) second-degree Precambrian trend surface; (W) third-degree Precambrian trend surface; (X) actual Precambrian structure (generalized from Cole, 1962); (Y) second-degree Precambrian residuals; (Z) Precambrian residual axes.

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T
Z

All the state's major structural features are reflected by the third-degree surfaces, except the Nemaha Anticline. In the eastern part of the state, the westerly dip of the Ozark Uplift flank is discernible. The southerly dip of the Hugoton Embayment and the Sedgwick Basin appears southwest of the northwesterly trending Central Kansas Uplift. In northeastern Kansas, disregarding the Nemaha Anticline, the dip of the Precambrian and Arbuckle trend surfaces is northerly, reflecting the presence of the Forest City and Salina Basins. On the Lansing map (Fig. 3E, 3F), the influence of the Las Animas Arch, centered farther west in Colorado, is evident.

Residuals.--Residuals from the second-degree trend surface were contoured (Fig. 3G, 3M, 3S, 3Y) to permit comparison with actual structure (Fig. 3F, 3L, 3R, 3X). Positive residuals generally coincide with structural "highs" or anticlines, whereas negative residuals coincide with structural "lows" or synclines. Coincidence of structure and residuals was shown previously by Merriam and Harbaugh (1963) in several areas of gentle structural relief in Kansas, Colorado, and Wyoming. Axes of the principal residual highs and lows (Fig. 3H, 3N, 3T, 3Z) are generally parallel to actual regional features (Fig. 3F, 3L, 3R, 3X) outlined in Figure 3A.

NORTHWESTERN KANSAS - AREA II

General Statement

An area in northwestern Kansas forming a rectangle extending for about 145 miles east-west, and 135 miles north-south was studied in detail by trend-surface analysis (Fig. 4). Within this area, first-, second-, and third-degree trend surfaces were fitted to top of the Dakota Formation (Cretaceous), Stone Corral Formation (Permian), Lansing Group (Pennsylvanian), Mississippian rocks, Arbuckle Group (Cambrian-Ordovician) and Precambrian rocks. In addition, contours of second-degree residuals permit comparison with actual structure.

Major structural elements in northwestern Kansas in late Paleozoic time and in late Mesozoic time are outlined (Fig. 4S, 4T). The northern part of the Hugoton Embayment is bounded on the northeast by the Central Kansas Uplift and Cambridge Arch, and on the northwest by the Las Animas Arch. The beds generally dip toward the basin axis and southward. Many lesser structural features, some of which control oil production, also are present. Structural development in the Mesozoic differed from that in the Paleozoic. In the Paleozoic, the Anadarko Basin in Oklahoma exerted a dominant influence, whereas during the Mesozoic, the structure of northwestern Kansas was influenced principally by the Denver Basin in Colorado. Beds older than the Stone Corral in northwestern Kansas dip generally toward the south.

Control points used in fitting the trend surfaces were selected on the basis of random-number coordinate pairs, and are more or less equally spaced, although the available control points are much more numerous in the eastern part of the area (Fig. 4U). Control points used in fitting surfaces to the Dakota are shown in Figure 4V. The number of control points for each horizon differs slightly (Table 3).

Trend-Surface Analysis

First-degree surfaces.--The first-degree Dakota and Stone Corral trend surfaces (Fig. 4A, 4D) strike west-northwest and dip northeast, whereas the first-degree Lansing and Mississippian trend surfaces (Fig. 4G, 4J) strike northeast and dip southeast, almost at right angles to the Dakota and Stone Corral trend surfaces. However, the first-degree Arbuckle and Precambrian trend surfaces (Fig. 4M, 4P) strike west and west-northwest, respectively, and dip toward the south.

Except for the Mississippian surface, the percent of total sum of squares of the first-degree surfaces ranges from about 57 to 85 (Table 3); the Mississippian first-degree trend surface, however, represents only 25 percent. The low percentage of the Mississippian trend surface may reflect the irregularity of the Mississippian surface, which has been affected by erosion. The percent of total sum of squares decreases, except for the Mississippian, with increasing age of the map horizons, reflecting an increase in structural complexity in the older horizons.

Second-degree surfaces.--Second-degree surfaces provide an improved fit, as shown by higher percentages of total sum of squares (Table 3). The major structural elements, except for the Cambridge Arch, noticeably affect the second-degree trend surfaces.

Third-degree surfaces.--The third-degree trend surfaces provide percentages of total sum of squares ranging from about 74 to 97 (Table 3). The third-degree Dakota and Stone Corral trend surfaces are similar and they contrast with Lansing and Mississippian surfaces. In turn, Lansing and Mississippian surfaces contrast with those of the Arbuckle and with the Precambrian. The Dakota and Stone Corral trend surfaces suggest that the Western Kansas Basin (Fig. 4T) can be considered an extension of the Denver Basin. The influence of the Las Animas Arch is revealed along the western side of the area in the trend surfaces on Mississippian through the Dakota (Fig. 4C, 4F, 4I, 4L). On the Arbuckle and Precambrian trend maps (Fig. 40, 4R), the broad, south-plunging Southwest Kansas Basin (an early development of the Hugoton Embayment) is prominent.

Structural pattern recognition.--Comparison of trend surfaces of given degree fitted to different horizons is useful in recognizing gross structural patterns. For example, the first-degree surfaces reveal that both the Dakota and Stone Corral trend surfaces (Fig. 4A, 4D) are

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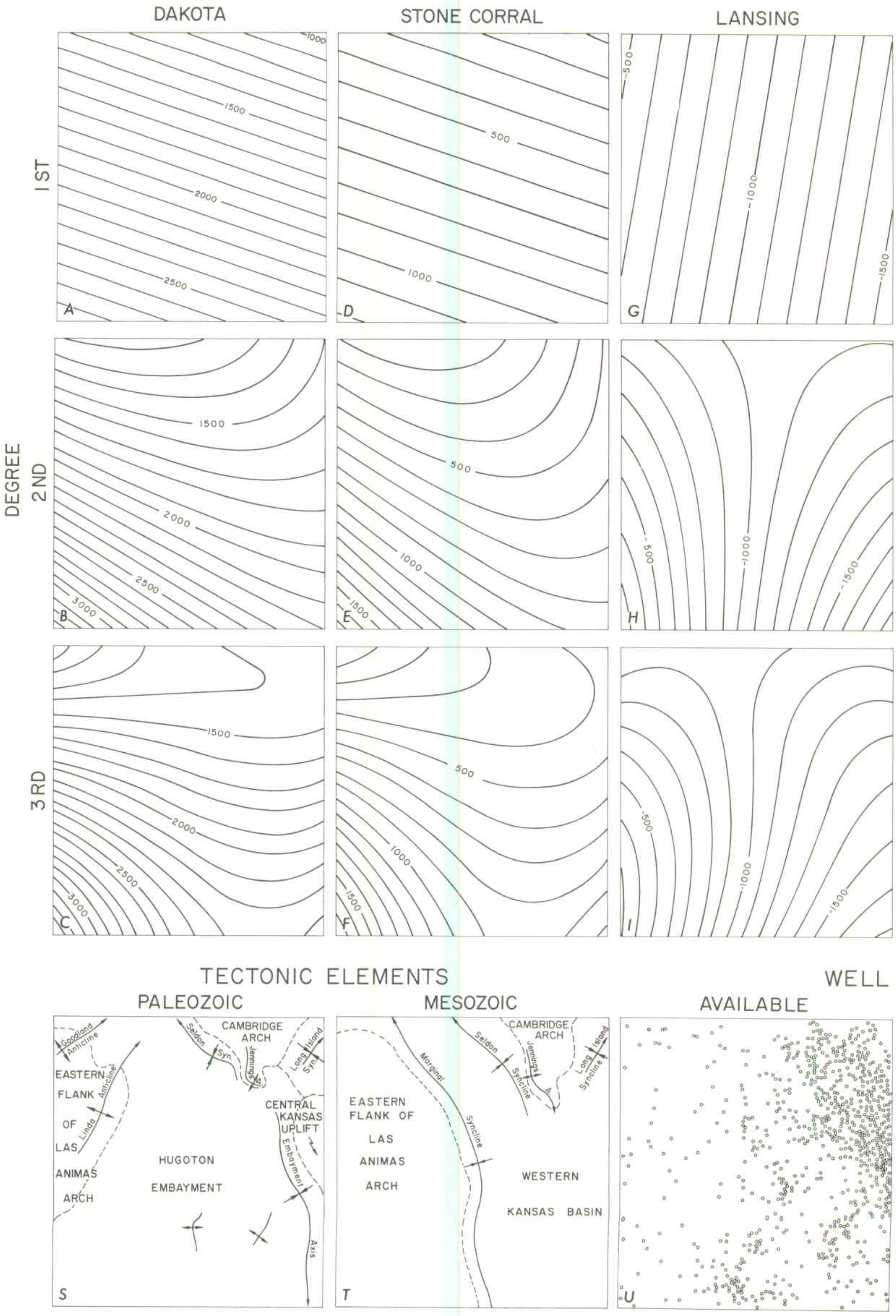
Figure 4.--Comparison of trend surfaces for six structural horizons in northwestern Kansas: (A) first-degree trend surface fitted to structure on top Dakota (Cretaceous) rocks; (B) second-degree Dakota trend surface; (C) third-degree Dakota trend surface; (D) first-degree trend surface fitted to structure on top Stone Corral (Permian) Formation; (E) second-degree Stone Corral trend surface; (F) third-degree Stone Corral trend surface; (G) first-degree trend surface fitted to top Lansing (Pennsylvanian) Group; (H) second-degree Lansing trend surface; (I) third-degree Lansing trend surface; (J) first-degree trend surface fitted to structure to top Mississippian rocks; (K) second-degree Mississippian trend surface; (L) third-degree Mississippian trend surface; (M) first-degree trend surface fitted to top Arbuckle (Cambrian-Ordovician) rocks; (N) second-degree Arbuckle trend surface; (O) third-degree Arbuckle trend surface; (P) first-degree trend surface fitted to top Precambrian rocks; (Q) second-degree Precambrian trend surface; (R) third-degree Precambrian trend surface; (S) late Paleozoic structural features in northwestern Kansas; (T) Mesozoic structural features; (U) location of available well control (from Merriam, 1957);(V) location of control points used in trend-surface analysis of structure on top Dakota rocks.


DAKOTA
STONE CORRAL
LANSING
1ST
DEGREE
2ND
3RD
1000
1500
2000
2500
A
500
1000
D
500
1000
1500
G
1500
2000
2500
3000
B
500
1000
1500
E
500
1000
1500
H
1500
2000
2500
3000
C
500
1000
1500
F
500
1000
1500
I
TECTONIC ELEMENTS
PALEOZOIC
MESOZOIC
WELL
AVAILABLE
Goodland Anticline
EASTERN FLANK OF LAS ANIMAS ARCH
Linda Anticline
Seldon Syn
CAMBRIDGE ARCH
Jennings Syn
Long Island Syn
CENTRAL KANSAS UPLIFT
Embayment
Axis
HUGOTON EMBAYMENT
S
Marginal Syncline
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Jennings Syncline
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EASTERN FLANK OF LAS ANIMAS ARCH
WESTERN KANSAS BASIN
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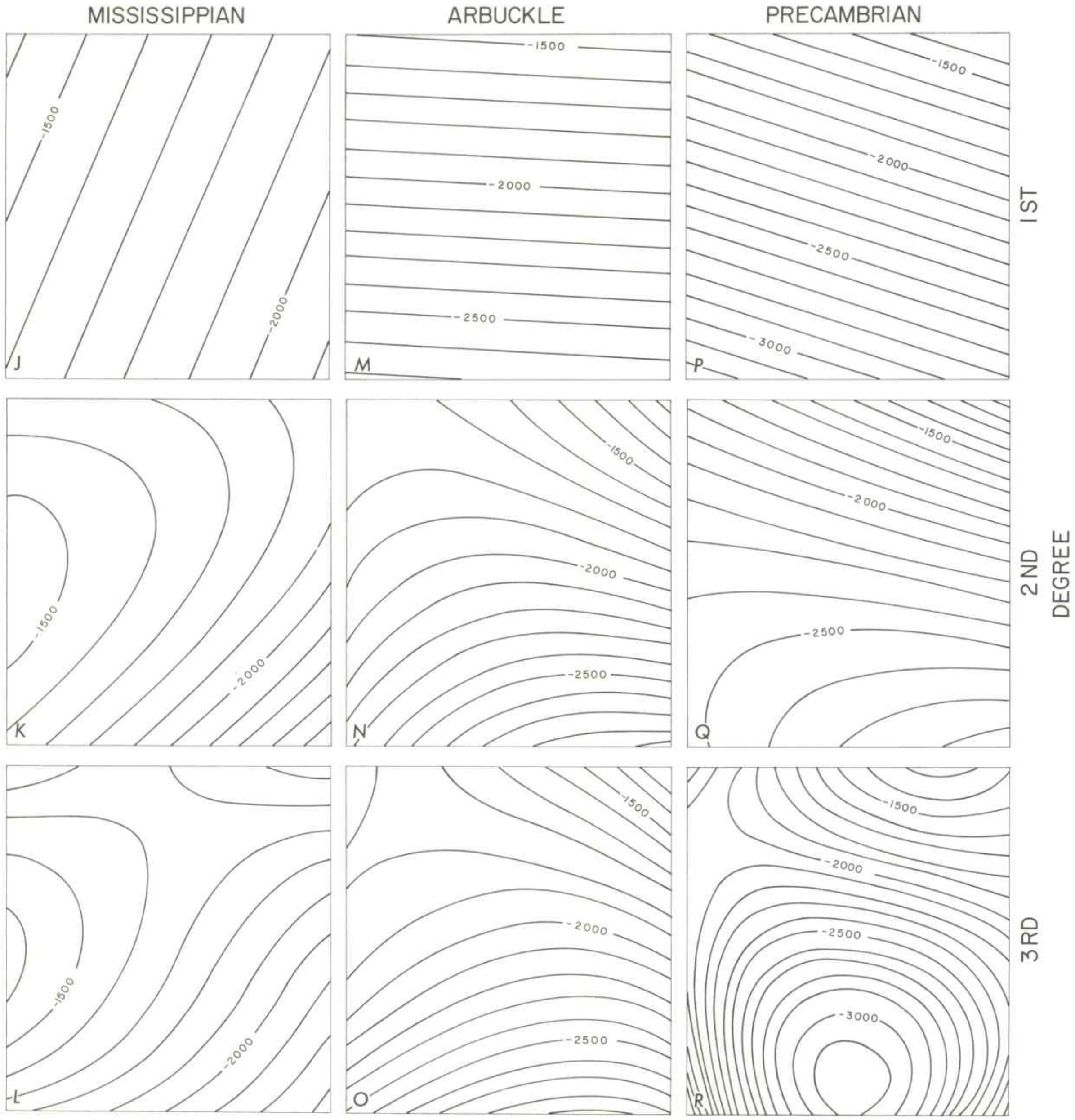
MISSISSIPPIAN
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PRECAMBRIAN
1ST
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3RD
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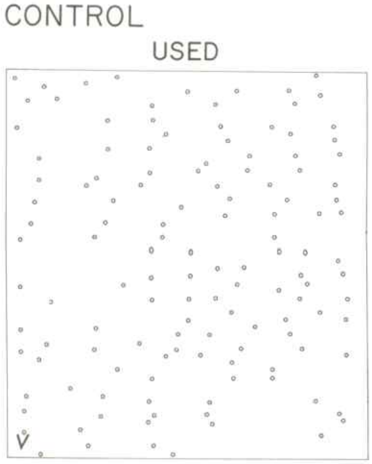
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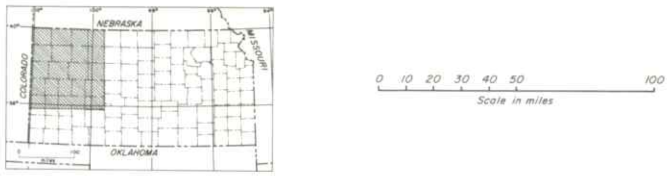
NEBRASKA
COLORADO
MISSOURI
OKLAHOMA
0 10 20 30 40 50 100
Scale in miles

similar in strike and slope, but contrast strongly with both the Lansing and Mississippian trend surfaces (Fig. 4G, 4J), which strike north-northeast, and dip southeasterly. In turn, however, the Arbuckle and Precambrian trend surfaces (Fig. 4M, 4P) strike essentially east-west and dip southward, opposite to the Dakota and Stone Corral trend surfaces. The same general tendencies are also revealed in the second- and third-degree trend surfaces, but the relationships are less simple. Of course, the same tendencies are also revealed on the actual structures (Fig. 5A, 5D, 5G, 5J, 5M, 5P).

A second interesting relationship revealed by the first-degree trend surfaces is that the upper horizons in the two younger pairs of horizons (Fig. 4A, 4G) slope more steeply than the lower horizons (Fig. 4D, 4J). However, the reverse is true for the Precambrian-Arbuckle pair, where the Precambrian first-degree trend surface (Fig. 4P) slopes more steeply than the Arbuckle surface (Fig. 4M). Major regional structural unconformities occur between each pair of the three pairs of horizons.

Residuals.--Actual structure, second-degree residuals, and axes of principal residual highs and lows are shown in Figure 5. The major tectonic elements are shown in Figure 4S, and are revealed in most of the residual maps; for example, the Central Kansas Uplift is reflected in Precambrian to Lansing residuals (Fig. 5R, 5O, 5L, 5I, 5F). The Cambridge Arch, and adjacent Long Island and Selden Synclines are reflected in residuals of all horizons (Fig. 5C, 5F, 5I, 5L, 5O, 5R), and the eastern flank of the Las Animas Arch is revealed in all horizons except the Dakota.

It is concluded that mapping of residuals is a useful method of outlining the extent of major tectonic features on an horizon-by-horizon basis. However, there is little apparent relationship between oil fields (Fig. 5S) and residuals because structures which control oil entrapment are too small to be shown at the scale of these maps.

SOUTHEASTERN KANSAS - AREA III

General Statement

Trend surfaces were fitted to structure on the top of Mississippian rocks in an area about 80 by 90 miles in southeastern Kansas (Fig. 1). The purpose was to establish a relationship, if any exists, between trend-surface residuals and oil and gas fields. The area embraces Cowley, Elk, Chautauqua, and parts of Butler and Greenwood Counties (Fig. 6B), and includes parts of the Nemaha Anticline and Cherokee Basin (Fig. 3A). Mississippian rocks are absent over the El Dorado and Augusta Anticlines, which lie on the Nemaha Anticline. The dip of the rocks in the area is southwest, toward the Brownville Syncline (Fig. 6B), which forms the axis of the Cherokee Basin.

Trend-Surface Analysis

The first-degree trend surface (Fig. 6E) reflects the west-southwest regional dip, but fails to indicate directly the Nemaha Anticline. The second- and third-degree trend surfaces (Fig. 6F, 6G), however, reflect the presence of the Nemaha Anticline. The progressive improvement in goodness of fit afforded by the higher degree trend surfaces is shown in the percentage of total sum of squares ranging from 89 to 97 (Table 3).

Relationship of Residuals to Oil and Gas Fields

Oil and gas fields that are believed to be essentially controlled by geologic structure are shown in Figure 6D; shoestring sand pools (Bass, 1936) have been omitted. Fields on the Nemaha Anticline occur on residual highs (Fig. 6C, 6D). There is also good agreement between the occurrence of oil fields and residual highs in the southeastern and south-central parts of the area, and in an arcuate band extending from the center northeastward. However, many oil fields in the west-central part of the area are associated with moderate residual lows (Fig. 6C, 6D). It should be noted that no production from structurally controlled fields occurs in certain of the large residual lows, but it also is true that there are several residual highs which have no production. Therefore, it can be concluded that most of the fields in this area are stratigraphic traps.

In assessing the value of mapping trend-surface residuals as a guide to oil and gas productive localities, it is concluded that mapping an area this size is useful in outlining residual highs which may coincide with structural traps. However, this area is too large and the control points used in the study too few to reveal the relatively small geologic structures that directly control oil entrapment.

SOUTH-CENTRAL KANSAS - AREA IV

General Statement

Trend surfaces sharply emphasize the relationship between structural features and oil fields in an area on and adjacent to the Pratt Anticline in south-central Kansas (Merriam and Harbaugh, 1963). The area is about 30 by 36 miles in size and includes all of Pratt and parts of Barber, Kingman, and Reno Counties (Fig. 7B). Regional dip is southerly. The area includes part of the western flank of the Sedgwick Basin and part of the Pratt Anticline.

Trend-Surface Analysis

The first-, second- and third-degree trend surfaces (Fig. 7E, 7F, 7G) fitted to top of the Lansing are more or less similar, and in turn, the residuals are also similar (*see*, Merriam and Lippert, in press). The surfaces are similar because the regional structure of the area is essentially that of a homocline, and therefore, a plane or first-degree surface provides a good model of regional structure. Only a slight improvement in percentage of total sum of squares is obtained in the second- and third-degree surfaces (Table 3).

Figure 5.--Comparison of second-degree trend surface residuals with actual structure, and residual axes in northwestern Kansas: (A) actual structure on top Dakota rocks (adapted from Merriam, 1957); (B) second-degree Dakota residuals; (C) axes of principal Dakota second-degree residual "highs" and "lows," (residual highs are coarsely stippled); (D) Stone Corral structure (adapted from Merriam, 1958); (E) second-degree Stone Corral residuals; (F) Stone Corral residual axes; (G) Lansing structure (adapted from Merriam, Winchell, and Atkinson, 1958); (H) second-degree Lansing residuals; (I) Lansing residual axes; (J) Mississippian structure (adapted from Merriam, 1960); (K) second-degree Mississippian residuals; (L) Mississippian residual axes; (M) Arbuckle structure (adapted from Merriam and Smith, 1961); (N) second-degree Arbuckle residuals; (O) Arbuckle residual axes; (P) Precambrian configuration (adapted from Cole, 1962); (Q) second-degree Precambrian residuals; (R) Precambrian residual axes; (S) oil and gas fields (adapted from Goebel and others, 1961).

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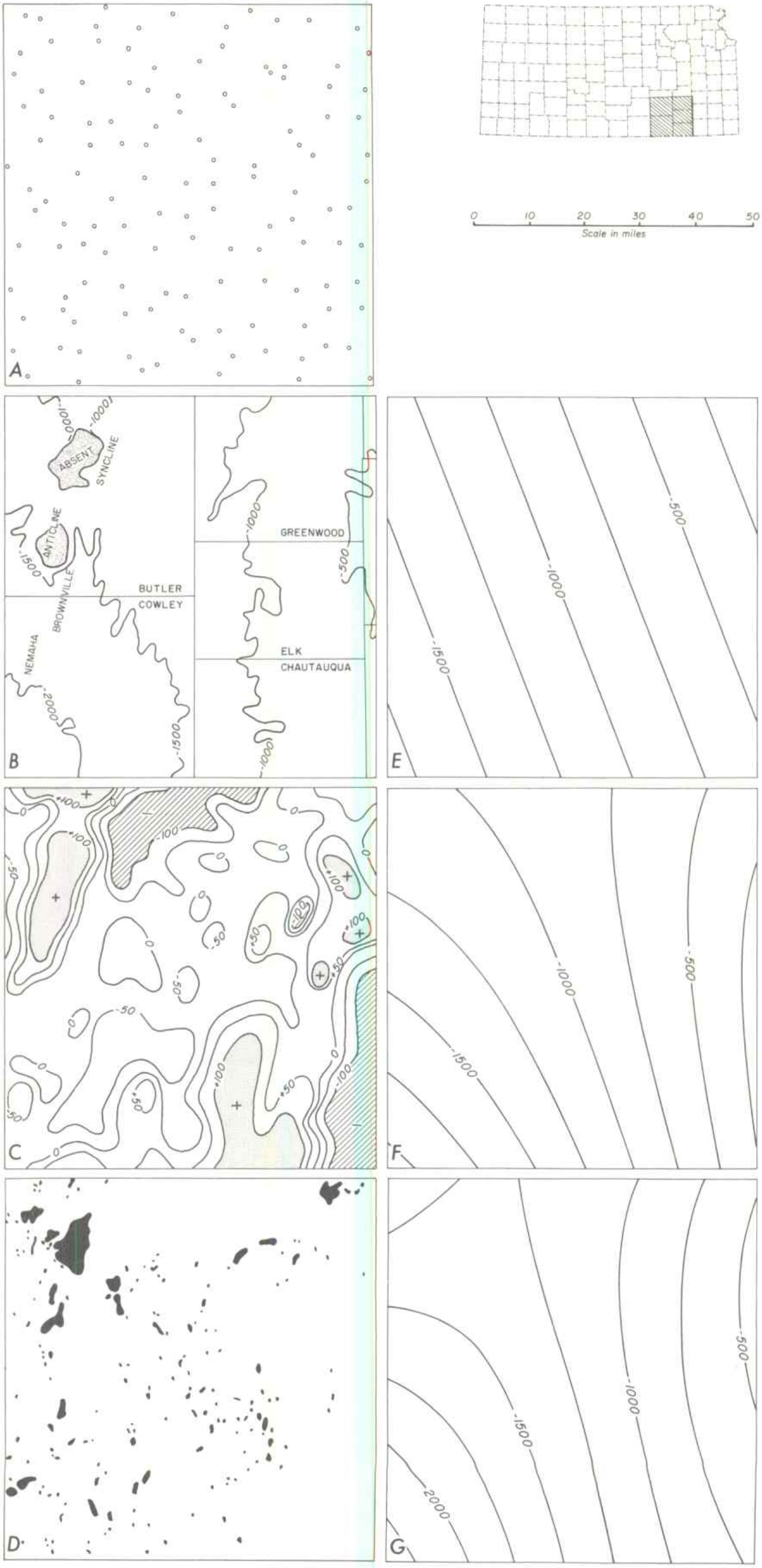
ACTUAL STRUCTURE
SECOND-DEGREE RESIDUAL
RESIDUAL AXES
DAKOTA
STONE CORRAL
LANSING
OIL AND GAS FIELDS
A
B
C
D
E
F
G
H
I
S
1500
2000
2500
3000
0
500
1000
-100
-50
+50
+100
HUGOTON GAS AREA
0 10 20 30 40 50 100
Scale in miles
NEBRASKA
COLORADO
MISSOURI
OKLAHOMA


ACTUAL STRUCTURE
SECOND-DEGREE RESIDUAL
RESIDUAL AXES
MISSISSIPPIAN
ARBUCKLE
PRECAMBRIAN
ABSENT
1500
2000
2500
3000
3500
+100
-100
-50
0
J
K
L
M
N
O
P
Q
R


A
B
ABSENT
SYNCLINE
ANTICLINE
BROWNVILLE
NEMAHA
BUTLER
COWLEY
GREENWOOD
ELK
CHAUTAUQUA
-1000
-1500
-2000
-500
C
+100
-100
+50
-50
0
D
E
F
G
0
10
20
30
40
50
Scale in miles

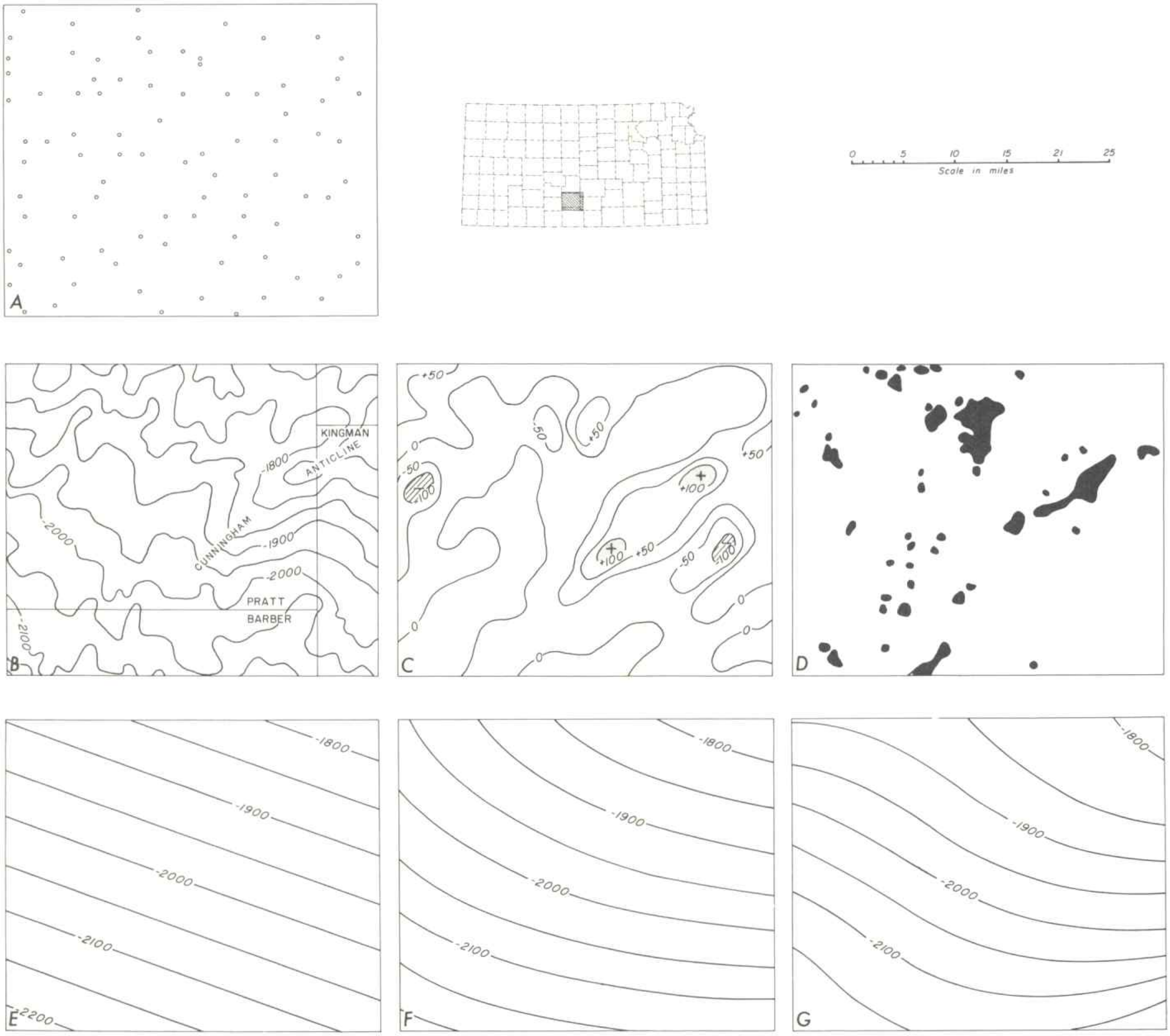


Figure 7.--Relationship of trend-surface residuals to oil and gas fields in part of south-central Kansas: (A) location of wells used as control; (B) actual structure on top Lansing Group (adapted from Merriam, Winchell, and Atkinson, 1958); (C) second-degree trend surface residuals; (D) oil and gas fields (from Goebel and others, 1961); (E) first-degree trend surface; (F) second degree; (G) third degree.

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Figure 6.--Relationship of oil and gas fields in southeastern Kansas to trend-surface residuals; (A) location of wells which provide control for trend maps; (B) structure on top of Mississippian rocks (generalized from Merriam, 1960); (C) second-degree trend surface residuals; (D) oil and gas fields (fields that produce from Pennsylvanian shoestring sands are omitted; from Goebel and others, 1961); (E) first-degree trend surface; (F) second-degree trend surface; (G) third-degree trend surface.

Relationship of Residuals to Oil and Gas Fields

If the location of oil and gas fields (Fig. 7D) is compared with structure on top of the Lansing Group (Pennsylvanian), (Fig. 7B), some relationship between oil and gas fields and structural features may be observed. But, residuals from the second-degree trend surface (Fig. 7C) emphasize the close relationship between the oil and gas fields and residuals because the majority of oil and gas fields are associated with residual highs.

Several oil fields, including Sawyer, Chitwood, Cunningham, and Dresden are associated with the northeast-trending Cunningham Anticline, located in northwestern Kingman County and southeastern Pratt County, are discernible on the structural map, but appear as pronounced highs on the residual maps. Similarly, the Iuka-Carmi field, located in north-central Pratt County, is associated with a prominent residual high. The relationship of other fields to residual highs is less pronounced, but, even small fields in the southwestern part of the area are associated with a broad, gentle residual high.

It is concluded that mapping trend-surface residual highs in areas the size of this part of south-central Kansas should be worthwhile, because the probability of discovering oil is greater in residual highs than elsewhere.

LOST SPRINGS - AREA V

General Statement

The Lost Springs area is located in east-central Kansas (Fig. 1) and embraces parts of Dickinson, Marion and Morris Counties (Fig. 8B). Structurally, the area is part of the eastern flank of the Salina Basin, just west of the crest of the Nemaha Anticline (Fig. 3A). Regional dip is to the west.

Trend-Surface Analysis

Trend surfaces (Fig. 8E, 8F, 8G) were fitted to top of the "Mississippi chat" to determine if there is a relationship between trend-surface residuals and the Lost Springs oil field. Forty-eight control points were used (Fig. 8A). The three trend surfaces are essentially alike, there being only a slight improvement in percentage of total sum of squares from first- to third-degree surfaces (Table 3). Furthermore, the cubic component of the third-degree trend surface is of doubtful significance, because only about a 50 percent confidence level is associated with it.

Relationship of Residuals to Lost Springs Oil Field

Production in the Lost Springs oil field is from the Pennsylvanian basal conglomerate and uppermost "Mississippi chat" (Shenkel, 1955). Lost Springs is associated with a structural terrace or gentle flattening of westward regional dip. Maximum structural closure in the field is only about 20 feet, and most of the field lies outside the various small areas of closure (Fig. 8B). A large sinkhole is prominent immediately west of the north end of the field. A close relationship between the oil-producing area (Fig. 8D), and a pronounced residual high (Fig. 8C) is shown when trend surfaces (Fig. 8E, 8F, 8G) are subtracted from actual structure (Fig. 8B).

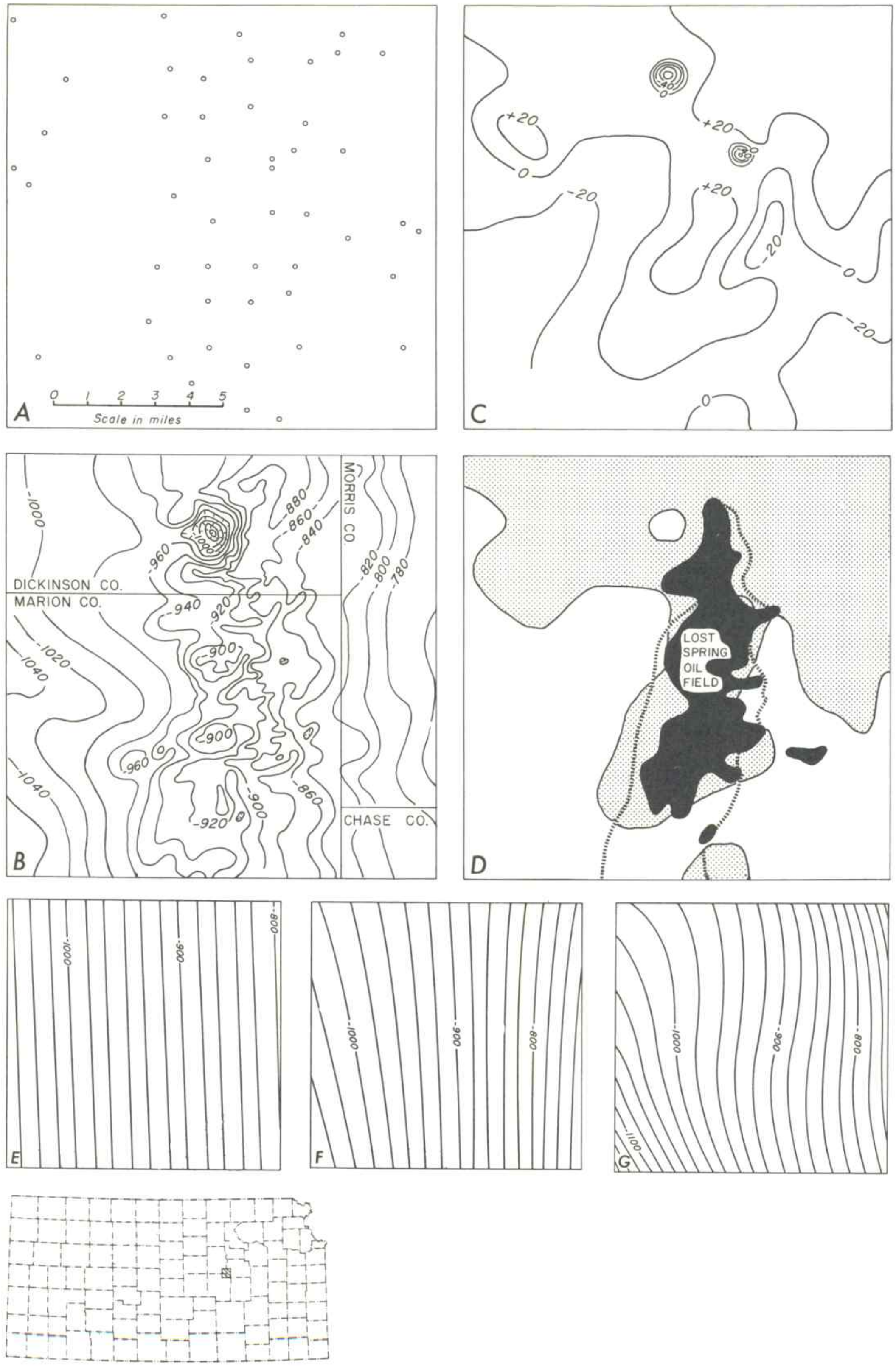

Figure 8.--Relationship of trend-surface residuals to the Lost Springs oil field in east-central Kansas: (A) location of wells used as control; (B) actual structure on top of "Mississippi chat" (from Shenkel, 1955); (C) second-degree trend surface residuals; (D) outline of Lost Springs oil field; dashed line shows outline of producing area in 1964 (residual highs are coarsely stippled); (E) first-degree trend surface; (F) second-degree trend surface; (G) third degree trend surface.

SUMMARY

Mathematically computed trend surfaces, plane or gently curving surfaces that have regular trends and fitted by the least-square method, may represent large-scale or "regional" structural features, whereas the residuals, the remainder found by subtracting the actual from the computed value, may represent small-scale or "local" structure.

Trend-surface residual maps are especially useful in emphasizing local structural features in areas of county size or less by subtracting the regional structure. There is generally a close relationship between local structural features and residual "highs" and "lows." Inasmuch as there is also a close relationship between local structural features and oil and gas accumulations, mapping of residuals may be useful in prospecting for oil and gas.

Trend-surface analysis does not reveal features that cannot be perceived in the original data with close scrutiny; however, trend-surface analysis does strongly accentuate structural features that are of less than regional magnitude, and in this way bring out details that may have gone unnoticed previously.

If trend surfaces are fitted and contoured by high-speed, electronic computers, the costs are extremely low. It is suggested that trend analysis be carried out routinely by oil-exploration geologists.

It is further suggested that the trend-surface analysis be applied to: (1) predicting projected depths to geologic horizons within a region, (2) emphasizing the magnitude of unconformities by indicating major changes in structural patterns, and (3) projecting structural features into areas of no control.

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