A BOTTOM-HOLE TEMPERATURE ANALYSIS IN THE AMERICAN MIDCONTINENT (KANSAS): IMPLICATIONS TO THE APPLICABILITY OF BHTs IN GEOTHERMAL STUDIES

Andrea Forster and **Daniel F. Memam**

GeoForschungsZentrum Potsdam, Telegrafenberg A3, 14473 Potsdam, Germany
Kansas Geological Survey, The University of Kansas, Lawrence, KS 66047, USA

Key words: bottom-hole temperature, correction factor, temperature maps

ABSTRACT

Most boreholes drilled in the search for hydrocarbons record a BHT (Bottom-Hole Temperature). Unfortunately, these data represent disturbed formation temperatures and may be overlain by noise. Although the value is noted on the well record, sufficient information may not be recorded to apply one of the correction algorithms. In the densely drilled and thinly veneered sedimentary covered cratonic area of the North American Midcontinent, literally thousands of these values are available. If sufficient temperature values are available, an empirical correction factor can be used to calculate true formation conditions. Also, the raw BHTs can provide information about noise by mapping the data at different depth levels and for different stratigraphic/lithologic units. Considering that the BHTs are relatively incorrect by the same amount, searching for abnormal values in a mass of BHT values becomes the objective of some studies In eastern Kansas, 15,000 BHT values are available for checking different influences and for relating the values to the geological and geothermal conditions. Several quantitative techniques are available to help in this evaluation, such as trend analysis and algebraic map comparison/integration These two techniques were applied to the eastern Kansas data set to evaluate the applicability of BHTs for the evaluation of the geothermal conditions of the area.

1. INTRODUCTION

The sedimentary veneer with its vertical and lateral changes of thermal properties (e g thermal conductivity) as well as its contained fluids alter the thermal structure in a sedimentary basin For the evaluation of the geothermal potential and resources of an area, information about heat-flow distribution, is necessary In the best situation, heat-flow density can be determined on the basis of (1) interval temperature gradients obtained by continuous temperature logging under equilibrium conditions in the borehole and **(2)** thermal-conductivity estimations on rock samples from the different formations through which the thermal measurement was made On the basis of those data, steady-state conductive heat flow usually is predicted if no vertical variation in heat-flow density along the depth profile can be outlined

In most areas however, results from boreholes especially designed for heat-flow density measurements are not available so that other geothermal data have to be taken into consideration. Bottom-hole temperature (BHT) data are abundant and usually easy to obtain. Unfortunately, these data are of limited applicability when dealing with single values. Most of the problems are concerned with the way in which the measurements were taken and the conditions under which they were made. Essentially a bottom-hole temperature is taken shortly after the cessation of drilling a well and under conditions not at equilibrium. Also, there is no evaluation as to the accuracy of the instrument nor recognition of the problems in obtaining, recording, and filing of the data. In many instances too, there is no central database where the BHT values are readily accessible nor information about the drilling regime and drillmud circulation, parameters that are essential for applying many of the theoretical correction approaches Different methods that might be applied to correct the nonequilibrium BHTs to 'true' formation temperature are available (e g Dowdle and Cobb, 1975, Fertl and Wichmann, 1977, and Luheshi, 1983) The approaches published until 1988 are summarized by Deming (1989) Recently, additional **work** on the inversion of industrial temperature data to formation temperatures was done by Nielsen and others (1990) The major disadvantage in applying those methods is that none of them, neither the mathematical models of the temperature buildup in a borehole nor the empirical corrections are totally satisfactory In most instances, information on the input data for the correction algorithms are not available or the area for which the correction scheme was developed does not match the conditions in another situation

Despite the limitations of working with these data, under certain conditions they may be useful and add considerable information to a particular problem. There has been considerable interest in developing the handling and interpreting of large BHT data sets (e.g Chapman and others, 1984; Drury and others, 1984; Majorowicz and others, 1984; Bachu, 1985; Speece and others, 1985; Lucazeau and Ben Dhia, 1988; Deming and Chapman, 1988).

Using geothermal anomalies have been, and are, of interest as an exploration tool (e.g. Ball, 1982; Meyer and McGee, 1985; McGee, Meyer, and Pringle, 1989, and contained references). The area of an anticline may correspond with positive geothermal anomalies indicated by BHTs. Most explanations of these 'hot spots' are that the petroleum is a low-heat conductor in comparison to other formation fluids and thus, forms an identifiable anomaly.

In our instance, we feel that the BHTs available on the craton area of the Midcontinent, USA probably can be used in geothermal studies for regional interpretations. We believe they are useful for the following reasons: (1) they have been taken through the years with normal devices by few companies with extensive experience in the area; (2) they are uniformally and consistently biased so that, although the actual value may be incorrect, the pattern formed by them reflects the correct visualization; and (3) because they are taken at shallow depths, for the most part, 1,800 m or less, and the correction factor (if known) would be small. On the other hand, in this area extensive data on the geophysical properties of the underlying basement are available, and also data on the regional aquifers, their recharge and discharge areas, as well as their hydrological regime This information allows a prediction in which manner the variation in heat flow may be the result of pure heat conduction or overprint by fluids.

With this background then, a study of the spatial variation of BHT values was made for an area in southeastern Kansas, an area with a thin veneer of Paleozoic clastic and carbonate sediments in a depth range of 400-1,400 m The sediments cover the Precambrian crystalline basement complex in a relatively simple tectonic and structural setting (Fig 1) The study area in the Cherokee Basin comprises Chautauqua and Elk Counties, an area of about 4,000 square kilometers

2. THE DATA

637 BHT values in: (1) Lower Pennsylvanian (Upper Carboniferous mostly clastics with thin carbonate units), **(2)** Mississippian (Lower

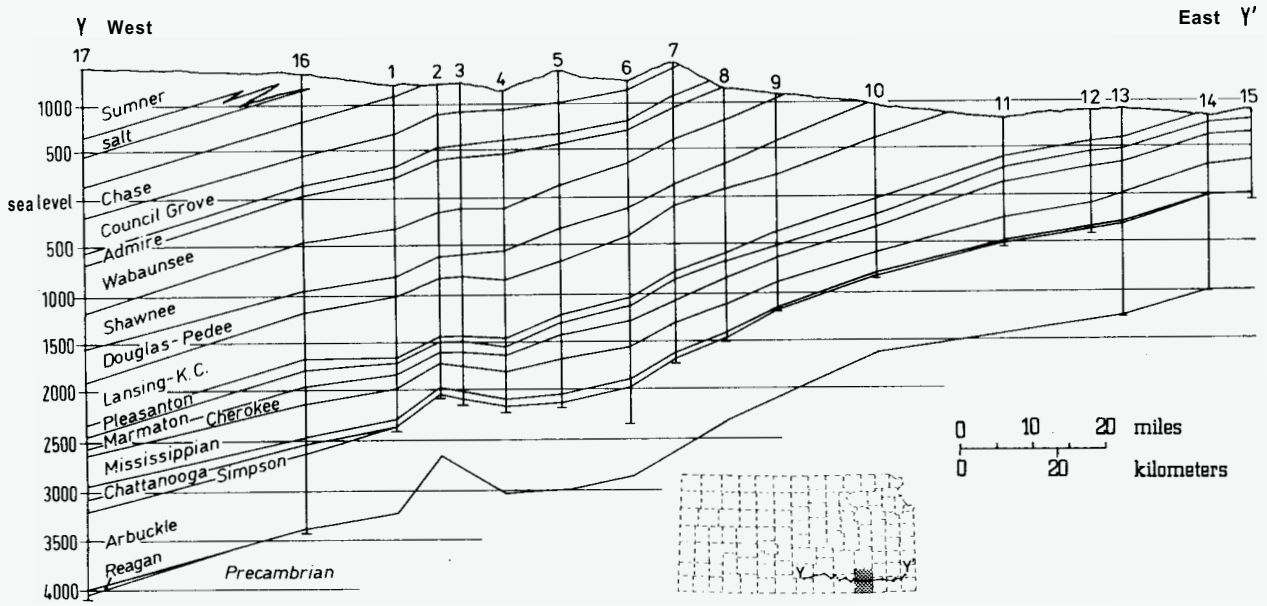


Figure 1. East-west cross section through southeastern Kansas (modified from Merriam, 1963) showing major stratigraphic units. Area of BHT/DST analysis (Chautauqua and Elk Counties, Cherokee Basin) marked on index map

Carboniferous carbonates), and (3) the Arbuckle Group (Cambro-Orodovician carbonates), were collected and analyzed by stratigraphic unit. Each BHT represents a single borehole, thus not allowing a temperature correction using the Homer technique. In addition to the BHTs, 287 temperatures recorded in drillstem test (DSTs) were collected and compared to the BHT scatter. It is believed that the DSTs measured in the formation fluid represent values close to formation temperatures.

The background information for evaluating the BHTs and DSTs consists of interval gradients obtained from continuous temperature logging under equilibrium conditions in two boreholes of an area adjacent to our area (see Blackwell and Steele, 1989). In these boreholes also interval thermal conductivity was measured and for the shaly units inferred from the context of vertically stable heat-flow density distribution. The values obtained by Blackwell and Steele are summed up by **us** in terms of formation gradients and thermal conductivity for the stratigraphic units from which BHTs are collected (Table 1). Because of the similar basement characteristics and the similar lithology of the relatively homogeneous and widespread formations we assume that the measured values of the adjacent area are valid also for our study.

Table 1. Formation thermal conductivity and geothermal gradient averaged for major stratigraphic units.

Stratigraphic unit	Lithology	Formation thermal gradient ($°Ckm^{-1}$)	Formation thermal conductivity ($Wm^{-1}K^{-1}$)
Lower Pennsylvanian	mostly clastics with some intercalated thin limestone and coals	**38 ± *6***	**1.6 ± *0.3***
Mississippian	limestone and dolomite	21 ± 3	3.0 ± 0.4
Arbuckle Group	mostly dolomite	15 ± 1	4.1 ± **0.2**

3. THE ANALYSIS

In Kansas, a reconnaissance study of subsurface temperatures and geothermal gradients was done by Stavnes (1982) and Stavnes and Steeples (1982) as part of the evaluation of the geothermal potential of the entire State **As** part of that study, two types of gradients were computed and mapped: (1) average gradients from a few thermal logs at shallow depths and **(2)** average gradients of uncorrected BHTs using a two-point straightline (BHT and surface temperature). It was believed that the problem of using nonequilibrium BHTs was minor and that from the spatial pattern of the two types of maps, relation to the geology could be subtracted.

We analyzed by multivariate statistics and map comparison/integration these gradients from a different data source and depth in regard to their relation to each other and to geological features (Forster, Merriam, and Brower, 1993) and a map comparison technique (Forster and Merriam, 1993; Herzfeld and Merriam, 1990). In Figures 2A and 2B the two geothermal gradient maps are shown together with the resultant map generated by pairwise comparison of the two data sets. The maps comprise Chautauqua and Elk Counties but also parts of adjacent counties in the west and north (see Fig. 1). The major result in comparing the two gradient maps - BHTs and logged values - is that both data sets show only vague similarity and little coincidence (Fig. 2C) and their interpretation is manyfold in the context of geological features in the sedimentary veneer as well **as** of basement characteristics.

Here, in a different approach, BHTs and DSTs were collected and analyzed by depth for three major stratigraphic units, in a small area that is structurally uniform. In such a way, conditions that might affect the temperatures are predictable. The analysis comprises:

- calculation of formation geothermal gradients using uncorrected BHTs and DST data,
- comparison of uncorrected BHT formation gradients and DST formation gradients with gradients of the two data sets averaged for the entire stratigraphic sequence,
- application of the empirical BHT correction scheme of the AAPG (Kehle, 1972) for checking its validity in the Kansas part of the Midcontinent,
- determination of a correction function for BHTs using DSTs,
- analysis of the spatial BHT and DST pattern by mapping and trend-surface analysis.

The investigation of the spatial distribution of BHTs and DSTs in the different stratigraphic units is essential for a better understanding of the pattern outlined in the temperature-depth plots (Figs. 3 and **4).** To search for anomalous areas the raw data were analyzed by trend-surface analysis. The first-, second-, third-, and fourth-degree

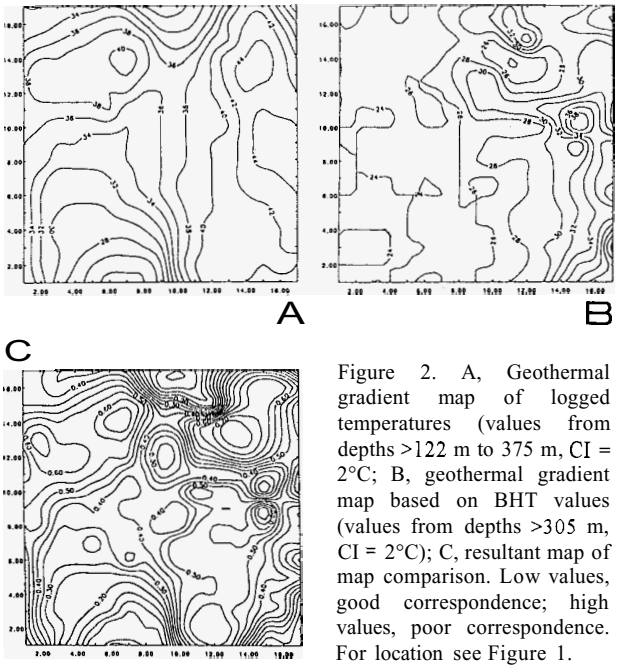


Figure 2. A, Geothermal gradient map of logged temperatures (values from depths >122 m to 375 m, CI = 2°C; B, geothermal gradient map based on BHT values (values from depths >305 m, CI = 2°C); C, resultant map of map comparison. Low values, good correspondence; high values, poor correspondence. For location see Figure 1.

surfaces were computed for each data set. By analyzing the residuals from the regional trend, the areas with anomalous temperatures are emphasized. The same procedure is done with the DST data.

4. RESULTS

4.1. Tempetaturn-Depth Plots

Different plots of BHT and DST data versus depth are summarized in Figure 3. The BHT data collected in the three stratigraphically and lithologically different units (depth range from about 200 m to 1,050 m) show a considerable scatter and a poor fit by the regression line (Fig. 3A). The maximum scatter of BHTs at the same depth is about 15°C-18°C. The formation geothermal gradients computed for each unit are about in the same range yielding an average geothermal gradient for the area of about 16°C/km (Table 2). This was surprising in view of the three different lithotypes making up the section and in view of the expected small disturbance effects on the data by drilling in that relatively shallow depth. We checked the gradients for consistency by separating BHTs from a limited depth range of 500-800 m. In this situation, the highest gradients are observed in the Arbuckle Group (21.6°C/km) followed by the Mississippian (18.7°C/km), and Lower Pennsylvanian (13.0°C/km).

In contrast, DST values collected for the entire depth range show an average geothermal gradient of 27.8°C (Figs. 3B and 3C). The DST values in general are better correlated, but also show a scatter of about 12°C, especially in the deeper Mississippian and Arbuckle units.

If the empirical AAPG-correction constants averaged for the area of North America are applied to the BHT data set the average geothermal gradient for Chautauqua and Elk Counties yields 18.6°C/km (Fig. 3B), a value which is only slightly higher than the uncorrected gradient, but smaller than the gradient indicated by DST values. Both BHT regression lines (the corrected and the uncorrected) have a temperature intercept higher than the ambient surface temperature of 13°C whereas the DST intercept yields 20.0°C, a value closer to the surface temperature.

Table 2. Formation BHT and DST gradients in comparison with geothermal gradients for Chautauqua and Elk Counties, Kansas

Unit	BHT gradient (°C/km)	DST gradient (°C/km)
Lower Pennsylvanian	16.0	**29.2**
Mississippian	**15.7**	**22.4**
Arbuckle	**15.9**	20.3
entire depth range	15.7	21.8

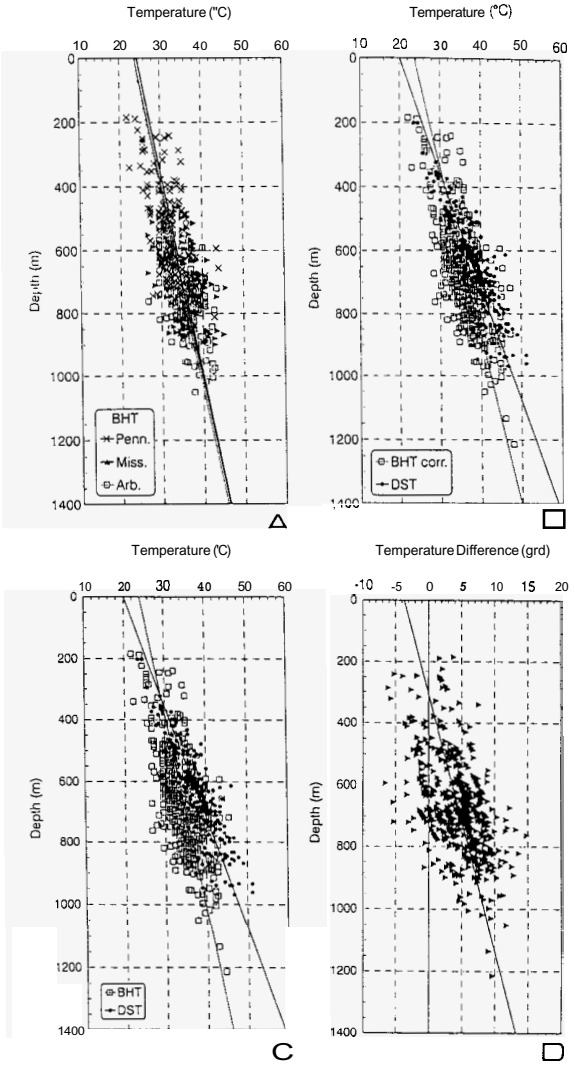


Figure 3. Borehole temperatures in Chautauqua and Elk Counties vs depth. Data fitted by linear regression. A, BHT values of Lower Pennsylvanian *(n=141)*, Mississippian *(n=313)*, and Arbuckle Group *(n=183)* with about same slope of 16°C/km for each unit; B, BHT values corrected using AAPG scheme and compared to DST values; BHT slope 18.6°C/km; C, measured BHTs in comparison to DST values, R^2_{BHT}=0.38; R^2_{DST}=0.71; D, plot of temperature difference AT (DST trend - BHT value) vs. depth, R^2=0.26.

Considering that the DSTs reflect data close to formation temperatures, BHTs can be corrected to formation conditions on the basis of the observed temperature difference (DST geotherm - BHT) as a function of depth (Fig. 3D):

$$AT(z) = 0.012\,z - 3.68$$

where AT is the temperature correction in degree Celsius, and z is depth in meters. It is obvious from the data set analyzed here that the DSTs from depths greater 400 m are statistically in excess of BHT data and that at shallower depth most of the BHTs are higher than the DSTs.

With regard to true formation geothermal gradients as needed in heat-flow density estimations, DST data better reflect the thermal conditions than BHT data. From the DSTs separated by stratigraphic unit and plotted versus depth (Fig. 4A) formation

gradients closer to the gradients determined by thermal logging can be outlined (see Tables 1 and 2). The DST gradient of the Lower Pennsylvanian of 29.2°C/km corresponds with an intercept temperature of 18.8°C, which is in reasonable closeness to the ambient surface temperature. The DST gradient of the Mississippian of 22.4°C/km matches the logged gradient, whereas the DST gradient of the Arbuckle is slightly higher than the logged gradient. At this stage of the investigation it can not be substantiated if this is caused by the different formation fluid recorded during the well tests, the limited number of DST collected in the Arbuckle carbonates, or by warm fluids from the deeper basins in the south and present in the Mississippian/Arbuckle aquifer. However, it is obvious that the DST gradients can be put in order as follows: gradient (water) > gradient (oil) > gradient (mud) (Fig. 4B).

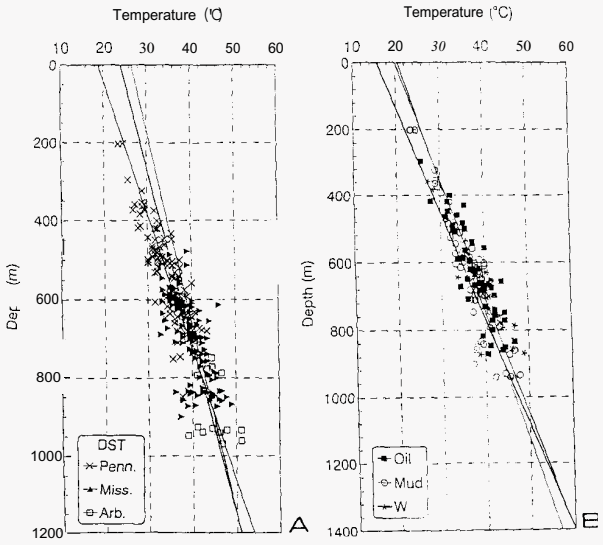


Figure 4 DST values in Chautauqua and **Elk** Counties vs depth Data fitted by linear regression A, DST values by stratigraphic units, R^2_{Penn}=0 74, R^2_{Miss}=0 44, R^2_{Arb}=0 37, B, DST values according to major fluid measured during well test (oil, mud, or water)

4.2. Temperature Maps

For analyzing the BHT and DST scatter observed in the temperature-depth plots, the data were mapped separately for each stratigraphic unit a trend-surface analysis was applied All three maps (Figs. 5) are similar in overall appearance. By visual comparison a general trend of increasing temperatures toward the west can be observed. This is in correlation with the overall structural trend of increasing depth of the subsurface units to the west and the thickening of the insulating Permo-Pennsylvanian clastics on top of the carbonate units. The statistical data for the computer-generated maps utilizing Surface III (Sampson, 1988) is given in Table 3.

Table 3 Statistics of data used in construction of BHT/DST maps

Strat unit	mean		sd		range		no points	
	BHT	DST	BHT	DST	BHT	DST	BHT	DST
L Penn	31 6	35 0	4 31	3 88	21-43	23-43	101	132
Miss	346	396	3 59	348	25-45	32-49	213	134
Arbuckle	349	43 5	3 14	3 71	26-43	38-51	150	21

BHT data for the *Lower Pennsylvanian* map (Fig. 5A), comprising a depth interval from about 200 m to 800 m, are scarce compared to the two other maps The data are concentrated on the central and western part of the area and range from 21°C to 43°C with most values in the range of 25°C to 35°C. Few small 'hot spots' with temperatures from 35°C to 43°C occur in the western part. The *Mississippian* BHT map (Fig. 5B) comprising a depth interval of about 450 m to *900* m is the most detailed map because of data control. The temperatures are in the range between 25°C and 45°C, which is slightly higher than temperatures in the Pennsylvanian. Numerous small 'hot spots' of temperatures in excess of 38°C are scattered mostly over the central and western part of the area The southeastern and northern part of the map is devoid of data so that the smooth pattern of low values there is not reliable. The *Arbuckle* BHT map (Fig. 5C) comprises data from a depth interval of about 550 m to 1,050 m being in a temperature range from 26°C to 43°C. This is the same temperature range as recognized for the Mississippian. Positive anomalies of temperatures between 37°C and 43°C are scattered over the central and western part of the map.

The Mississippian BHT data was fit by polynomial first- to fourth-degree trend surfaces (Fig 6) The first- (Fig 6A) and second-degree surfaces (Fig 6B) show similar patterns indicating a general temperature increase from 31°C on the east to 38°C on the west The third- (Fig 6C) and fourth-degree surfaces (Fig 6D) reflect a more complex pattern with lower temperatures on the east, a flattening of values in the center of the map resulting from the complex of temperature highs and lows, and an increase in temperature again on the west

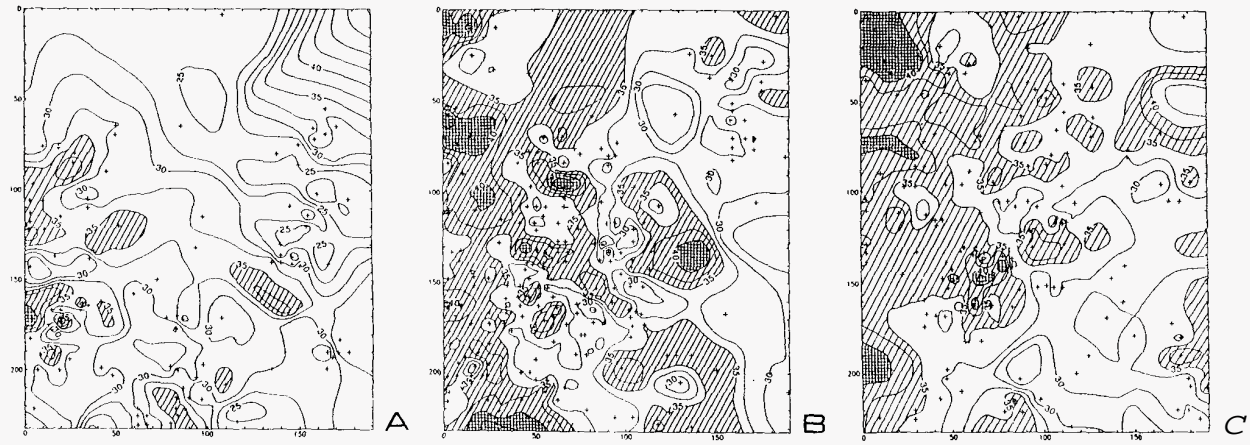


Figure 5 Contour maps of BHTs in Chautauqua and Elk Counties, Kansas for A, Lower Pennsylvanian, B, Mississippian, and C, Cambro-Ordovician Arbuckle CI = 2 5°C Location of data point shown as + See Table 3 for statistics on map Local 'hot spots' are noted by shading

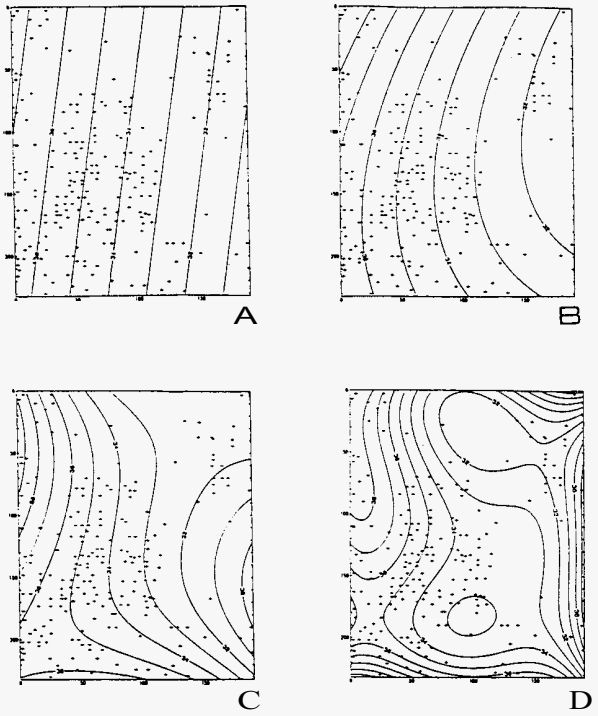


Figure 6. Trend-surface maps of Mississippian BHTs in Chautauqua and Elk Counties, Kansas for A, first degree ($R^2 = 0.43$); B, second degree ($R^2 = 0.45$); C, third degree ($R^2 = 0.47$); D, fourth degree ($R^2 = 0.51$), CI = 1°C.

The Mississippian BHT data (Fig. 7A) and the residuals of third-degree trend surface of data are similar as would be expected. By removing the trend or regional effect from the data, the local or small-scale effects are sharpened and emphasized. The temperature anomalies indicated by the residuals are in the range of about -2.5°C to 2.5°C with few values of -7.5°C and 7.5°C on each map. On both maps a criss-cross pattern is noticeable, but perhaps slightly more evident on the residual map.

The DST trend surfaces of Mississippian data (Figs. 8A and B) show the same trend as the BHT data by increasing values from the east to the west. However, the increase is larger (32°C to 45°C) and the actual DST values are higher. Numerous anomalies are scattered over the central and western part of the map. It remains to investigate if there are relationships between the BHTDST pattern and the structural grain of the area and the location of oil- and gas-producing anticlinal features abundant in the area.

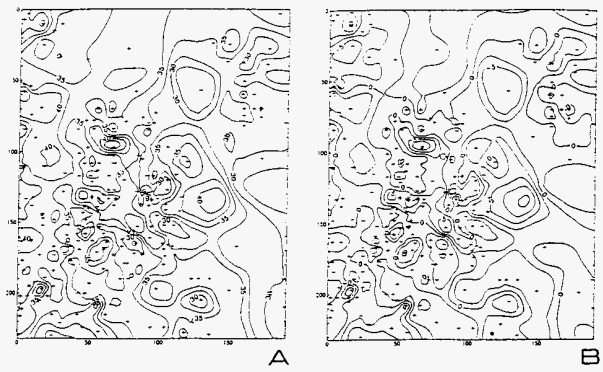


Figure 7. A, Contour map of Mississippian BHT data for Chautauqua and Elk Counties, Kansas, CI = 2.5°C. B, Contour map of third-degree trend-surface residuals for CI = 2.5°C.

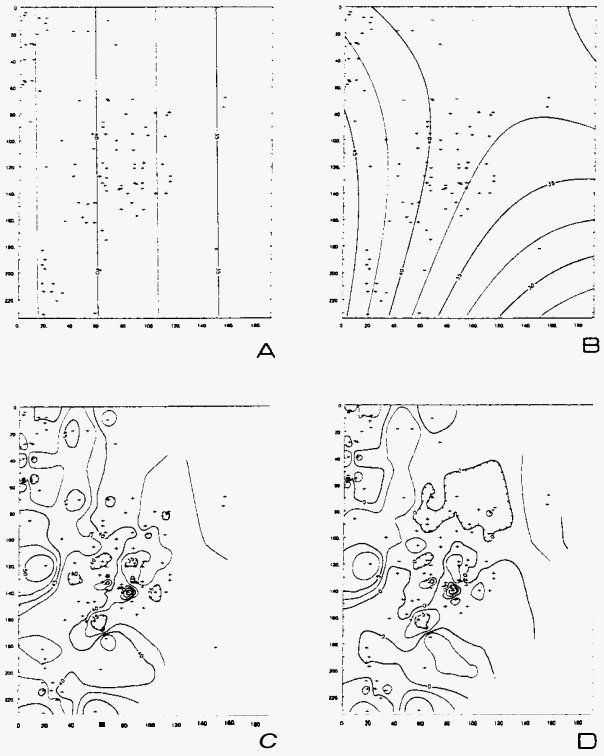


Figure 8. Contour maps of DSTs recorded from Mississippian tests in Chautauqua and Elk Counties, Kansas. A, First-degree trend surface ($R^2 = 0.55$); B, second-degree trend surface ($R^2 = 0.61$); CI = 5°C. C, actual Mississippian DST data; D, residuals from first-degree trend surface; CI = 2.5°C. Location of data points (boreholes) shown as +.

5. CONCLUSIONS

BHT data can be corrected to near-formation temperatures on the basis of large DST data sets. In the situation of Southeastern Kansas, formation gradients on the basis of DST values provide a better-quality estimate than gradients obtained from corrected BHT data. The reliability of BHTDST gradients strongly depend on the number of data points included in the study. Statistical analysis such as trend analysis and other quantitative methods, for example algebraic map comparison, can bring out relationships not otherwise noted in the original data and can be used for searching for the signal/noise ratio especially inherent in the BHT data.

6. ACKNOWLEDGMENTS

We would like to thank John C. Davis and W. Lynn Watney of the Kansas Geological Survey for reading a preliminary copy of the manuscript. We would like to thank John C. Davis for help in processing and interpreting the statistical data. Lea Ann Davidson also of the Kansas Geological Survey helped with the typing and layout of the material.

7. REFERENCES

Bachu, S. (1985). Influence of lithology and fluid flow on the temperature distribution in a sedimentary basin: a case study from the Cold Lake area Alberta, Canada. ***Tectonophysics,*** v. 120(3/4), pp. 257-284.

Ball, S.M. (**1982**). Exploration application of temperatures recorded on log heading - and up-the-odds method of hydrocarbon-charged porosity prediction. ***Am. Assoc. Petroleum Geologists Bull.,*** v. 66(8), pp. 1108-1123.

Blackwell, D.D., and Steele, **J.L. (1989).** Heat flow and geothermal potential of Kansas. ***Kansas Geol. Survey Bull.,*** v. **226,** pp. 267-**291.**

Chapman, D.S., Keho, T.H., Bauer, M.S., and Picard, M.D. **(1984).** Heat flow in the Uinta Basin determined from bottom-hole temperature (BHT) data. ***Geophysics,*** v. 49(4), pp. **453-466.**

Deming, D., and Chapman, D.S. **(1988).** Inversion of bottom-hole temperature data: the Pineview field Utah-Wyoming thrust belt. ***Geophysics,*** v. 53(3), pp. 707-720.

Deming, D. **(1989).** Application of bottom-hole temperature corrections in geothermal studies. ***Geothermics,*** v. 18(5/6), pp. 775-**786.**

Dowdle, W.L., and Cobb, W.M. **(1975).** Static formation temperature from well logs: an empirical method. ***Jour Petrol. Tech.,*** v. **27,** pp. 1326-1330.

Drury, M.J., Jessop, A.M., and Lewis, T.J. **(1984).** The detection of groundwater flow by precise temperature measurements in boreholes. ***Geothermics,*** **v.** 13(3), pp. 163-174.

Fertl, W.H., and Wichmann, **P.A. (1977).** How to determine static BHT from well log data. ***World Oil,*** v. **184,** pp. 105-106.

Forster, A., and Merriam, D.F. **(1993).** Geothermal field interpretation in south-central Kansas for parts of the Nemaha Anticline and flanking Cherokee and Sedgwick Basins. ***Basin Research,*** v. 5(4), pp. 213-234.

Forster, A., Merriam, D.F., and Brower, J.C. **(1993).** Relationship of geological and geothermal field properties: Midcontinent area, **USA,** an example. ***Jour Math. Geology,*** v. 25(7), pp. 937-947.

Herzfeld, U.C., and Merriam, D.F. **(1990).** A map-comparison technique utilizing weighted input parameters. In: ***Computer Applications in Resource Estimation, Prediction, and Assessment for Metals and Petroleum,*** Pergamon Press, Oxford, pp. **43-52.**

Kehle, R.O. **(1972).** ***Geothermal survey of North America*** Annual progress report. AAPG, Tulsa, Oklahoma.

Lucazeau, F., and Ben Dhia, H. **(1989).** Preliminary heat-flow density data from Tunisia and the Pelagian Sea. ***Can. Jour. Earth Sci.***, v. 26(5), p. **993-1000.**

Luheshi, M.N. **(1983).** Estimation of formation temperature from borehole measurements. ***Geophys. Jour Roy. Soc. London,*** v. 74(3), pp. 747-776.

Majorowicz, J., Jones, F.W., Lam, H.L., and Jessop, A.M. **(1984).** The variability of heat flow both regional and with depth in southern Alberta, Canada: effect of groundwater flow? ***Tectonophysics,*** v. 106(1/2), pp. **1-29.**

McGee, H.W., Meyer, H.J., and Pringle, T.R. **(1989).** Shallow geothermal anomalies overlying deeper oil and gas deposits in Rocky Mountain region. ***Am. Assoc. Petroleum Geologists Bull.,*** v. 73(5), pp. 576-597.

Meyer, H.J., and McGee, H.W. **(1985).** Oil and gas fields accompanied by geothermal anomalies in Rocky Mountain region. ***Am. Assoc. Petroleum Geologists Bull,*** v. 69(6), pp. **933-945.**

Merriam, D.F. **(1963).** The geologic history of Kansas. ***Kansas Geol. Survey Bull.*** **162,** 317pp.

Nielsen, **S.B.,**Balling, N., and Christiansen, H.S. **(1990).** Formation temperatures determined from stochastic inversion of borehole observations. ***Geophys. Jour Intern.,*** **v.** 101(3), pp. 581-590.

Sampson, R.J. **(1988).** ***SURFACE III.*** Interactive Concepts, Inc., Lawrence, Kansas, 277pp.

Speece, M.A., Bowen, T.D., Folcik, J.L., and Pollack, H.N. **(1985).** Analysis of temperatures in sedimentary basins: the Michigan Basin. ***Geophysics,*** v. 50(8), pp. **1318-1334.**

Stavnes, **S.A. (1982).** ***A preliminary study of the subsurface temperature distribution in Kansas and its relationship to the geology:*** unpubl. masters thesis, University of Kansas, 311pp.

Stavnes, S.A., and Steeples, D.W. **(1982).** ***Assessment of the geothermal resources of Kansas.*** Kansas Geol. Survey, map.