DOE/ET/27204--T1-Vol.1 Sect. 1

ASSESSMENT OF THE GEOTHERMAL RESOURCES OF KANSAS

Volume I - TEXT

Section 1

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ASSESSMENT OF THE GEOTHERMAL RESOURCES OF KANSAS

VOLUME I - TEXT
FINAL REPORT

Submitted to the Geothermal Division
of the U.S. Department of Energy

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AS07-79ET27204

June, 1982

VOLUME I

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ACKNOWLEDGEMENTS

This study has been supported by funding from the United States Department of Energy under grant number DE-AS07-79ET27204. Thanks are due the Kansas Geological Survey, especially its clerical, computational and administrative personnel. The following student assistants made substantial contributions to this project: Nelda Roehl, Anne Sheehan, Lance Tomlin, Mitchell Hall, Dave Kvam and Ginger Lin.

The following students made significant contributions to the aeromagnetic project. Roubik Avanessians assisted in the equipment acquisition, installation and testing. Robert Robertson's competence was a key influence in all phases of the project including data aquisition, reduction and interpretation. Robert Wentland developed several excellent computer programs including the FFT filtering program. Mike Wolf made some important modifications to the equipment. King Ng did an outstanding job of merging the preliminary partial maps into a final composite data set. Al Martin played a key role in the second half of the project in the areas of data acquisition and reduction. Rita Sooby efficiently carried out large responsibilities in the area of data reduction and interpretation.

We are in great debt to Dennis Sooby, University pilot for the chancellor's plane, who devoted a great deal of his time to expert piloting of our aircraft during his off hours. Stewart Giesick, a veteran Beech D-18 pilot, did a commendable job of flying western Kansas.

This work was supported principally by the Kansas Geological Survey, supported in part by special appropriation by the Kansas Legislature for an Automated Resource Evaluation System; by the U.S. Geological Survey, under grant 14-08-001-G-137; by the U.S. Nuclear Regulatory Commision, under grant AT(49-24)-0256; and by the U.S. Department of Energy, under grant DE-AS07-79ET27204.

For the geochemistry project, the help and patience extended by Jim Deputy for system orientation, WATSTORE and other programming problems is much appreciated. The support and guidance of Joe Brentano in contouring in FELIX, and the assistance of Charlie Ross in projection and mapping in GIMMAP made the accuracy and existence of the contour maps possible. The work of Lance Tomlin in producing the linear regression and correlation statistics and diagrams is appreciated.

INTRODUCTION

The purpose of this research is to provide a regional assessment of the geothermal energy potential for Kansas, using both of geological and geophysical information. In addition to evaluation of low temperature geothermal resource areas for the state, information obtained on the geology of the Precambrian basement rocks may provide the basis for future geological and geophysical studies for the Midcontinent.

METHOD OF INVESTIGATION

This report includes the following regional geological and geophysical studies:

1a - establishment of a geothermal gradient data base from approximately 45,000 bottom hole temperatures recorded from well logs and interpretation of this data in terms of regional geology,

1b - establishment and interpretation of a second data base of geothermal gradients from thermal logging data from 144 "holes of opportunity" in the state under the auspices of Dr. Don Steeples and Sandra Stavnes of the Kansas Geological Survey,

2 - detailed evaluation of heat flow and geothermal potential for Kansas on the basis of data from nine holes carried out under the auspices of Dr. David Blackwell and John Steele of Southern Methodist University,

3 - development of a thermal conductivity probe that could be used both *in situ* and in the laboratory by Dr. Marios Sophocleous and Mitchell Hall of the Kansas Geological Survey,

4 - aquisition and analyses of aeromagnetic and gravity (southeastern Kansas) data for Kansas carried out under the auspices of Dr. Harold Yarger and George Lam (gravity) of the Kansas Geological Survey,

5 - paleomagnetic investigation of two Precambrian basement cores from KGS-USGS observation holes located in northeastern Kansas carried out under the auspices of Dr. Ken Kodama of Lehigh University,

6 - evaluation of the silica geothermometer technique with special consideration for the postulated heat flow anomaly in northwestern Kansas (Swanberg and Morgan, 1979) carried out under the auspices of Dr. Don Whittemore and Nelda Roehl of the Kansas Geological Survey.

Abstracts for these studies follow:

GEOTHERMAL GRADIENT VALUES FOR KANSAS FROM BOTTOM HOLE TEMPERATURES AND THERMAL LOGGING DATA

A United States Department of Energy sponsored geothermal resource survey for the State of Kansas was undertaken in 1979. This paper is a partial summary of that survey. The purpose of this study was to investigate the subsurface temperature distribution for the state and to explain any geographic variation observed.

Geothermal gradient values are extrapolated from bottom hole temperatures recorded on oil and gas well logs. These gradients are used to delineate general geothermal trends which were examined in the field by thermal logging. The results of the thermal logging indicate that geothermal gradients for the state range from 25 ^{o}C/Km to 55 ^{o}C/Km.

Variations in the geothermal gradient data for Kansas appear to be controlled by:

1) topography of the crystalline basement surface

2) variations in rates of heat production in the crystalline basement, presumably, but not necessarily, resulting from variations in basement rock type

3) variation in thermal conductivity in the sedimentary section.

4) possible convection eastward and upward from the Denver-Julesberg Basin.

The effects of factor 1 are most evident statewide (i.e., thousands of square miles) whereas those for factors 2, 3 and 4 are evident over smaller areas for which factor 1 is essentially invariant.

HEAT FLOW AND GEOTHERMAL POTENTIAL OF KANSAS

Temperature, thermal conductivity measurements and heat flow values are presented for four holes originally drilled for water resources investigations by the U.S. and Kansas Geological Surveys. These holes cut most of the sedimentary section and were cased and allowed to reach temperature equilibrium. Several types of geophysical logs were also run for these holes. Temperature data from an additional five wells are also presented. Temperature gradients in the sedimentary section vary over a large range (over 4:1), and there are significantly different temperatures at the same depth in different portions of the state. Temperatures as high as 34°C occur at a depth of 500 m in the south-central portion of the state and 28°C or lower in other parts of the state. In addition to cuttings measurements, thermal conductivities were estimated from geophysical well log parameters; the results are useful and more use of the technique is suggested. Using these results geophysical well logs can be used to predict temperatures as a function of depth in areas for which no temperatures are available if heat flow is assumed. The extreme variation in gradients observed in the holes occur because of the large contrast in thermal conductivity values. Shale thermal conductivity values appear to have been overestimated in the past and the Paleozoic shales in Kansas have thermal conductivity values of about 1.18 ± 0.03 $Wm^{-1}K^{-1}$. On the high side, evaporite and dolomite units have thermal conductivities of over 4 $Wm^{-1}K^{-1}$. In spite of the large variations of gradient the heat flow values throughout the holes do not vary more than 10 per cent and any water flow effects which might be present due to the lateral motion on any of the aquifers are less than 10 per cent. The best estimates for heat flow in the four holes come from the carbonate units below the base of the Pennsylvanian and the values range from 48 mWm^{-2} to 62 mWm^{-2}. Two of the holes were drilled to basement and correlation of the heat flow with the basement radioactivity suggests that the heat flow-heat production line postulated for the Midcontinent by Roy et al (1968a) applies to these data. Because of the low thermal conductivity of the shales the radiogenic pluton concept should apply to the Midcontinent. Thus if very radioactive plutons can be identified, much higher temperatures may occur in the sedimentary section than has been thought possible in the past. However, the past overestimation of shale conductivity values suggests that some previous high heat flow values in the Midcontinent are probably not correct and the high gradients are merely due instead to normal heat flow and very low thermal conductivity values. In spite of its presence in the Midcontinent region there could be significant use of geothermal energy in Kansas for space heating, thermal assistance and heat pump applications because the temperatures in the sedimentary section in much of Kansas are in excess of 40°C.

DEVELOPMENT OF A LOW COST THERMAL CONDUCTIVITY PROBE

Low cost thermal conductivity probes were developed that could be used *in situ* and in the laboratory. These cylindrical type probes were calibrated by comparing thermal conductivity measurements obtained in Ottawa sand to those available for Ottawa sand in the literature. Cylindrical probes are most suited for soft rock thermal conductivity measurements where the probe can be inserted into the sediments with little effort. However, it was found that reliable measurements were obtained in the laboratory from dolomite core from the Arbuckle Group. A hole was drilled in the center of the core the diameter of the probe and the probe was inserted. Thermal conductivity measurements obtained were compatible with those obtained by Blackwell and Steele (Chapter 3, this report) for similar dolomite samples from the Arbuckle Group in Kansas.

REGIONAL INTERPRETATION OF KANSAS AEROMAGNETIC DATA

The Kansas Geological Survey has completed a 72,000 line kilometer aeromagnetic survey of the state. The total intensity magnetic field contour map, along with spectrally filtered versions, provide a better understanding of basement composition and paleotectonics within the state.

The magnetic data indicate that the southern part of the Proterozoic Central North American Rift System (CNARS) does not terminate in central Kansas but continues along a southeastern trend to at least the Oklahoma border. Some of the current seismicity within the state appears to be correlated with reactivated faults within CNARS.

There are indications of a distinct (paleoplate?) boundary between the 1600-1700 m.y. old mesozonal granitic terrane to the north and the 1400 m.y. old epizonal granitic terrane to the south.

There are numerous highly magnetic shallow granitic plutons, several known from drilling to be 1350 m.y. old, embedded in the older granitic crust in northeastern Kansas.

PALEOMAGNETIC RESULTS FROM THE OSAWATOMIE CORE AND BIG SPRINGS CORE, KANSAS

Paleomagnetic studies of nine independently oriented samples from a core drilled into the Precambrian basement rocks at an aeromagnetic high near Osawatomie, Kansas and four samples from a basement core drilled at a separate aeromagnetic high near Big Springs, Kansas suggest that these rocks are magnetic enough to produce the observed total field anomalies. The characteristic directions derived from Zijderveld plots of the alternating field demagnetization data have inclinations (Osawatomie I = -20.5^{o}, Big Springs I = 51.5^{o}) which agree reasonably well with the radiometric ages (1355 m.y.b.p.) for these rocks based on Irving and McGlynn's (1976) apparent polar wander path for the North American Precambrian. The difference in mean inclinations for the two cores, however, does suggest that there may be a 50-80 m.y. difference in the cooling age of the two intrusive bodies. Steep NRM inclinations in most of the Osawatomie samples and some of the Big Springs samples suggest the presence of an IRM in the rocks which may have been acquired during drilling. This could indicate that the *in situ* NRM intensity for the Osawatomie core may be less than the measured NRM intensity by a factor of two.

GRAVITY MEASUREMENTS IN KANSAS

Approximately 16,000 new gravity measurements have been taken in Kansas in recent years. The average spacing in eastern Kansas is one mile east-west by four miles north-south and in western Kansas is one mile east-west by two miles north-south. Bouger gravity maps of the first 6000 points reveal numerous basement related anomalies not apparent in the earlier statewide Bouger gravity map (Woolard, 1958). A new gravity map of entire eastern Kansas will be completed by fall, 1982. Approximately 15,000 additional measurements will be taken in western Kansas during the next two years with a new map expected in 1984. These new data are proving very useful in the study of basement lithology and tectonics.

GEOTHERMAL MAPPING OF WESTERN KANSAS BASED ON CHEMICAL GEOTHERMOMETERS

Geothermal temperatures were computed from five chemical geothermometers for approximately 1,200 irrigation well waters from the broad, unconsolidated aquifers in the western two-thirds of Kansas. The chalcedony and Na-K-Ca geothermometers gave the most reasonable temperatures, although ranging widely between 3-88^{o}C. Higher temperatures computed from both equations were distributed throughout northwestern Kansas and extended into the west-central part of the state. Quartz and Na/K geothermometer temperatures were unreasonably high and many temperatures from a Na-K-Ca geothermometer modified for carbon dioxide were below 0^{o}C. The correlation between chalcedony geothermometer temperature and subsurface temperatures at 300 meters derived from thermal logging of boreholes is statistically highly significant; the correlation coefficient is 0.68. However, the geochemistry of sediments in the aquifers, which are less than 200 meters in depth, is probably a much more important control on dissolved silica and cation concentrations than temperatures underneath the aquifers. The Pliocene strata of the Ogallala aquifer generally contain a greater percentage of volcanic ash than the Pleistocene sediments across Kansas. Larger deposits of silicified rock cemented with opal, (derived from ash leaching), occur more frequently in the northern part than elsewhere in the Ogallala Formation of western Kansas. The greater volumes of ash and opal, (containing silica more soluble than chalcedony and quartz), give rise to the higher silica concentrations in groundwaters of northwest and parts of west-central Kansas. Leaching of the potassium-rich ash and feldspar in the Ogallala aquifer could also explain a similar distribution of higher ratios of dissolved potassium to higher total dissolved solids.

REGIONAL GEOLOGY

Kansas, located in the Midcontinent of the United States, is geographically part of the "Central Stable Region" (Merriam, 1963, p.14). There have been no major tectonic events in Kansas since late Paleozoic time.

PHANEROZOIC GEOLOGY (after Merriam, 1963)

All Phanerozoic geologic systems are represented in Kansas. However, nowhere in the state is the geologic section complete. Phanerozoic strata reach a maximum thickness of three kilometers in the Hugoton Embayment of the Anadarko Basin in southwestern Kansas (Figure 1-1). Overall, the Phanerozoic stratigraphic section is relatively thin (several hundreds of meters) and the structure is simple (strata are essentially flat-lying).

Cenozoic deposits occur mainly in the western half of the state. They consist primarily of semi- and unconsolidated terrigenous sediments. Rocks of Mesozoic age are also confined to western Kansas and consist predominantly of shale with some carbonate. A widespread erosional episode prior to deposition of the Ogallala Formation (Tertiary) removed rocks of Mesozoic age from eastern Kansas.

The Permian (western four-fifths of the state) and Pennsylvanian (entire state) systems consist of alternating marine and non-marine carbonate and shale. Mississippian units are present throughout much of eastern Kansas except over basement topographic highs. Silurian and Devonian rocks are confined to northern and northeastern Kansas, whereas Cambro-Ordovician rocks occur everywhere in the subsurface except over portions of the Nemaha Ridge and the Central Kansas Uplift. Pre - Pennsylvanian rocks in Kansas are predominantly carbonate.

Major unconformities in Kansas occur between the Mesozoic and Paleozoic, Pennsylvanian and Mississippian, Mississippian (following deposition of the Chattanooga Shale) and Devonian, and the Paleozoic and Precambrian.

PHANEROZOIC IGNEOUS ACTIVITY

Phanerozoic igneous activity in Kansas is limited to two possibly related localities. At least six kimberlite bodies are known to exist in Riley County in northeastern Kansas (Figure 1-2) with more likely to be found in the future. Based on petrologic evidence, geometry (inferred from magnetic and well data) and the presence of xenoliths, Brookins (1970) estimated that final emplacement occurred in post - Dakota/pre - Graneros time (late early Cretaceous - maximum of 120 $\pm$ 10 m.y. ago) at temperatures between 70 and 150 ^{o}C. No high-temperature, contact metamorphic effects have been observed in the lower Permian carbonate (Ft. Riley Limestone - Chase Group) country rocks and xenoliths of Phanerozoic sedimentary rocks show only minor alteration effects from the kimberlite magma. These observations suggest that there was rapid injection into the near-surface locus of final cooling (Brookins and Meyer, 1974).

The second area in which Phanerozoic igneous activity occurred is in southern Woodson County about 200 kilometers southeast of the Riley County kimberlites (Figure 1-2). Here two alkaline ultramafic (peridotitic) bodies have intruded the local upper Pennsylvanian strata, forming structural features known as the Rose and Silver City domes. Both of these peridotitic bodies, which are probably genetically related, were emplaced in middle Cretaceous time, approximately 90 m.y. ago (Zartman et al, 1967). At Rose Dome, granitic xenoliths of Precambrian age (1400 m.y.) were apparently incorporated into the peridotitic magma and eventually brought closer to the surface (Bickford et al, 1981). As a result of inclusion in the magma, the xenoliths were partially melted and retain both high and low temperature phases of feldspars (high-sanidine and microcline; high-albite and low-albite; Franks et al, 1971). Contact metamorphic effects are also present in the country rock (Weston Shale - Douglas Group; Stanton Limestone - upper Kansas City Group). On the basis of this evidence, Franks et al (1971) concluded that the Rose and Silver City Domes were probably emplaced at relatively high temperatures on the order of 800 ^{o}C.

The emplacement mechanisms of the Riley County kimberlites and the Woodson County peridotites were certainly different (Brookins, 1970). However, both the kimberlites and the peridotites are of Cretaceous age, both are ultramafic in composition and probably originated in the upper mantle, and both occur in eastern Kansas and are the only Phanerozoic igneous events known in the state. Because of their age, they are not likely to affect the present geothermal gradient other than in a passive sense, i.e., as thermal conductivity anomalies, or by providing fractured pathways to the surface for geothermal fluids.

PRECAMBRIAN BASEMENT COMPLEX

Recent studies of the Precambrian basement complex in Kansas (Muehlberger et al, 1966; Lidiak, 1972; Van Schmus and Bickford, 1981; Bickford et al, 1981; Denison et al, in press) have found it to be a more diverse rock assemblage than imagined by previous investigators. As the data available include geophysical maps (aeromagnetic and gravity surveys) only, limited core and cutting samples and attempted correlation with exposed Precambrian rocks outside the state, only major distinctions in basement rock type and structure can be discerned. The Precambrian complex in Kansas can be generally divided into a northern, older (1630 m.y.) terrane (Figure 1-3) and a younger terrane (Bickford et al, 1981) ranging from 1350 m.y. to 1480 m.y. in age, in the southern one-third of the state (Figure 1-4).

Bickford et al (1979) recently compiled a basement-rock-type map of Kansas and adjacent Midcontinent states, based on available basement well samples (Figures 1-3 and 1-4). The Kansas portion of this map is based on a study of more than 800 thin sections from basement well samples. The basement terrane in northern Kansas is characterized by granitic to quartz monzonitic intrusive rock, estimated to have been emplaced at depths of 6.5 to 13 km. These mesozonal rocks often have cataclastic to extensively sheared textures, particularly along the Nemaha Ridge. Zircon dates (U/Pb) in northeastern Kansas and northwestern Missouri indicate an age of 1625 m.y. for this terrane. In contrast, basement wells in southern Kansas reveal silicic volcanic rocks and associated shallowly emplaced granite. These volcanic and epizonal rocks are not cataclastically deformed and have a nominal age of 1400 m.y.

The dominant rock types in the northern area range in composition from granite to granodiorite and are, at most, moderately foliated. Metamorphic rocks in this area occur either as isolated bodies with diameters on the order of several kilometers or in distinct belts several tens of kilometers long.

The southern terrane consists mostly of rhyolitic to dacitic volcanic rocks which are associated with granitic plutons. U-Pb measurements of zircons indicate that these rocks were formed 1350 m.y. to 1500 m.y. ago (Bickford et al, 1981). Sedimentary rocks are rare and there are almost no mafic igneous rocks in this area.

The Midcontinent Geophysical Anomaly (MGA), a major magnetic and gravity anomaly in the northern terrane, (Figure 1-3), trends northeasterly and can be traced to Minnesota. It is inferred that mafic igneous rocks present in the subsurface are responsible for the anomaly and that these rocks are probably related to the Keweenawan basalts which outcrop in Minnesota adjacent to and along the trend of the MGA. Unpublished data from the Consortium for Continental Reflection Profiling (COCORP) indicate that basalt flows as thick as 5 kilometers are present, in the subsurface, along the axis of the MGA in north central Kansas. The Keweenawan basalts are approximately 1100 m.y. old (Goldich et al, 1961; Silver and Green, 1972; Chaudhuri and Faure, 1967; Van Schmus, 1971). The areal persistence and geometry of the MGA and the subsurface proximity of Precambrian(?) sedimentary rocks designated Rice Formation (Scott, 1966) in Kansas adjacent to the mapped area of the MGA has led most investigators to conclude that this feature represents a failed, late-Proterozoic rift system designated the Central North American Rift System (CNARS; Ocola and Meyer, 1973).

The Nemaha Ridge, which extends in Kansas from Nemaha County to Sumner County (Figures 1-3 and 1-4), consists of granitic rocks that are fault bounded on the east side (Humboldt Fault Zone) with more than 800 meters of vertical displacement. These rocks probably represent deeper crustal material that moved up along faults in the basement and was exposed to erosion during Paleozoic time. Xenolith pebbles of granite have been found in cores of lower Paleozoic aged rocks from proprietary wells along the west flank of the Nemaha Ridge in northeastern Kansas. At present, the Nemaha Ridge comes to within 180 meters of the surface in Nemaha County (Cole, 1976). The configuration of the Precambrian surface (Figure 5-10) exhibits a northeasterly trending grain in a swath through Kansas approximately 90 miles wide. Outside this zone the prevailing grain trends northwest.

The Central Kansas Uplift is a broad region in which basement rocks have been moved upward and which is characterized by fault zones and cataclasis. The feature is evidently coextensive with the Cambridge Arch in Nebraska. Although the Central Kansas Uplift was active during the Paleozoic, little is known about its Precambrian history. A relatively high level of microearthquake activity (more than 20 events per year larger than magnitude 1) occurs along this structural trend (Steeples, 1980).

The Forest City Basin is located mostly in Iowa, Missouri and Nebraska. The southwestern corner, which is the deepest part of the basin, lies in northeastern Kansas and is bounded on the west by the Nemaha Ridge. The Cherokee Basin in southeastern Kansas and northeastern Oklahoma could be considered a shallow southern extension of the Forest City Basin. However, a mildly positive feature, the Bourbon Arch, separates the two basins.

The southern end of the Salina Basin, which is its deepest part, lies in north central Kansas. In Kansas it is bounded on the east by the Nemaha Ridge and on the west by the Central Kansas Uplift. It terminates to the south at an unnamed saddle. Before post-Mississippian deformation, it formed part of the larger ancestral North Kansas Basin. The maximum thickness of sediment found in the basin is 1400 m (Merriam, 1963). To the south lies the Sedgwick Basin, which is a northern shelf extension of the large Anadarko Basin in Oklahoma. The Hugoton Embayment which covers much of western Kansas is also an extension of the much deeper Anadarko Basin in Oklahoma.

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FIGURE CAPTIONS

FIGURE 1-1: Location map of major structural features in Kansas (after Paul *et al*, 1979).

FIGURE 1-2: Location map of Phanerozoic igneous events in Kansas.

FIGURE 1-3: Major features of the Precambrian crystalline basement in the Midcontinent, including the northern terrane in Kansas (after Bickford *et al*, 1981).

FIGURE 1-4: Major features of the Precambrian crystalline basement in the Midcontinent, including the southern terrane in Kansas (after Bickford *et al*, 1981).

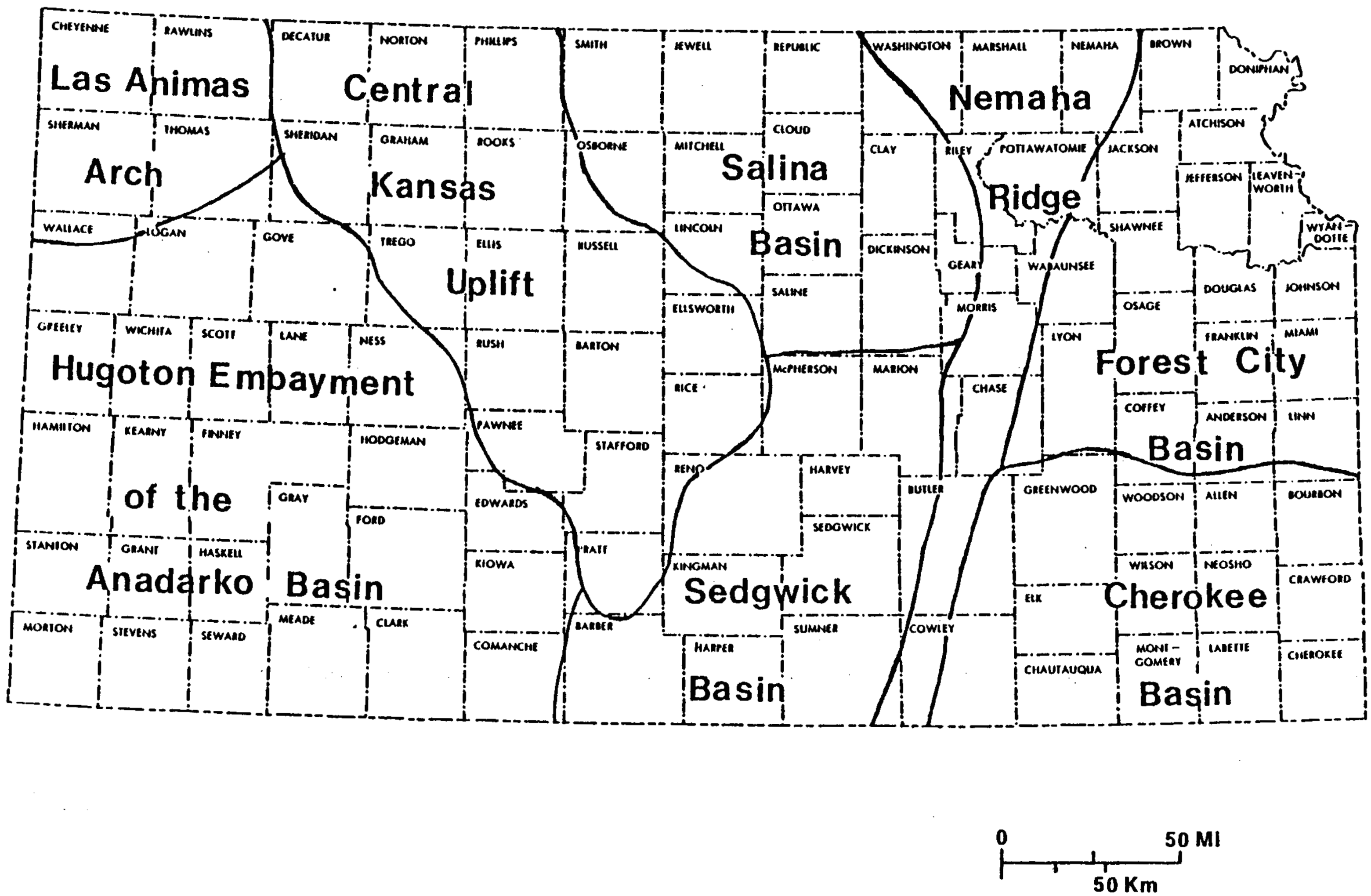
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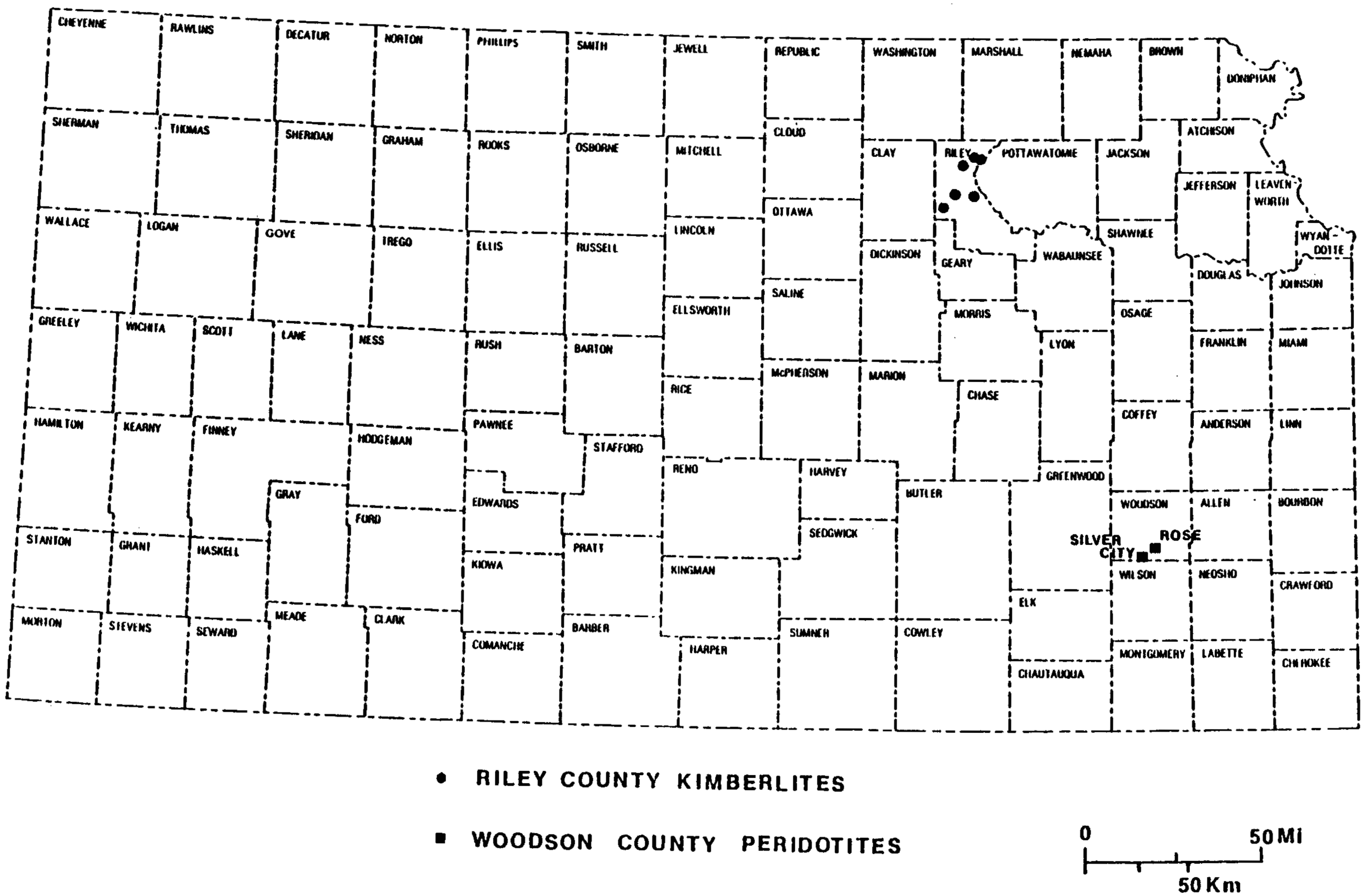
FIGURE 1-1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ATCHISON
JEFFERSON
LEAVEN-WORTH
WALLACE
LOGAN
GOVE
TREGO
ELLIS
RUSSELL
LINCOLN
OTTAWA
DICKINSON
GEARY
WABAUNSEE
SHAWNEE
WYAN-DOTTE
DOUGLAS
JOHNSON
SALINE
GREELEY
WICHITA
SCOTT
LANE
NESS
RUSH
BARTON
ELLSWORTH
MORRIS
OSAGE
LYON
FRANKLIN
MIAMI
McPHERSON
MARION
RICE
CHASE
COFFEY
ANDERSON
LINN
HAMILTON
KEARNY
FINNEY
HODGEMAN
PAWNEE
STAFFORD
RENO
HARVEY
GREENWOOD
BUTLER
GRAY
EDWARDS
FORD
WOODSON
ALLEN
BOURBON
STANTON
GRANT
HASKELL
KIOWA
PRATT
SEDGWICK
SILVER CITY
ROSE
KINGMAN
WILSON
NEOSHO
CRAWFORD
ELK
MORTON
STEVENS
SEWARD
MEADE
CLARK
COMANCHE
BARBER
SUMNER
COWLEY
HARPER
MONTGOMERY
LABETTE
CHEROKEE
CHAUTAUQUA
RILEY COUNTY KIMBERLITES
WOODSON COUNTY PERIDOTITES
0
50 Mi
50 Km

FIGURE 1-2

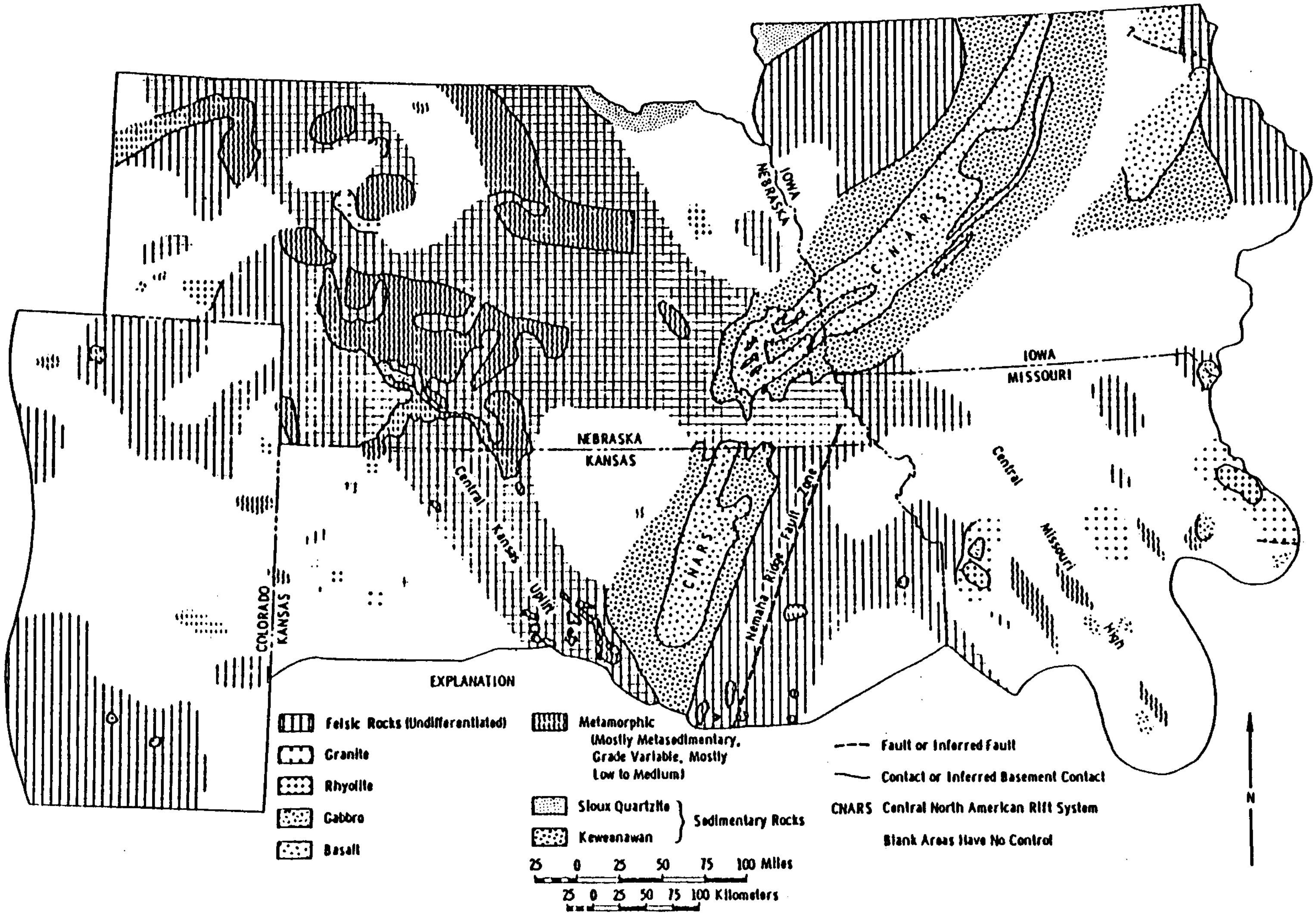
IOWA
NEBRASKA
CNARS
IOWA
MISSOURI
NEBRASKA
KANSAS
Central Kansas Uplift
Nemaha Ridge Fault Zone
Central Missouri High
COLORADO
KANSAS
EXPLANATION
Felsic Rocks (Undifferentiated)
Granite
Rhyolite
Gabbro
Basalt
Metamorphic
(Mostly Metasedimentary, Grade Variable, Mostly Low to Medium)
Sioux Quartzite
Keweenawan
Sedimentary Rocks
Fault or Inferred Fault
Contact or Inferred Basement Contact
CNARS Central North American Rift System
Blank Areas Have No Control
25 0 25 50 75 100 Miles
25 0 25 50 75 100 Kilometers
N

FIGURE 1-3

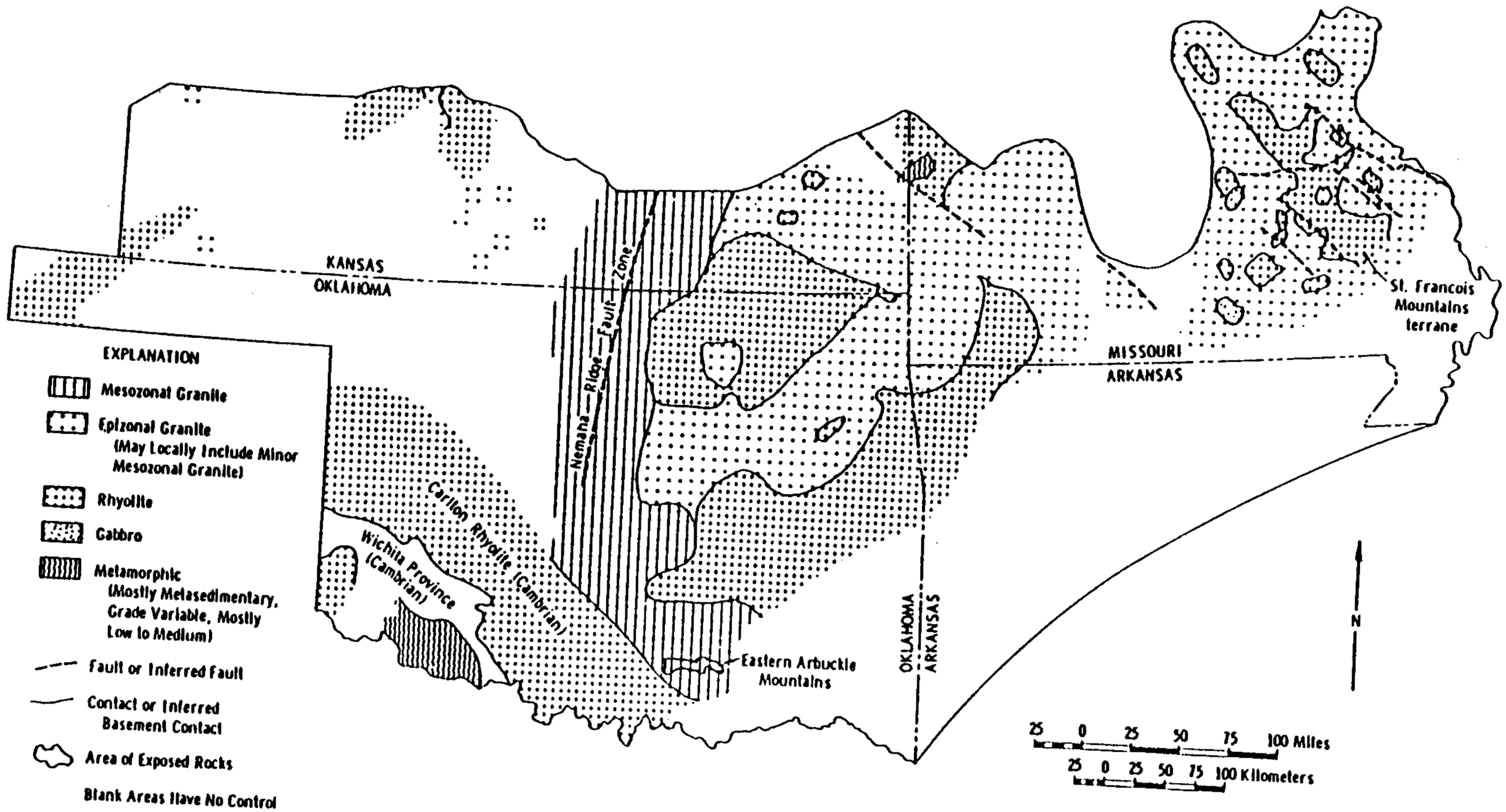
KANSAS
OKLAHOMA
MISSOURI
ARKANSAS
OKLAHOMA
ARKANSAS
Nemaha Ridge Fault Zone
Carlton Rhyolite (Cambrian)
Wichita Province (Cambrian)
Eastern Arbuckle Mountains
St. Francois Mountains terrane
N
25 0 25 50 75 100 Miles
25 0 25 50 75 100 Kilometers
EXPLANATION
Mesozonal Granite
Epizonal Granite (May Locally Include Minor Mesozonal Granite)
Rhyolite
Gabbro
Metamorphic (Mostly Metasedimentary, Grade Variable, Mostly Low to Medium)
Fault or Inferred Fault
Contact or Inferred Basement Contact
Area of Exposed Rocks
Blank Areas Have No Control

FIGURE 1-4

GEOTHERMAL GRADIENT VALUES FOR KANSAS FROM BOTTOM HOLE TEMPERATURES AND THERMAL LOGGING DATA

by

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INTRODUCTION

BOTTOM HOLE DATA

Bottom hole data for the State of Kansas were compiled from 42,521 of 66,765 well records (electric logs) on file in the Oil and Gas Library at the Kansas Geological Survey (a typical well log header is shown in Figure 2-1). The location of each well from which bottom hole data were obtained is shown in Figure 2-2.

THERMAL LOGGING DATA

During the 1980 summer field season, an assistant and I thermally logged wells in the northwestern and southeastern quarters of Kansas, an area including 52 counties (Figure 2-3). Our goal was to obtain at least two temperature logs per county in order to achieve the minimum areal spacing in the time available - approximately one well every 2500 square kilometers. In total, 125 wells were logged of which 93 are considered useable (p.30-34, this paper).

In 1981, similar field work was done in southwestern and northeastern Kansas (Figure 2-3). We logged 58 wells of which 51 are considered useable (p.30-34, this paper). Because most of the 1980 data are from wells penetrating only Cenozoic deposits, it was decided for 1981 to log only wells deeper than 150 meters. This limited the choice of wells to those drilled for oil and gas and necessarily restricted coverage to oil and gas fields. Only wells that had been temporarily abandoned or recently drilled were logged.

One concern in logging recently drilled wells is that the time interval between completion of the hole and the thermal logging of the well should be long enough for the rock temperatures to reach equilibrium. We selected wells that had been completed at least three weeks prior to our logging date. This restriction eliminated many wells that were put into service almost immediately after completion.

Hydrologic disturbances in the borehole are usually associated with uncased wells or wells with screened intervals (e.g., water supply wells; observation wells). All of the thermal logging data used in this study were obtained from cased wells. The bulk of these holes are oil and gas wells and therefore only open to the formation where the casing is perforated (usually near the bottom of the hole).

In 1981, we returned to portions of northwestern and southeastern Kansas and thermally logged several holes to depths between 183 and 366 meters (deeper than the logs obtained from holes in these areas in 1980). Field data are still unavailable for much of north-central and northeastern Kansas because of the lack of suitable wells in those areas.

Thermal Logging Method.

The thermal logging data were obtained by lowering the well probe into the well and measuring temperatures at regular depth intervals (Figure I-1). Selection of the depth intervals used was based either on total depth logged or the depth to water. Shallow holes (less than 125 meters) were logged using a 1.5 meter interval. Medium (125 to 250 meter) and deep (250 to 375 meter) holes were logged using a 3.0 meter interval, in most cases.

The heat capacity of water is 1.00 gcal/g (Eschbach, 1936, p.1-124) (where gcal/g are units of gram-calories per gram) whereas that for air at constant volume is 0.173 gcal/g (Eschbach, 1936, p.7-17). The relatively high heat capacity of water allows the logging apparatus to reach an equilibrium temperature faster in water-filled as opposed to air-filled holes. Most researchers believe that temperature measurements in air-filled holes are less reliable because air is less likely to be thermally stable than water in a borehole (Misener and Beck, 1960; Blackwell and Steele, Chapter 3, this report).

We were generally unable to log air-filled holes deeper than 183 meters because the long response time of the thermal logging instrument in air (up to 30 minutes per reading) and extreme surface temperatures caused it's internal circuitry to overheat after three to four hours of continuous use (Appendix I., p.2). In such cases, we used a 4.6 meter depth interval. However, in holes that had water levels less than 183 meters below ground level, we were often able to log to the total depth of the hole or a maximum of 366 meters (total length of logging cable). This was possible because the readings could be taken faster in water (manufacturer specified response time of 10 to 15 seconds; see "Appendix I.", p.2) and the instrument was not operating continuously over long time periods during which individual measurements were taken.

DATA ANALYSIS

BOTTOM HOLE DATA

A geothermal gradient map for the State of Kansas was generated using bottom hole data. The gradients (assumed to be linear) were calculated using the BHT at total depth as recorded from the well logs and a fixed value of 56 ^{o}F at 50 feet below ground level:

$$\nabla T_z = 100[(BHT - 56\ ^{o}F)/(TD - 50\ feet)] \qquad \text{(Eqn. 2-1)}$$

where, ∇T_z is the magnitude of the vertical component of the geothermal gradient in ^{o}F/100 feet

BHT is the bottom hole temperature in ^{o}F

TD is the total depth of the well in feet

56 ^{o}F and 50 feet are the temperature and depth intercepts, respectively.

(The conversion factor from ^{o}F/100 feet to ^{o}C/km is 18.23.)

The statewide average annual ambient surface temperature of 12.8 ^{o}C (55 ^{o}F) could not be used for the surface temperature in computing gradients because the thermal logging data obtained for most holes revealed highly variable geothermal gradients in the upper 15 meters. A value of 13.3 ^{o}C (56 ^{o}F) at -15 meters (50 feet) was finally selected because this was the temperature most frequently recorded in the thermal logging, at that depth, throughout the entire state.

42,521 geothermal gradient values were computed from bottom hole data using Equation 2-1. In order to generate a geothermal gradient map for Kansas using these data, a selection process had to be devised whereby the "best" data would be used for this map. The best data would obviously be those data calculated from BHTs that were from wells in equilibrium with the surrounding rock.

Previous workers have used information on the time interval between cessation of circulation of drilling mud in the hole (time since circulation) and measurement of the BHT to estimate the true formation temperature at bottom of the hole (Evans and Coleman, 1974; Nwachukwu, 1975). Because times since circulation are recorded on only 40 per cent of the well logs available for Kansas (16,878 data), methods using this information to evaluate all of the bottom hole data are out of the question. When this information is given, it is typically on the order of two to five hours. Because the temperature of the drilling mud (assumption: initial temperature = surface temperature) circulating through the well during drilling is lower than the true formation temperature the BHT values measured after cessation of drilling are generally lower than the equilibrated bottom hole temperatures (Nwachukwu, 1975; Evans and Coleman, 1974; Carvalho and Vaquier, 1977). In Kansas, the mud would act to cool holes that were drilled deeper than approximately 800 meters.

The time required for a hole to reach temperature equilibrium depends upon the length of time it took to drill the hole. Near the bottom of the hole thermal equilibrium with the surrounding formation may be achieved as soon as a day after drilling has ceased. The entire hole, on the other hand, may take months to reach temperature equilibrium as the disturbance due to drilling lasted longer in the upper portions of the hole (Bullard, 1947). Bullard suggested that a multiple of 10 to 20 times the drilling time is required for the entire hole to equilibrate within one per cent of the true temperature profile. This would require a period of at least one month before logging during which the hole was not disturbed.

In this study, times since circulation on the order of 24 hours were the minimum required for the recorded BHT to be considered a measure of the true formation temperature. Times of this order were found on only seventeen well records (0.1 per cent of bottom hole data with time since circulation information; 0.04 per cent of entire bottom hole data set). Therefore, it is probable that some of the BHT's recorded on the well logs do not represent equilibrium temperatures. However, if it is understood that the bottom hole data can only indicate relative geothermal gradient values over a region, this problem of equilibrium is of minor concern. Also, it is assumed that the quantity of data will compensate for the few extreme values that may be present.

The bottom hole data were analyzed as follows:

1) geothermal gradients computed from bottom hole data were selected from each township and range in the state on the basis of the following six criteria:

   a) well with highest computed geothermal gradient

   b) well with highest geothermal gradient and total depth of at least 380 meters

   c) well with highest geothermal gradient and total depth of at least 760 meters

   d) mean value of geothermal gradient for all wells drilled deeper than 305 meters

e) mean value of geothermal gradient for all wells drilled deeper than 305 meters since 1955

f) mean value of geothermal gradient for all wells

2) separate geothermal gradient maps were generated from each of the above.

Each map was produced by setting up a grid on a base map of the State of Kansas (1:1,000,000; Lambert Projection). The geothermal gradient value at each grid point (point of intersection of two grid lines; every 0.04 degrees latitude and longitude) was computed by selecting data, according to one of the criteria established above (1a-1f), for the eight townships and ranges nearest the grid point and gradients were contoured using computer plotting programs available at the Kansas Geological Survey. To examine areas where data coverage was poor, the location of each well from which bottom hole data were compiled (42,521 data points) was plotted (Figure 2-2).

The maps generated for each criterion were compared and geothermal gradient trends (highs and lows) that were present on several of the maps were considered to be "real". This was demonstrated to be a valid assumption on the basis of results from the BHT Correction Factor Analysis (p.35, this paper). In this analysis it was found that bottom hole data from oil and gas wells in six areas (each area 1600 square kilometers) of the state could be fit with a significant regression line (Appendix IV., p.55-57). It follows that, for each area, most of the data would yield a similar geothermal gradient value and this lends credence to the map selection process discussed above. The geothermal gradient map based on bottom hole data used in the interpretation is the map generated from data for wells drilled to depths in excess of 305 meters (map 1d, above; Plate 2-1). This data set included 99.6 per cent of the available bottom hole data.

A map of the temperature distribution based on a datum of 300 meters below ground level was prepared (Plate 2-2) using the BHT data for wells drilled to depths in excess of 305 meters. The temperature at 300 meters below ground level was calculated from the value of the geothermal gradient as follows:

$$T_{300m} = [(\nabla T_z)(1km/1000m)(300m - 15.2m)] + 13.3\ ^{o}C \qquad \text{(Eqn. 2-2)}$$

where, ∇T_z is the magnitude of the vertical component of of the geothermal gradient in ^{o}C

300m is the depth datum

15.2m is the value of the minimum depth (see Eqn. 2-1)

13.3 ^{o}C is the temperature intercept at a depth of 15.2 meters.

The grid was layed out as before on a base map of Kansas (1:1,000,000; Lambert Projection) and temperatures were contoured using the appropriate computer contouring programs. This map will be compared to the similar map prepared from thermal logging data.

THERMAL LOGGING DATA

Well codes referred to in this section and elsewhere were generated by combining the Kansas Department of Transportation's County code, a prefix of "1" (useable well) or blank (non-useable well) and a numeric suffix indicating the order in which the well was logged.

For example:

1AN3 - third useable well logged in Anderson County
BB1 - first non-useable well logged in Bourbon County.*

Geothermal gradients were calculated for wells that were logged in 1980 and 1981. Temperature data for 144 of these wells were used in this study. It was observed that temperature generally increased linearly with depth in Kansas and linear regression analyses (Appendix IV.) were performed on the data from every well logged. The thermal logging data are classified as useable if they can be fit with a significant linear regression (greater than 95 per cent significance level by t-test) and if the regression coefficient (B) is positive (i.e., temperature increased with depth; Appendix IV.).

Some of the thermal logging data showed essentially no increase of temperature with depth. This could be due to movement of fluid in the hole (convection), flow of groundwater, or some recent man-made disturbance in the well (such as recent pumping). To study the potential for convection Misener and Beck (1960) plotted the radius of the borehole compared to the critical geothermal gradient for constant temperatures (Figure 2-4). These temperature curves represent typical temperatures measured in the hole. If the geothermal gradient computed for a hole exceeds the critical gradient the temperatures measured in the hole may be unstable (Misener and

*Referred to by township-range location in Blackwell and Steele, Chapter 3; by county in Yarger, Chapter 4; by town near where hole is located in Kodama, Chapter 6.

Beck, 1960; Diment, 1967). For a measured temperature of 15 °C and computed geothermal gradient of 30 °C/km, instability may occur if the borehole radius is 3 centimeters or greater. For example, OT1 (Appendix IV., p.165) shows a linear increase of temperature with depth, probably due to movement of water in the hole, resulting in an isothermal temperature profile. Well OT1 has a casing diameter of 0.5 meters. Well CD1 (Appendix IV., p.159) is another example of a well with a low linear geothermal gradient of -1.9 °C/km; there was no net increase in temperature between ten and 35 meters (Appendix IV., p.106). After this well was logged we discovered that the owner had pumped it less than two hours before. Wells that show little or no increase in temperature with increasing depth are classified as non-useable.

Geothermal gradients computed from field data were then contoured using the same computer programs as those used for the bottom hole data. Well locations are designated by a "+" on the map (Plate 2-3) and gradient values are posted. Only wells logged to at least 122 meters are plotted. As a result, data are lacking for some areas in north-central Kansas where there is little or no oil or gas production. A subset of this data was used to generate geothermal gradient maps for wells logged to at least 183 meters (Plate 2-4).

A map of the temperature distribution at 300 meters below ground level was also produced using data for wells at least 122 meters deep (Plate 2-5). On this map temperatures (°C) at a depth of 300 meters are posted. A "+" designates that the well was actually logged to 300 meters, while a "0" indicates that a temperature value was projected for the well from the geothermal gradient.

Temperature profiles (plots of temperature verses depth) were plotted (Appendix III.) for the thermal logging data (on the Hewlett Packard model 7221a plotter at the University of Kansas Academic Computer Center). Generalized stratigraphic columns are included on the profiles for 1980 data. The stratigraphic information was obtained from pertinent KGS and USGS bulletins, referenced in Appendix III. This information was found to be of little use in the analysis because the thermal logging equipment was not calibrated finely enough (to 0.1 degree Fahrenheit or Celcius) to record small scale changes in thermal conductivity (i.e., lithology) and because most of the stratigraphic information on the profiles was only presented at the group level.

There are two wells (not included on the geothermal gradient or temperature maps) for which the computed geothermal gradients are approximately half the value of the gradients from surrounding wells. The first well, a temporarily abandoned oil well in southern Russell County (1RS1), yielded a geothermal gradient of 17 $^{o}C/km$ (Appendix IV., p.133). Because these measurements were taken in air and the hole is located in a large active oil field (Trapp Field) undergoing enhanced oil recovery at the time it was logged (i.e., water flooding; Paul and Bahnmaier, 1981), the data are questionable. The second well, in Clark County (1CA1), yielded a geothermal gradient of 13 $^{o}C/km$ (Appendix IV., p.143). This well was full of water and completed more than a month before we logged it. There is a good possibility that the gradient computed for this well is not spurious but a result of the regional easterly groundwater movement that is controlled by faulting in the upper Permian strata (principally the "Taloga" and Whitehorse Formations; Frye, 1950). Well 1CA1 is located on the southeastern edge of the Ashland - Englewood lowland: "...the largest solution-subsidence feature in Kansas..." (Frye, 1950, p.7). Downward movement of groundwater along faults and into the Permian strata has resulted in the development of "solution-subsidence depressions" in portions of Meade and Clark Counties due to the dissolution of salt, gypsum and limestone.

I have thermally logged twenty wells to depths of aproximately 300 meters. Temperature profiles for these wells are included in Appendix III. D.D. Blackwell of Southern Methodist University has subsequently re-logged five of these wells to depths in excess of 500 meters (for more information see Chapter 3, this report). Figure 2-5 compares my thermal logging data for the KGS-USGS Big Springs hole located in Douglas County (1DG1-III) to Blackwell's data for the same hole (1DG1-B). Geothermal gradients computed from the data are essentially the same and the temperature profiles are similar over the interval from zero to 366 meters. The actual temperatures measured differ by one degree Celcius because of calibration.

<u>Repeatability of Measurements</u>.

A repeatability study of the logging method was done using the KGS-USGS Big Springs hole located in Douglas County (Figure 2-6). Regression coefficients in 1DG1-I and 1DG1-III were compared because these two logs are the most dissimilar (Appendix IV., p.222). Because the two regression coefficients are not significantly different from each other I conclude that the thermal logging data obtained are reproducable and also that seasonal variation of surface temperature has little effect on the geothermal gradient below 30 meters.

BHT CORRECTION FACTOR ANALYSIS

A comparison was made between the bottom hole data from oil and gas wells in the vicinity of holes that were logged to depths in excess of 500 meters and the temperature profile for these holes (Appendix III., p.55-57). The purpose of this comparison was to see whether the BHT's recorded for an area could be corrected to some equilibrium temperature (assuming the temperatures measured in the logged well are representative of the rock temperatures). A circular area of radius 40 kilometers centered on the logged hole was searched for available bottom hole data. In all cases, the bottom hole data from wells for a particular area could be fit with a significant regression line (represented by dashed line on profiles in Appendices III., p.55-57 and IV., p.217-219). The difference between this regression line and the temperature profile of the logged hole, gives an indication of the correction needed for BHT values to be regarded as a measure of the true formation temperature at the bottom of the hole. This approach may be applicable to other investigations in correcting BHT data to true bottom hole temperatures if deep thermal logging data are available for several wells.

The size of the area required for this analysis is at least large enough to include several tens of wells with recorded BHTs (a potential problem in eastern Kansas), but small enough so that subsurface lithologies (and presumably thermal conductivities) do not vary a great deal in the horizontal direction. A 40 kilometer radius was chosen because, in all instances, this radius included at least 15 data points and the bottom hole data for this radius could be fit with a significant regression.

INTERPRETATION

Because there have been no known major Phanerozoic intrusive events of geothermal significance in Kansas the basement complex seems to be the most likely place to look for an explanation of observed regional differences in heat flow. In this context, the Phanerozoic rocks should act as thermal insulators, in which individual lithologic units differentially transmit heat produced in the crust and upper mantle. If there are no hydrologic disturbances affecting temperatures measured in a borehole (i.e., movement of groundwater, artesian flow) then any vertical variations observed in the geothermal gradient, in the borehole, must be related to variations in subsurface lithology (i.e., conductivity; see Chapter 3, this report); assuming that heat flow is constant in the vicinity of the borehole. None of the geothermal gradients computed from the thermal logging data and used to generate maps for the state (Plates 2-3, 2-4 and 2-5), indicate hydrologic disturbance. In the absence of hydrologic disturbance, variations in heat flow values over a region should be related to lateral variation in radiogenic heat production in the crystalline basement (Roy _et al_, 1968), and possibly to lateral variation in thermal conductivity of the basement rocks.

In Kansas, the effects of thermal conductivity variation in basement rocks would be most apparent between the CNARS rocks and the adjacent felsic rocks. No specific conductivity values are available for any basement rocks for Kansas, and conductivity data for igneous and metamorphic rocks in general is limited. However, Birch and Clark (1940, p.549-550) have measured thermal conductivity in several gabbros and granites and have found that thermal conductivity values for gabbros range from 1.88 to 2.30 W/^{o}K, whereas values for granites range from 2.09 to 2.93 W/^{o}K. Basement rocks, in Kansas, of gabbroic and granitic composition would have thermal conductivities similar to those found by Birch and Clark (1940) and therefore, would probably be of less importance in causing variation in heat flow than rates of heat production (which, for granite, differ by a factor of two at two different localities in eastern Kansas; Chapter 3, p.102, this report).

LIMITATIONS IN THE INTERPRETATION OF BOTTOM HOLE DATA

Most investigators believe that geothermal gradients based on BHT records from oil and gas wells can reveal trends in the lateral variation of temperature with depth attributable to subsurface geology (Schoeppel and Gilarranz, 1966; Harper, 1971; Evans and Coleman, 1973; Gosnold, personal communication, 1981). On the geothermal gradient map for Kansas generated from BHT data (Plate 2-1), relatively high gradients are indicated over the Nemaha Ridge and these continue from Nemaha County to northern Butler County. Relatively high geothermal gradients are also apparent in the southeastern quarter of Kansas, in the Cherokee Basin area. The trends may reflect real variation in basement rock type and presumably radiogenic heat production coupled with depth to basement and basement topographic variation.

Because the source data for this map (Plate 2-1) come exclusively from oil and gas well records the quantity and distribution of the data is dependent upon the locations of the oil and gas wells. Also, BHT's measured in holes drilled deeper than 800 meters are probably lower than the true bottom hole temperature, whereas BHT's for holes only a few hundred meters deep are probably higher than the equilibrium temperatures, due to the effect of the drilling mud (p.26, this paper).

COMPARISON OF THERMAL LOGGING AND BOTTOM HOLE DATA

In light of the previous discussion, the good correspondence between the geothermal gradients computed for data obtained in the field, in eastern Kansas, and those computed from BHT records is remarkable. In eastern Kansas, the average depth logged in the field (several hundred meters) is approximately equivalent to the total depth of oil and gas wells, whereas oil and gas wells in western Kansas are 1000 to 2000 meters deep. In extreme northwestern Kansas, in particular, the bottom hole data are not valid for estimating temperatures at depths of 200 to 400 meters because of variations in thermal conductivity in Cretaceous rocks and possible near-surface convection in waters of the Dakota Group.

Both data sets indicate relatively high geothermal gradients along the Nemaha Ridge from the Nemaha to northern Butler Counties (Plates 2-1 and 2-3). Relatively high gradients are present in the Cherokee Basin in southeastern Kansas (Figure 1-1; Plates 2-1 and 2-3). In northwestern Kansas (principally, Cheyenne and Sherman Counties), the high gradients computed from the thermal logging data (Plate 2-3) are probably enhanced by the low conductivity of the Pierre Shale (Appendix III., p.43 (1CN2), 48 (1SH4) and 49 (1TH3)). The bottom hole data also show a relatively high geothermal gradient trend in these same counties (Plate 2-1). Bottom hole temperatures responsible for this trend were measured in gas wells producing from the Niobrara

Formation. (Correspondence between the two data sets is indicated for other areas of the state, but only the most obvious have been deliniated here.)

GEOTHERMAL GRADIENTS AND STRUCTURAL PROVINCES

The following discussion of the geothermal gradient data is restricted to those gradients computed from the thermal logging data, unless otherwise noted. It should be kept in mind that the total range of geothermal gradients from the thermal logging data for Kansas is only 25 to 55 $^{o}C/km$.

To analyze the geothermal gradient data thoroughly on a regional scale it would be best to have corresponding conductivity data. Because of the paucity of thermal conductivity information for Kansas, the gradient data are treated in the analysis as most investigators treat heat flow data. This is a valid treatment because lithologic units in the Pennsylvanian section are continuous over the state and therefore conductivity should not vary much from place to place in that part of the section.

I have divided the State of Kansas into eight "structural provinces" (Figure 1; after Merriam's (1963, p.178-179) "structural features" or "major structural elements"). These areas are structurally distinct from one another as they essentially represent major basement structural features, but are not necessarily dominated by one basement rock type. Heat flow is the product of thermal conductivity and geothermal gradient over a particular lithologic interval. The assumptions for the structural province analysis of the geothermal gradient data are as follows:

1) Phanerozoic strata are:

   a) laterally continuous

   b) essentially uniform in thickness

   c) draped over the Precambrian surface

2) wells in a structural province will penetrate similar sequences of rock units.

Under these assumptions, the thermal conductivity of the Phanerozoic rock units can be considered laterally uniform in a particular province. Any variation observed in the geothermal gradient would then either be directly related to variation in heat flow in the area (i.e., conductivity is treated as a constant) or indicative of local convective aquifer systems. There is no evidence in the thermal logging data to support a convective geothermal model for any portion of the state.

Hugoton Embayment of the Anadarko Basin.

Geothermal gradients in the Kansas part of the Anadarko Basin are relatively uniform, averaging approximately 30 $^{\circ}$C/km (Plate 2-3). However, in the northern portions of the basin the gradients tend to be somewhat higher (35 to 45 $^{\circ}$C/km).

Las Animas Arch.

In this area of northwestern Kansas, extremely high (50 to 60 $^{\circ}$C/km), uniform geothermal gradients were computed from thermal logging data (Plate 2-3). Geothermal gradients were computed for the portion of the thermal logging data that penetrated the Pierre Shale. As previously mentioned, Blackwell et al (1981) found thermal conductivities for shales in the Midcontinent (specifically in Kansas) to be much lower than reported by previous workers (Garland and Lennox, 1962; Combs and Simmons, 1973; Scattolini, 1978). They believe that thermal conductivity values for shales in the Midcontinent have been overestimated by as much as 60 per cent (Blackwell et al, 1981). This means that the high gradients present over the Las Animas Arch are very likely the result of the low thermal conductivity of the Pierre Shale in an area of normal heat flow.

That these gradients are maintained in the units below the Pierre Shale is unlikely, even though a similar trend is observed in the bottom hole data from gas wells which were drilled into the Niobrara Formation in this area (Plate 2-1). These wells were drilled to a maximum of several tens of meters into the Niobrara Formation. Although the thermal conductivity of the Niobrara has not been measured it is probable that the Niobrara Formation is a better thermal conductor than the Pierre Shale because it consists primarily of limestone and chalk. An alternative interpretation of the high geothermal gradients is that heat derived from the Denver-Julesberg Basin is causing convection in the waters of the Dakota Group upward and eastward into Kansas and Nebraska (Gosnold, personal communication, 1981). Because I was unable to obtain any thermal logging data for rocks of the Dakota Group the thermal conductivity effect of the Pierre Shale is the preferred explanation for the high geothermal gradients computed or this portion of the state.

Central Kansas Uplift.

Over the Central Kansas Uplift (Plate 2-3) the geothermal gradients from the logging data are, for the most most part, high (37 to 47 ^{o}C/km) but decrease to 30 to 35 ^{o}C/km over the southeastern portions of the structural province (Plate 2-3). A low gradient trend encompasses all of Pawnee County over the southwestern flank of the uplift, and extends into the Anadarko Basin. This trend is misleading, as the lowest computed gradient is 27 ^{o}C/km, while the contour trend indicates that there are geothermal gradients lower than 24 ^{o}C/km in this area. This trend is probably enhanced by the computer contouring program and is caused by a lack of data.

Salina Basin.

Because of the paucity of logging data in the Salina Basin, not much can be said about the geothermal gradients in this area. However, the two geothermal gradient values in the southern part of the basin are essentially equivalent (Plate 2-3) and can be considered normal (30 ^{o}C/km) for an area in geothermal equilibrium (i.e., a tectonically stable area).

Sedgwick Basin.

Geothermal gradients from the logging data in the Sedgwick Basin show considerable diversity ranging from 36 to 40 ^{o}C/km (Plate 2-3). The north-south high that occurs in Kingman and Harper Counties, intersects a trend of similar magnitude that is present from western Marion County to central Stafford County. In the southeastern corners of the basin, normal to low gradients (24 to 30 ^{o}C/km) are observed.

Nemaha Ridge.

The northeast-southwest trend of the Nemaha Ridge is indicated fairly well by the geothermal gradients from the logging data. Geothermal gradients ranging from 35 to 45 $^{o}C/km$ are indicated along the northern half of the Nemaha Ridge from northern Morris to Nemaha and Marshall Counties (Plate 2-3). Unfortunately, no data were obtained for Nemaha, Marshall or Pottawatomie Counties (as stated previously), so the higher gradients indicated in these counties should be considered with caution. Geothermal gradients along the southern half of the Nemaha Ridge are generally uniform with values of 35 $^{o}C/km$.

Forest City Basin.

The Forest City Basin exhibits the most diverse geothermal gradients found in any of the structural provinces in Kansas. Although logging data are lacking for the northern portion of the basin, high gradients (45 to 50 $^{o}C/km$) are indicated in the eastern part of the basin along the Missouri border (Plate 2-3). In the center of the basin, including southern Leavenworth, Douglas, Shawnee and Osage Counties, normal gradients are observed (30 to 33 $^{o}C/km$). Geothermal gradients in the range of 40 to 50 $^{o}C/km$ are again present in the southeastern and southern portions of the Forest City Basin adjacent to the Bourbon Arch.

Cherokee Basin.

This structural province has the best coverage, in terms of thermal logging data, in the entire state (Plate 2-3). Geothermal gradients in the Cherokee Basin are relatively high and increase gradually southward from approximately 40 to 50 $^{o}C/km$.

Discussion.

It appears that three types of geothermal response may be observed in particular structural provinces. In the first type, the geothermal gradients are essentially uniform, or constant, as is seen in the Anadarko Basin and, where data are available, in the Salina Basin. The second, occurs over the Central Kansas Uplift and Nemaha Ridge, and in the Cherokee Basin. Geothermal gradients decrease systematically: north to south in the first two areas and south to north in the Cherokee Basin. This suggests the some type of regional control is operative in these areas. The third type of response occurs in the Sedgwick and Forest City Basins, where the geothermal gradient values are very diverse.

On a statewide scale, areas of relatively high geothermal gradients correspond to areas of low magnetic field intensity. This inverse relationship occurs both in provinces where geothermal gradients show what I have called regional variation (e.g., the Central Kansas Uplift and Nemaha Ridge) and where the gradient trends are very irregular (e.g., Forest City Basin). In southwestern Kansas, aeromagnetic data are obscured by the thick succession of Phanerozoic strata (Vaquier et al, 1951, p.5). In this area, both geothermal gradients and aeromagnetic data are uniform, but uniformity in the aeromagnetic data may result from the thick sedimentary cover rather than a relatively homogeneous crystalline basement (in terms of its magnetic response). As the aeromagnetic data theoretically represent a picture of the Precambrian crystalline rocks (if downward continued to the basement surface), its correspondence with the geothermal gradients tends to support the idea that variations in geothermal gradients are related to variations in basement rock type. Mafic rocks generally have high magnetic susceptibility and produce less heat due to radiogenic decay of uranium, thorium, and potassium than felsic rocks (Roy, et al, 1968). One would then expect that the inverse relationship between aeromagnetic and heat flow (geothermal gradient) data might result from compositional differences in the basement.

In Kansas, the crystalline basement complex is dominated by felsic rocks (except in the area of the MGA). The Precambrian complex in Kansas has been divided, on the basis of age and petrography, into a southern terrane and a northern terrane (Chapter 1, p.12-13, this report), in which further compositional differences have been observed (Bickford et al, 1981; Van Schmus and Bickford, 1981). The regional southerly decrease in the geothermal gradient along the Central Kansas Uplift and Nemaha Ridge may be related to this division. It could also be due to increasing sedimentary thickness to the south.

A series of highly positive circular magnetic anomalies, averaging 15 kilometers in diameter are present in the Forest City Basin in northeastern Kansas. Two of these anomalies were drilled by the KGS-USGS (1DG1 and 1MI1). Prior to drilling, it was believed that these anomalies were probably caused by Precambrian intrusives that were genetically related and mafic in composition. However the basement rock in both holes was found to be granite with a higher than normal magnetite content, and this is apparently responsible for the magnetic anomalies observed. Calculated heat production values for granite samples from these two holes are surprising as they are not equivalent but differ by a factor of two.

The heat production values for the granite are 4.9 $\mu W/m^3$ in hole 1MI1 and 2.4 $\mu W/m^3$ in 1DG1 (Chapter 3, p.102, this report). The latter is typical for granites in the central stable region, as determined by Roy et al, (1968).

There is no systematic correspondence between geothermal gradients and residual Bouger gravity values (computed by removing the gravity effect attributable to the Phanerozoic strata) for Kansas (Woollard, 1959, Plate 2). One would expect areas of low Bouger gravity to be indicative of less dense crust (e.g., predominantly felsic basement rock types), and felsic rocks to be indicative of higher rates of heat production. Except for over the Nemaha Ridge, areas where geothermal gradients are relatively high do not correspond to gravity lows (Wang, 1965; Scheffer, 1963). Considering the different heat production values measured by Blackwell for mineralogically similar basement rock (in holes 1DG1 and 1MI1), it may be unreasonable to expect an inverse relationship between geothermal gradients and gravity.

GEOTHERMAL GRADIENTS AND BASEMENT TOPOGRAPHY

Although the above analysis suggests some possible causes for the diversity in geothermal gradients in Kansas, little further can be said until more is known about thermal conductivity, variation of basement composition, basement radioactivity, or heat production. Even so, I am not satisfied that the causes suggested above can completely explain the diversity observed.

Prior to 1965, a great deal of geothermal gradient data was obtained in an effort to determine if there was a relationship between maturation of hydrocarbons and areas of high geothermal gradients. The results, in terms of the petroleum industry were inconclusive, but the investigators all arrived at similar interpretations of the gradient data. They observed a definite direct relationship between the value of geothermal gradients, depth to crystalline basement, and basement structure or topography (Barnes, 1932; Carlson, 1931; Lasky, 1963; McCutchin, 1930; Schoeppel and Gilarranz, 1966; Strong, 1930; Van Orstrand, 1932, 1934 and 1940). To illustrate their findings, they used isotherms. Cross sections and maps of "isothermal surfaces" (surfaces of constant temperature) were compared to geologic cross sections and maps. Generally, isotherms paralleled surface and basement topography, but were smoother. Most of the studies, unlike this one, were done in areas dominated by a single basement feature (eg. dome or anticline) and the basement in each area was essentially uniform in composition.

A combination of factors are probably responsible for the direct relationship between basement topography and geothermal gradients. Basement rocks have been thought of as a heat source in the present study. Displacement of these rocks (especially felsic types) toward the surface essentially brings the heat source closer to the surface. In another sense, crystalline rocks are generally better thermal conductors than sedimentary rocks. Over areas of extreme variation in basement topography (e.g., Nemaha Ridge), one must consider the effects of refraction of heat. Refraction of heat tends to occur in areas where there are extreme differences in thermal conductivity in a vertical and lateral sense resulting from subsurface structural highs or lows. In Figure 2-7 (A-E), simplified cross sections show the expected configuration of isotherms in cases of extreme changes in thermal conductivity. Sections E and F in Figure 2-7, represent a simplistic picture of the patterns one would expect over a buried anticline of good thermal conductivity. The effect of the structure would be more noticeable the closer it is to the surface (e.g., Nemaha Ridge in Nemaha, Marshall, Pottawatomie and Riley Counties). In Kansas, one would expect to find higher geothermal gradients (areas where isothermal surfaces are closer together) over the Nemaha Ridge, Central Kansas Uplift and perhaps in eastern Kansas, especially in the Cherokee Basin where the basement complex is within 600 meters of the surface.

W.D. Gosnold (personal communication, 1981) has investigated the effect of refraction on heat flow due to the Nemaha Ridge in southeastern Nebraska. His theoretical model (generated by numerical analysis), which takes into account the refraction effect, predicts higher heat flow values over the ridge that are compatible with observed heat flow in the area. This has already been indicated qualitatively in Figure 2-7, E and F.

Five generalized geologic cross sections, Figures 2-10a to 2-14a, illustrate the configuration of the basement rocks and thickness of overlying sediments in Kansas. The locations of these sections and well locations of the thermal logging data are shown in Figure 2-8. Geothermal gradients (solid) and subsurface temperatures at 300 meters (dashed) are also plotted along these section lines (Figures 2-10b to 2-14b; index map, Figure 2-9). This information is taken from corresponding maps (Plates 2-3 and 2-5) of the thermal logging data. The locations of thermal logging holes are also plotted to scale (vertical) on the nearest geologic sections to indicate the control for the geothermal data.

In sections A-A' and A_*-A_*' (Figure 2-10, a and b), geothermal data do not mimick the basement structure but, in general, temperatures and gradients over the Salina Basin are relatively low and become higher over the Nemaha Ridge. The high geothermal gradient and temperature values in the western part of the section are probably due to the influence of the Pierre Shale. Because of the lack of control points for geothermal data along line A-A', little more can be said about this portion of the state.

Along sections B-B' and B_{*}-B_{*}' (Figure 2-11, a and b), there is better control in the geothermal data for the eastern and western areas. Again, the relatively high values observed in the geothermal data in northwestern Kansas (approximately 100 kilometers west of the Central Kansas Uplift) are probably due to the effect of the Pierre Shale as there is no evidence of extreme basement topographic variation (Figure 2-11a). Relatively high gradient and temperature trends are observed over the Nemaha Ridge and much lower, though diverse, geothermal gradients and subsurface temperatures are observed in the Forest City Basin. The Salina Basin is represented by low gradient and temperature values. The geothermal gradient in the area of the Central Kansas Uplift seems to be offset to the east, while the subsurface temperature is relatively low as in the Salina Basin.

Sections C-C' and C_{*}-C_{*}' transect a portion of the state in which the basement complex is much deeper (Figure 2-12, a and b). In general, the geothermal gradients and subsurface temperatures increase from west to east, and there is good control along section C_{*}-C_{*}' (approximately one well every 30 kilometers, Figure 2-8). A relative high in western Sumner County does not obviously correspond to the position of the Nemaha Ridge in southern Kansas. However, basement topographic variation across the Nemaha Ridge is not extreme in Sumner County; instead, there is a general decrease in depth to the basement complex from eastern Sumner County to the Missouri border. This is indicated by the geothermal data for the area (Figure 2-12b; Plates 2-3 and 2-5).

Sections D-D' and D_*-D_*' (Figure 2-13, a and b) are essentially normal to the trend of the Central Kansas Uplift. The subsurface temperatures along D_*-D_*' are relatively uniform, but the geothermal gradient generally increases as the crest of the Central Kansas Uplift is approached. This may be the result of refraction on the Central Kansas Uplift. The control, for geothermal data, along this section is better than that for section B_*-B_*' and this suggests that the offset observed on B_*-B_*' is an effect of the computer contouring program.

Finally, sections E-E' and E_*-E_*' (Figure 2-14, a and b) cover eastern Kansas from the Forest City Basin to the Cherokee Basin. Aside from the northern quarters of the sections, where there are no thermal logging data, geothermal gradients and temperatures generally increase as the thickness of the Phanerozoic strata decreases.

It appears that there is a relationship between the major basement structural features in Kansas and available geothermal data (especially gradient data). It also is notable that, as these features become deeper and less pronounced (structurally), their effects on the geothermal gradient are reduced. In addition, the relatively high geothermal gradients observed in the Cherokee Basin may be the result of a general decrease in depth to the basement complex in this area.

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FIGURE CAPTIONS

FIGURE 2-1: An example of a typical well log header used in this study. Information compiled from each log includes:
1) location (section, township, range)
2) elevation when available (feet)
3) depth (feet)
4) bottom hole temperature (degrees Fahrenheit)
5) year drilled
6) "time (hours) since circulation" (interval between last circulation of drilling mud and measurement of bottom hole temperature).

FIGURE 2-2: Map showing distribution of data points available for the geothermal gradient map of Kansas based on gradients computed from BHT data. These data points represent locations of the wells from which BHT data were obtained.

FIGURE 2-3: Location map of the areas covered by the 1980 and 1981 thermal logging work.

FIGURE 2-4: Comparison of borehole radius with critical gradient for constant temperatures of 5, 10 15 and 25 ^{o}C (After Misener and Beck, 1960). The borehole is assumed to be full of water. For a particular temperature (temperatures from 5 to 20 ^{o}C are plotted) measured in the borehole, convection may occur if the value of the measured geothermal gradient and the borehole radius are above the temperature curve. For Kansas, this could effect thermal logging data from boreholes exceeding six centimeters in diameter.

FIGURE 2-5: Temperature profiles of KGS-USGS Big Springs hole. Profile 1DG1-III represents data I obtained in January 1981. Profile 1DG1-B represents data obtained by Blackwell in June 1980.

FIGURE 2-6: Temperature profiles of control well (1DG1). Profiles I and II result from summer 1980 logging data. Profile III results from data obtained in January 1981. Profile IV results from data obtained in May 1981.

FIGURE 2-7: Simplified cross sections showing the effects of lateral changes in thermal conductivity on the bahavior of isotherms. The upper boundaries on these cross sections represents the ground surface (after Strong, 1930).

FIGURE 2-8: Location map for geologic sections and control points of thermal logging data.

FIGURE 2-9: Index map for profiles of geothermal gradients and subsurface temperatures.

FIGURE 2-10a: Generalized geologic section along line A-A' (after Merriam, 1963, p.17).

FIGURE 2-10b: Profile of geothermal gradient (solid) and temperature at -300 meters (dashed) along line A_*-A_*'.

FIGURE 2-11a: Generalized geologic section along line B-B' (after Merriam, 1963, p.18).

FIGURE 2-11b: Profile of geothermal gradient (solid) and temperature at -300 meters (dashed) along line B_*-B_*'.

FIGURE 2-12a: Generalized geologic section along line C-C' (after Merriam, 1963, p.19).

FIGURE 2-12b: Profile of geothermal gradient (solid) and temperature at -300 meters (dashed) along line C_*-C_*'.

FIGURE 2-13a: Generalized geologic section along line D-D' (after Lee, 1953, Figure 2G).

FIGURE 2-13b: Profile of geothermal gradient (solid) and temperature at -300 meters (dashed) along line D_*-D_*'.

FIGURE 2-14a: Generalized geologic section along line E-E' (after Lee and Merriam, 1954, Plate 4).

FIGURE 2-14b: Profile of geothermal gradient (solid) and temperature at -300 meters (dashed) along line E_*-E_*'.

Welex

GAMMA-GUARD SIDEWALL NEUTRON LOG

COMPANY CHAMPLIN PETROLEUM COMPANY
WELL JOHNSON N-=2
FIELD RIVERVIEW
County ELLIS State KANSAS

COMPANY CHAMPLIN PETROLEUM COMPANY

WELL JOHNSON N-=2

FIELD RIVERVIEW

COUNTY ELLIS STATE KANSAS

Location 1

SE-NE-NW

Sec. 32 Twp. 11S Rge. 18W

Other Services:

CAVL-G-C

Permanent Datum GROUND LEVEL Elev. 2065'

Log Measured From KELLY BUSHING, 5 Ft. Above Perm. Datum

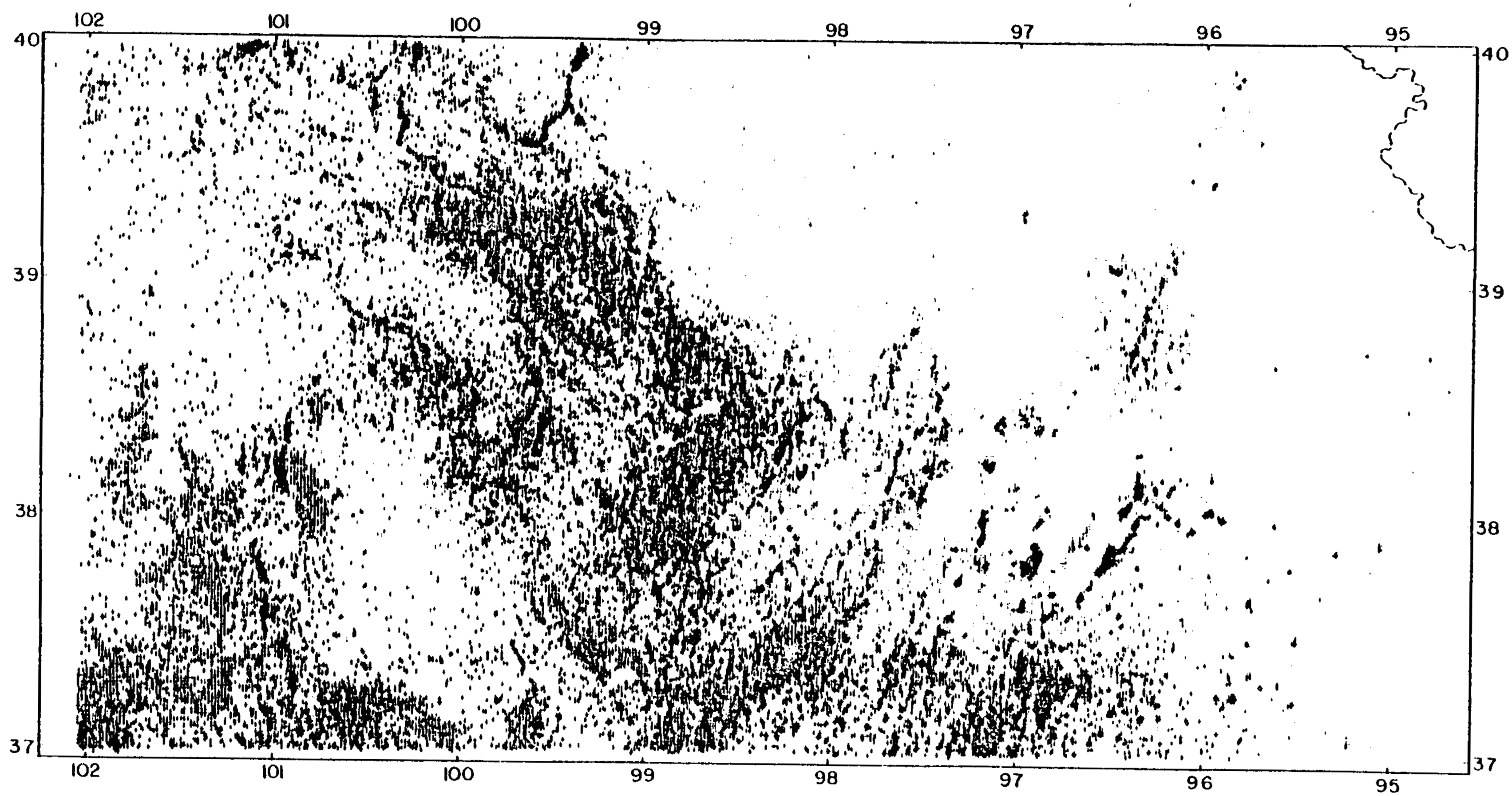
Drilling Measured From KELLY BUSHING

Elev.: K.B. 2070'
D.F.
2 G.L. 2065'

Date 5	6-17-80	6-17-80	6-17-80	6-17-80
Run No.	GAMMA	NEUTRON	GUARD	CALIPER
Depth—Driller	3800'	3800'	3800'	3800'
Depth—Welex 3	3800'	3800'	3800'	3800'
Btm. Log Inter.	3772.4'	3799'	3786.6'	3799'
Top Log Inter.	1800'	1800'	1800'	1800'
Casing—Driller	8-5/8@ 245'	8-5/8@ 245'	8-5/8@ 245'	8-5/8@ 245'
Casing—Welex	8-5/8"@245'	8-5/8"@245'	8-5/8"@245'	8-5/8"@245'
Bit Size	7-7/8"	7-7/8"	7-7/8"	7-7/8"
Type Fluid in Hole	STARCH	STARCH	STARCH	STARCH
Dens. | Visc.	9.9 | 43	9.9 | 43	9.9 | 43	9.9 | 43
pH | Fluid Loss	6.6 | 6.6 ml	6.6 | 16.6 ml	6.6 | 16.6ml	6.6 | 16.6 ml
Source of Sample	FLOW LINE	FLOW LINE	FLOW LINE	FLOW LINE
R_m @ Meas. Temp.	.11 @ 92°F.	@ °F	@ °F	@ °F
R_{mf} @ Meas. Temp.	.083 @ 92°F	@ °F	@ °F	@ °F
R_{mc} @ Meas. Temp.	.165 @ 92°F	@ °F	@ °F	@ °F
Source R_{mf} R_{mc}	MEASURED |	|	|	|
R_m @ BHT 4	.092 @112°F	@ °F	@ °F	@ °F
Time Since Circ. 6	2 HOURS	h		
Max. Rec. Temp.	112°F@ T.D.	°F@	°F@	°F@
Equip. | Location	1889 | COLBY	|	|	|
Recorded By	S. DUDLEY			
Witnessed By	MR. PETE STRAUB			

FIGURE 2-1

DATA POINTS FOR GEOTHERMAL GRADIENT MAP OF KANSAS



SOURCE DATA--ALL BHT DATA

FIGURE 2-2

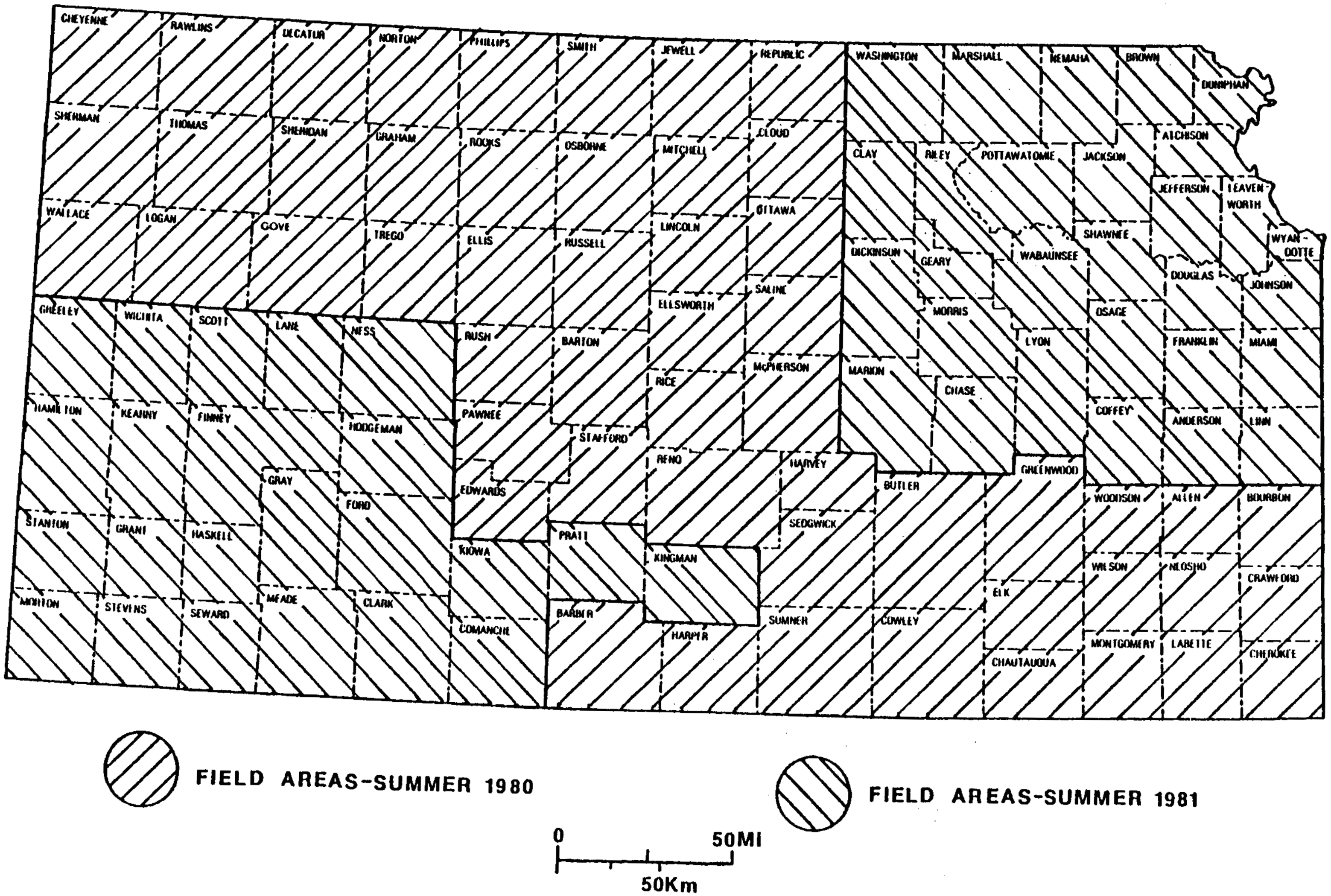
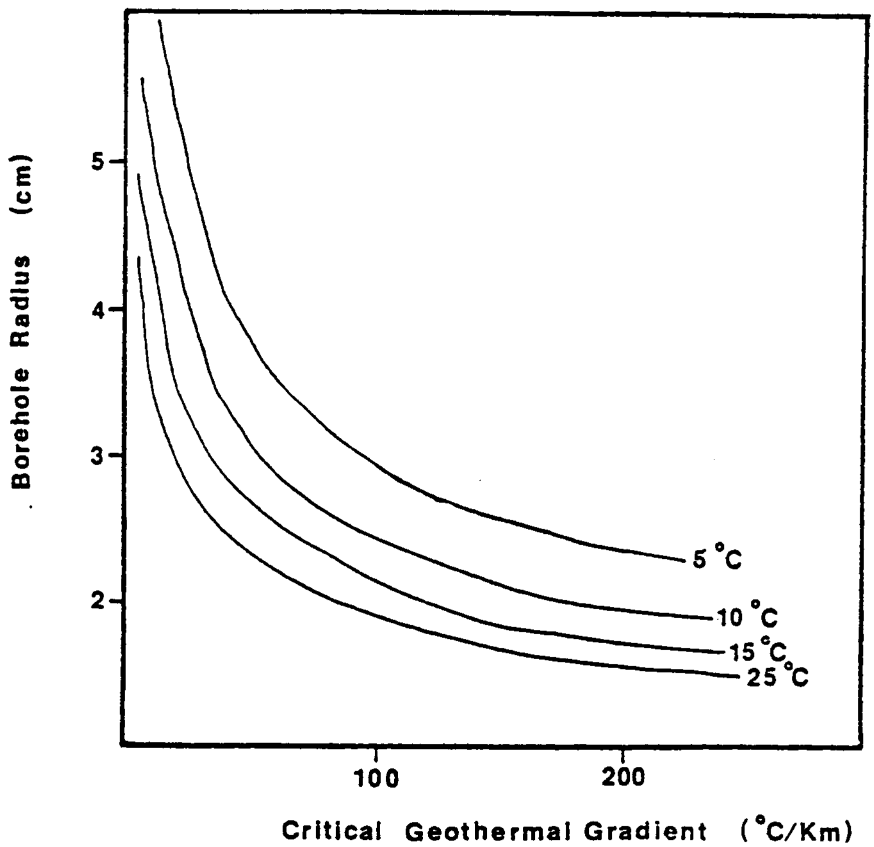
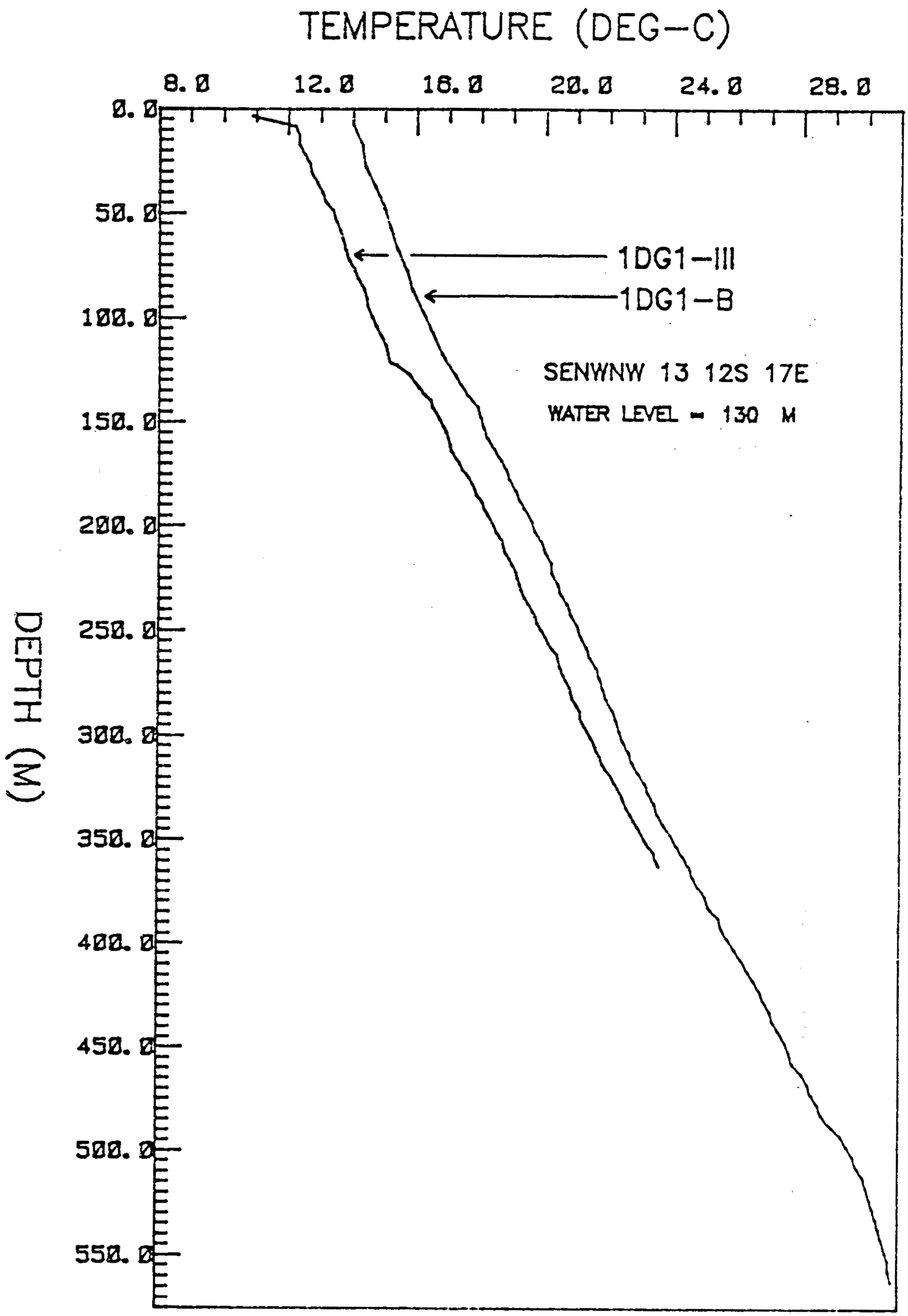

CHEYENNE
RAWLINS
DECATUR
NORTON
PHILLIPS
SMITH
JEWELL
REPUBLIC
WASHINGTON
MARSHALL
NEMAHA
BROWN
DONIPHAN
SHERMAN
THOMAS
SHERIDAN
GRAHAM
ROOKS
OSBORNE
MITCHELL
CLOUD
CLAY
RILEY
POTTAWATOMIE
JACKSON
ATCHISON
JEFFERSON
LEAVEN-WORTH
WALLACE
LOGAN
GOVE
TREGO
ELLIS
RUSSELL
LINCOLN
OTTAWA
DICKINSON
GEARY
WABAUNSEE
SHAWNEE
WYAN-DOTTE
DOUGLAS
JOHNSON
GREELEY
WICHITA
SCOTT
LANE
NESS
RUSH
BARTON
ELLSWORTH
SALINE
MORRIS
OSAGE
LYON
FRANKLIN
MIAMI
HAMILTON
KEARNY
FINNEY
HODGEMAN
PAWNEE
RICE
McPHERSON
MARION
CHASE
COFFEY
ANDERSON
LINN
STAFFORD
RENO
HARVEY
BUTLER
GREENWOOD
GRAY
FORD
EDWARDS
WOODSON
ALLEN
BOURBON
STANTON
GRANT
HASKELL
KIOWA
PRATT
KINGMAN
SEDGWICK
WILSON
NEOSHO
CRAWFORD
ELK
MORTON
STEVENS
SEWARD
MEADE
CLARK
COMANCHE
BARBER
HARPER
SUMNER
COWLEY
MONTGOMERY
LABETTE
CHEROKEE
CHAUTAUQUA
FIELD AREAS-SUMMER 1980
FIELD AREAS-SUMMER 1981
0
50MI
50Km

FIGURE 2-3



Borehole Radius (cm)
5
4
3
2
5 °C
10 °C
15 °C
25 °C
100
200
Critical Geothermal Gradient (°C/Km)

FIGURE 2-4



TEMPERATURE (DEG-C)
8.0
12.0
16.0
20.0
24.0
28.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
DEPTH (M)
1DG1-III
1DG1-B
SENWNW 13 12S 17E
WATER LEVEL = 130 M

FIGURE 2-5

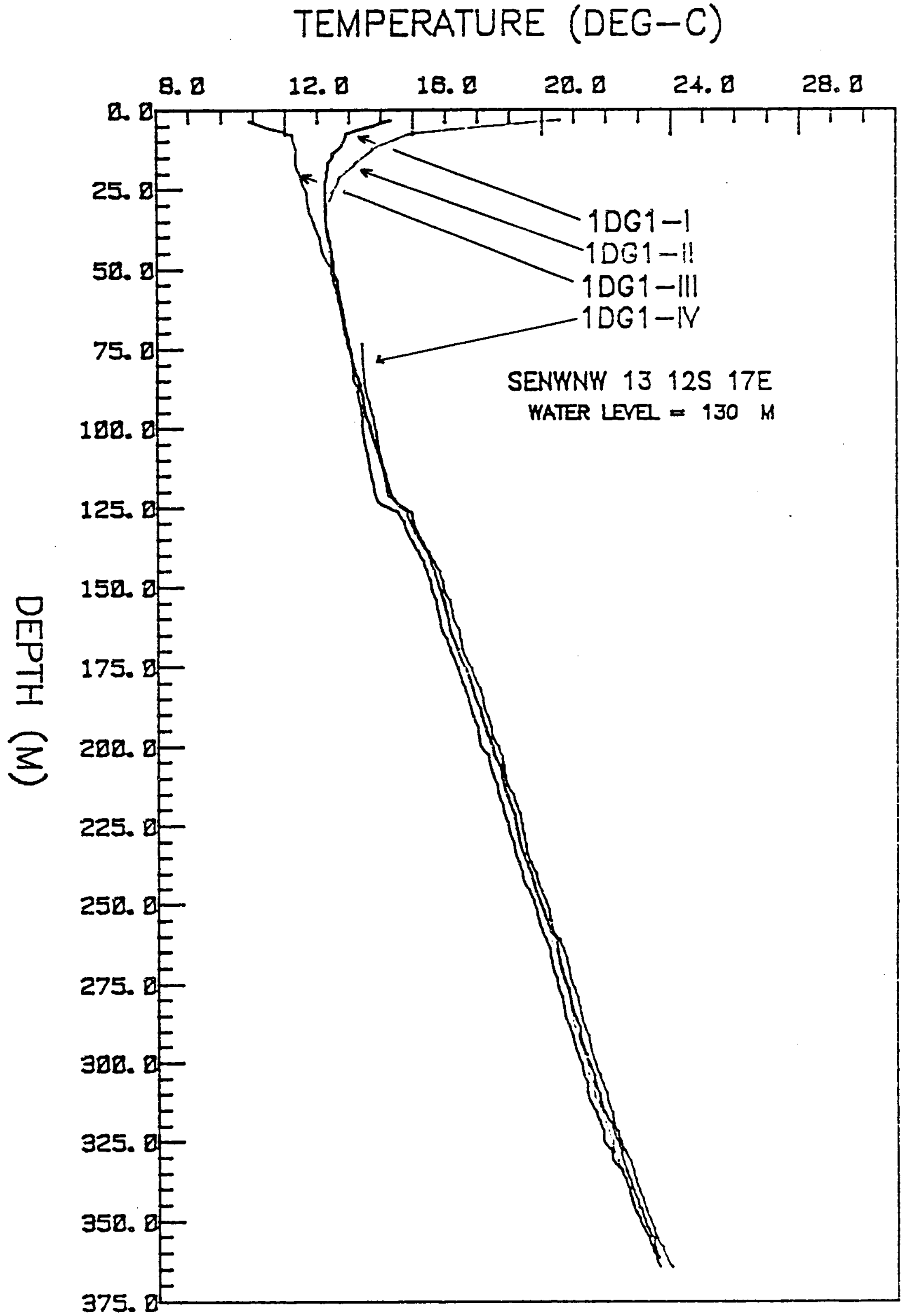
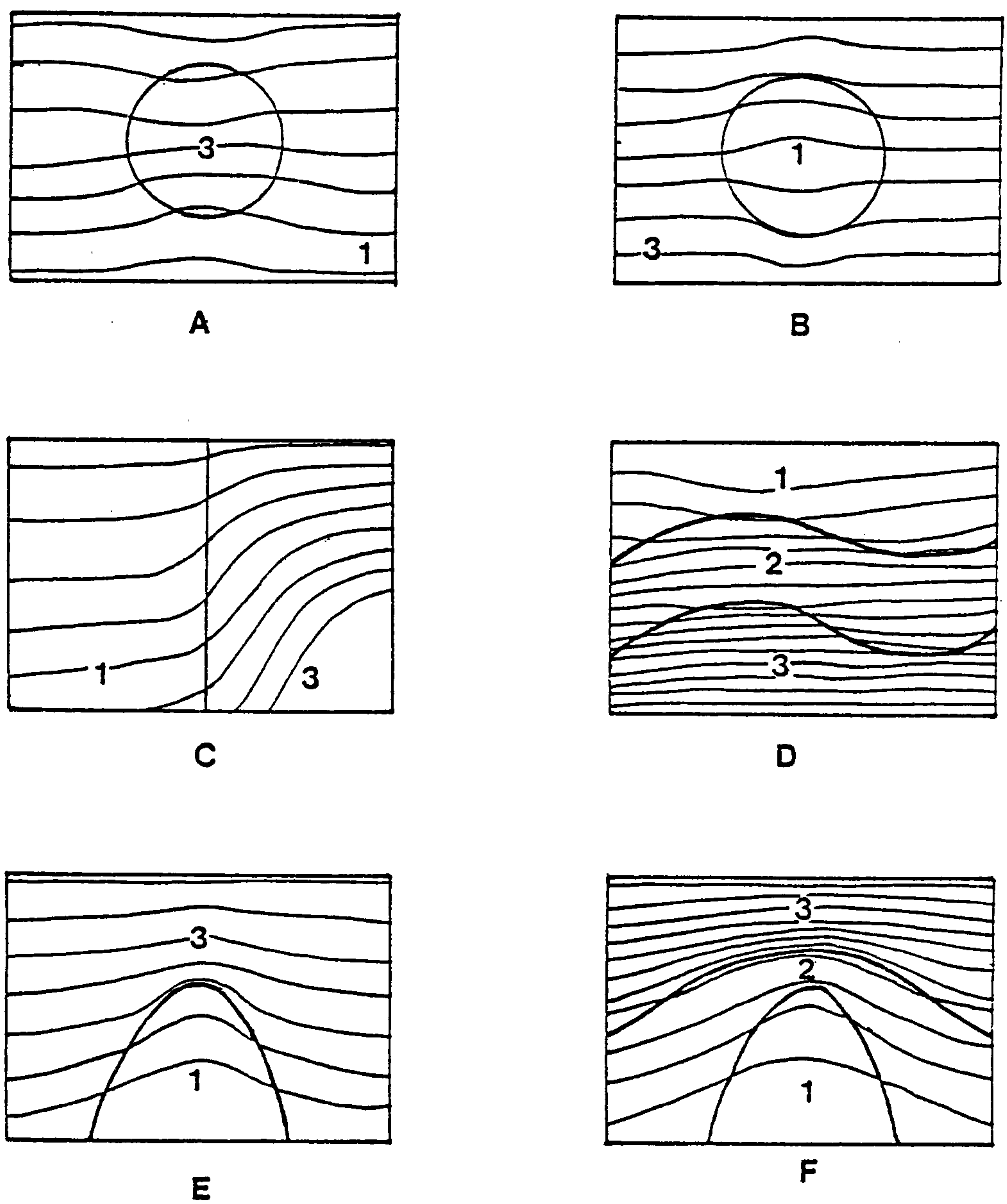

TEMPERATURE (DEG-C)
8.0
12.0
16.0
20.0
24.0
28.0
0.0
25.0
50.0
75.0
100.0
125.0
150.0
175.0
200.0
225.0
250.0
275.0
300.0
325.0
350.0
375.0
DEPTH (M)
1DG1-I
1DG1-II
1DG1-III
1DG1-IV
SENWNW 13 12S 17E
WATER LEVEL = 130 M

FIGURE 2-6

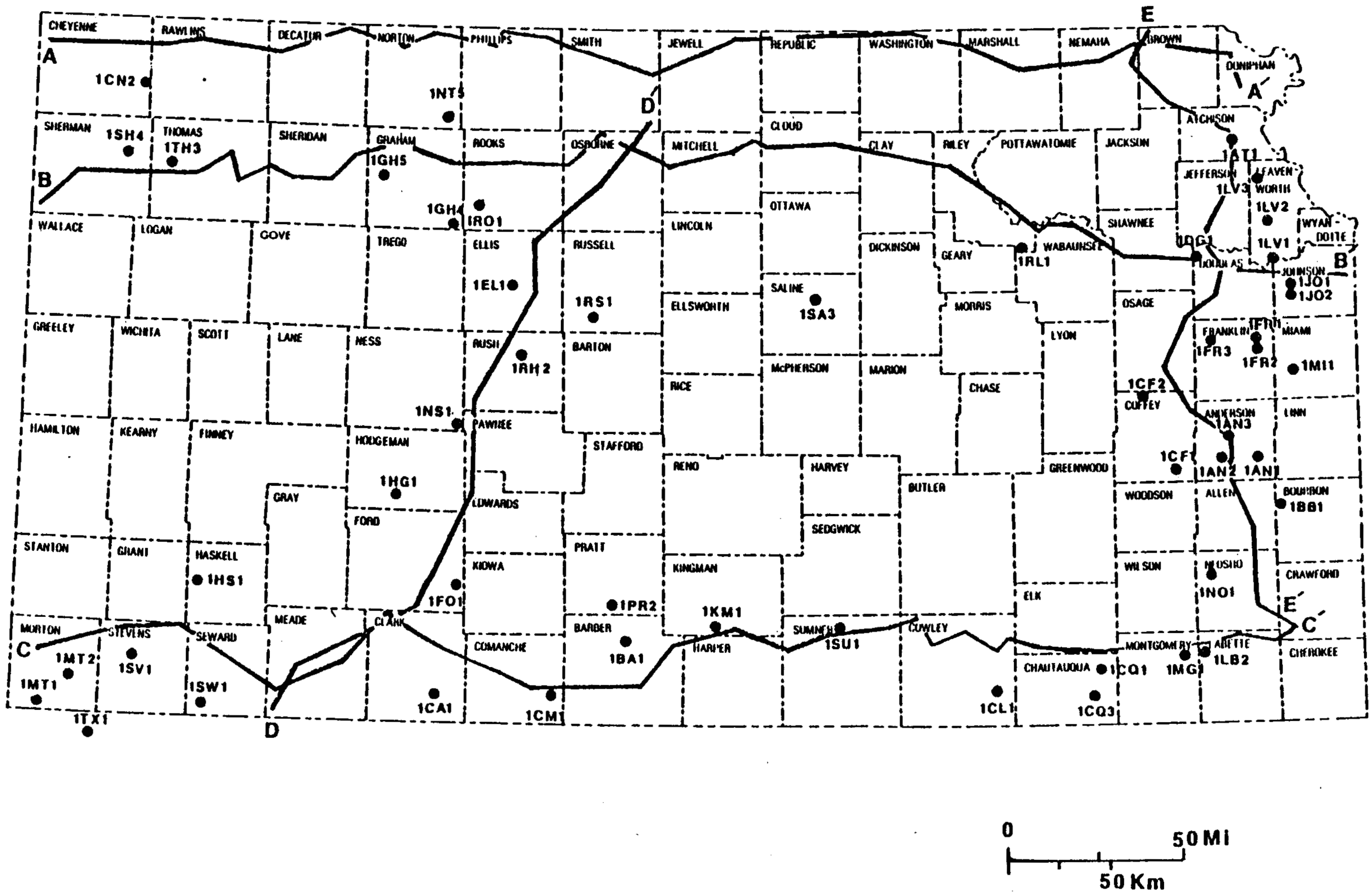


1- good

2-medium

3-poor

FIGURE 2-7



A
B
C
D
E
1CN2
1SH4
1TH3
1GH5
1NT5
1GH4
1RO1
1EL1
1RS1
1RH2
1NS1
1HG1
1HS1
1FO1
1PR2
1BA1
1KM1
1SU1
1SA3
1RL1
1AT1
1LV3
1LV2
1LV1
1DG1
1JO1
1JO2
1FR3
1FR2
1MI1
1CF2
1AN3
1CF1
1AN2
1AN1
1BB1
1NO1
1LB2
1MG1
1CQ1
1CQ3
1CL1
1CM1
1CA1
1SW1
1SV1
1MT1
1MT2
1TX1
CHEYENNE
RAWLINS
DECATUR
NORTON
PHILLIPS
SMITH
JEWELL
REPUBLIC
WASHINGTON
MARSHALL
NEMAHA
BROWN
DONIPHAN
SHERMAN
THOMAS
SHERIDAN
GRAHAM
ROOKS
OSBORNE
MITCHELL
CLOUD
CLAY
RILEY
POTTAWATOMIE
JACKSON
ATCHISON
JEFFERSON
LEAVENWORTH
WALLACE
LOGAN
GOVE
TREGO
ELLIS
RUSSELL
LINCOLN
OTTAWA
DICKINSON
GEARY
WABAUNSEE
SHAWNEE
DOUGLAS
WYANDOTTE
JOHNSON
GREELEY
WICHITA
SCOTT
LANE
NESS
RUSH
BARTON
ELLSWORTH
SALINE
MORRIS
LYON
OSAGE
FRANKLIN
MIAMI
RICE
McPHERSON
MARION
CHASE
COFFEY
ANDERSON
LINN
HAMILTON
KEARNY
FINNEY
HODGEMAN
PAWNEE
STAFFORD
RENO
HARVEY
BUTLER
GREENWOOD
WOODSON
ALLEN
BOURBON
GRAY
FORD
EDWARDS
SEDGWICK
STANTON
GRANT
HASKELL
KIOWA
PRATT
KINGMAN
ELK
WILSON
NEOSHO
CRAWFORD
MORTON
STEVENS
SEWARD
MEADE
CLARK
COMANCHE
BARBER
HARPER
SUMNER
COWLEY
CHAUTAUQUA
MONTGOMERY
LABETTE
CHEROKEE
0
50 MI
50 Km

FIGURE 2-8

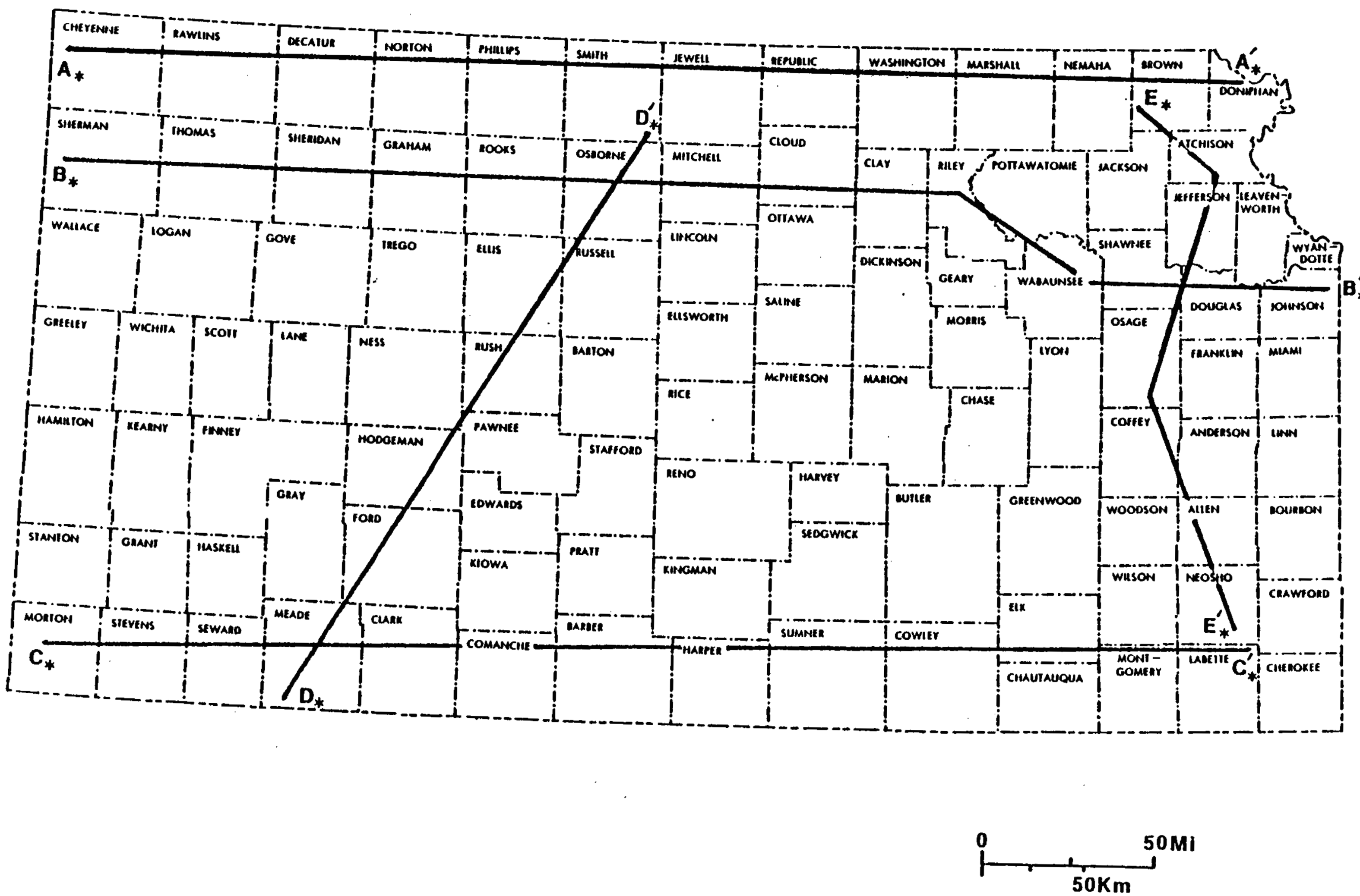

CHEYENNE
RAWLINS
DECATUR
NORTON
PHILLIPS
SMITH
JEWELL
REPUBLIC
WASHINGTON
MARSHALL
NEMAHA
BROWN
DONIPHAN
SHERMAN
THOMAS
SHERIDAN
GRAHAM
ROOKS
OSBORNE
MITCHELL
CLOUD
CLAY
RILEY
POTTAWATOMIE
JACKSON
ATCHISON
JEFFERSON
LEAVEN-WORTH
WALLACE
LOGAN
GOVE
TREGO
ELLIS
RUSSELL
LINCOLN
OTTAWA
DICKINSON
GEARY
WABAUNSEE
SHAWNEE
WYAN-DOTTE
GREELEY
WICHITA
SCOTT
LANE
NESS
RUSH
BARTON
ELLSWORTH
SALINE
MORRIS
LYON
OSAGE
DOUGLAS
JOHNSON
RICE
McPHERSON
MARION
CHASE
FRANKLIN
MIAMI
HAMILTON
KEARNY
FINNEY
HODGEMAN
PAWNEE
STAFFORD
COFFEY
ANDERSON
LINN
RENO
HARVEY
BUTLER
GREENWOOD
WOODSON
ALLEN
BOURBON
GRAY
FORD
EDWARDS
STANTON
GRANT
HASKELL
SEDGWICK
PRATT
KIOWA
KINGMAN
WILSON
NEOSHO
CRAWFORD
MORTON
STEVENS
SEWARD
MEADE
CLARK
COMANCHE
BARBER
HARPER
SUMNER
COWLEY
ELK
CHAUTAUQUA
MONT-GOMERY
LABETTE
CHEROKEE
A*
A'*
B*
B'*
C*
C'*
D*
D'*
E*
E'*
0
50Mi
50Km

FIGURE 2-9

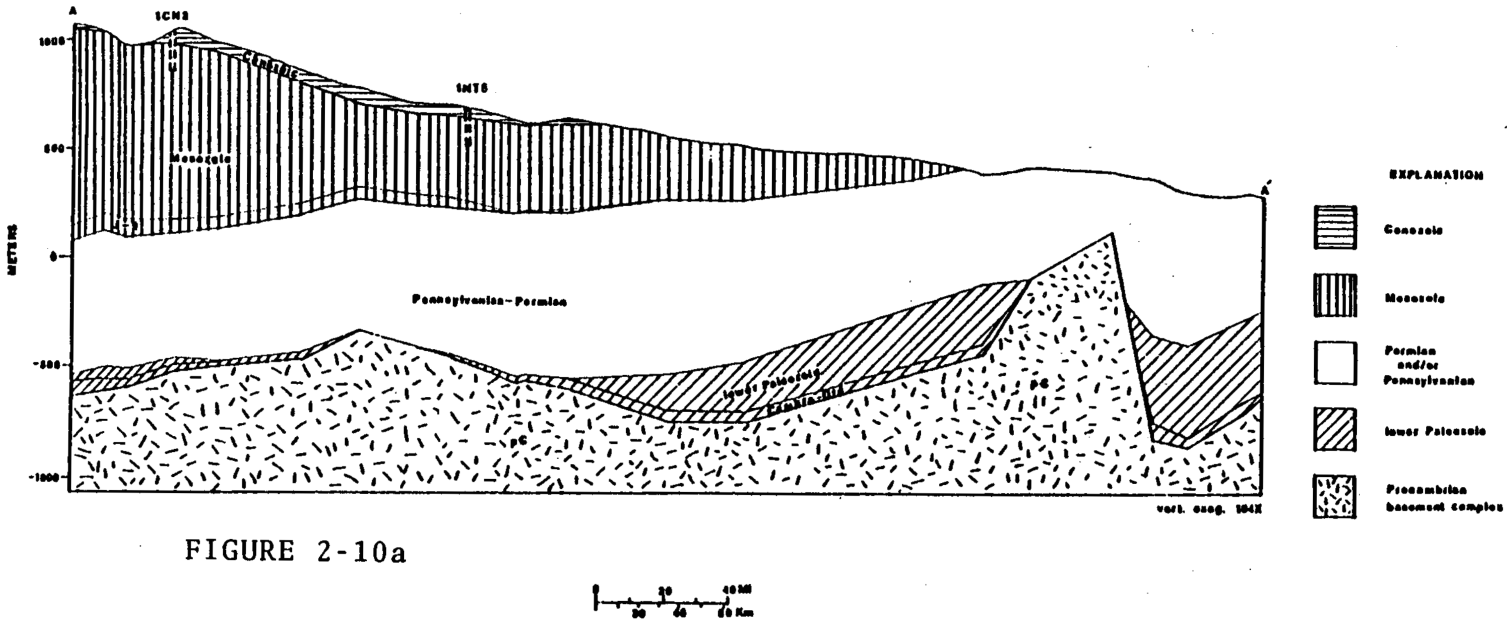


FIGURE 2-10a

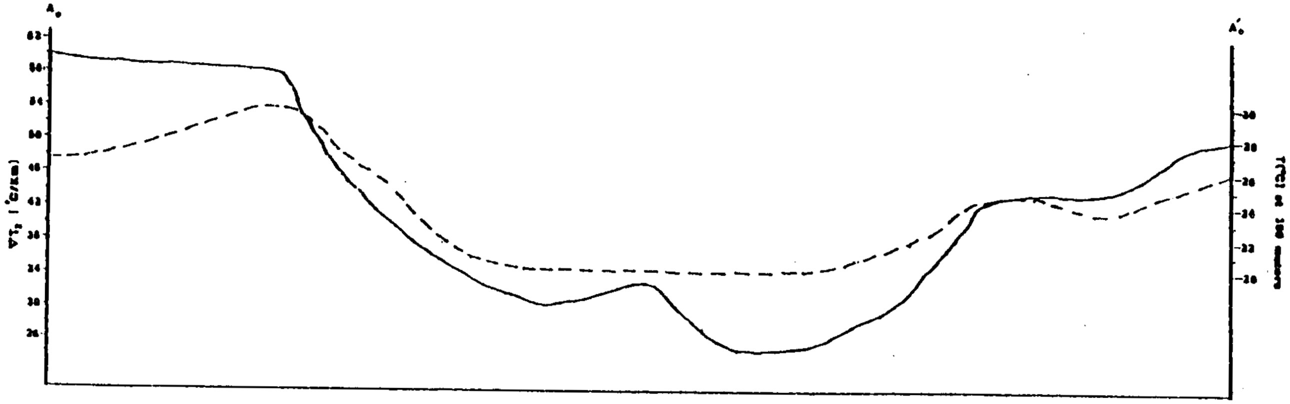


FIGURE 2-10b

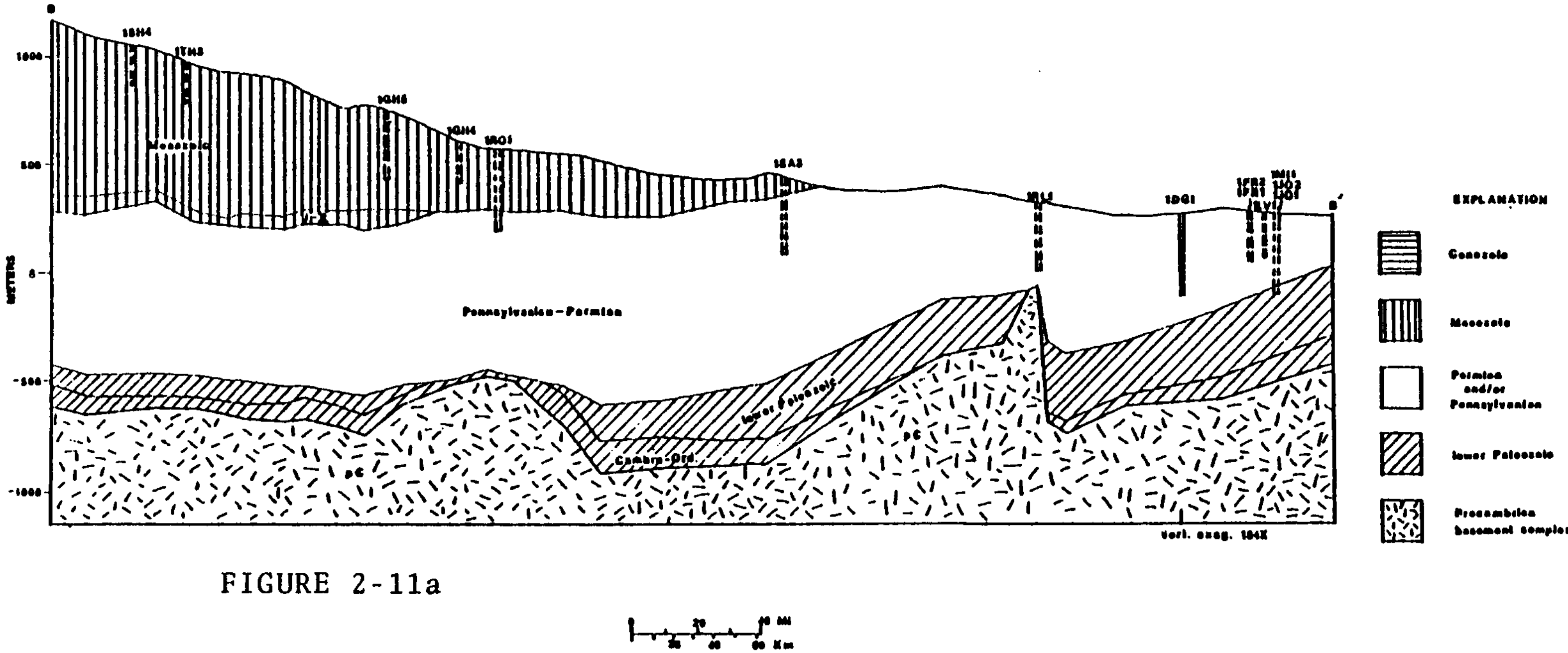


FIGURE 2-11a

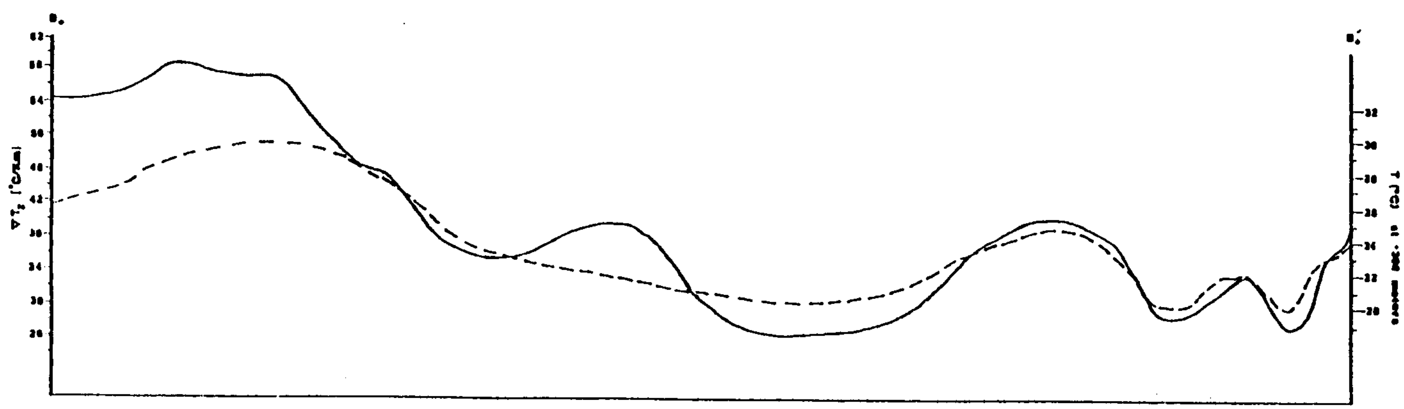


FIGURE 2-11b

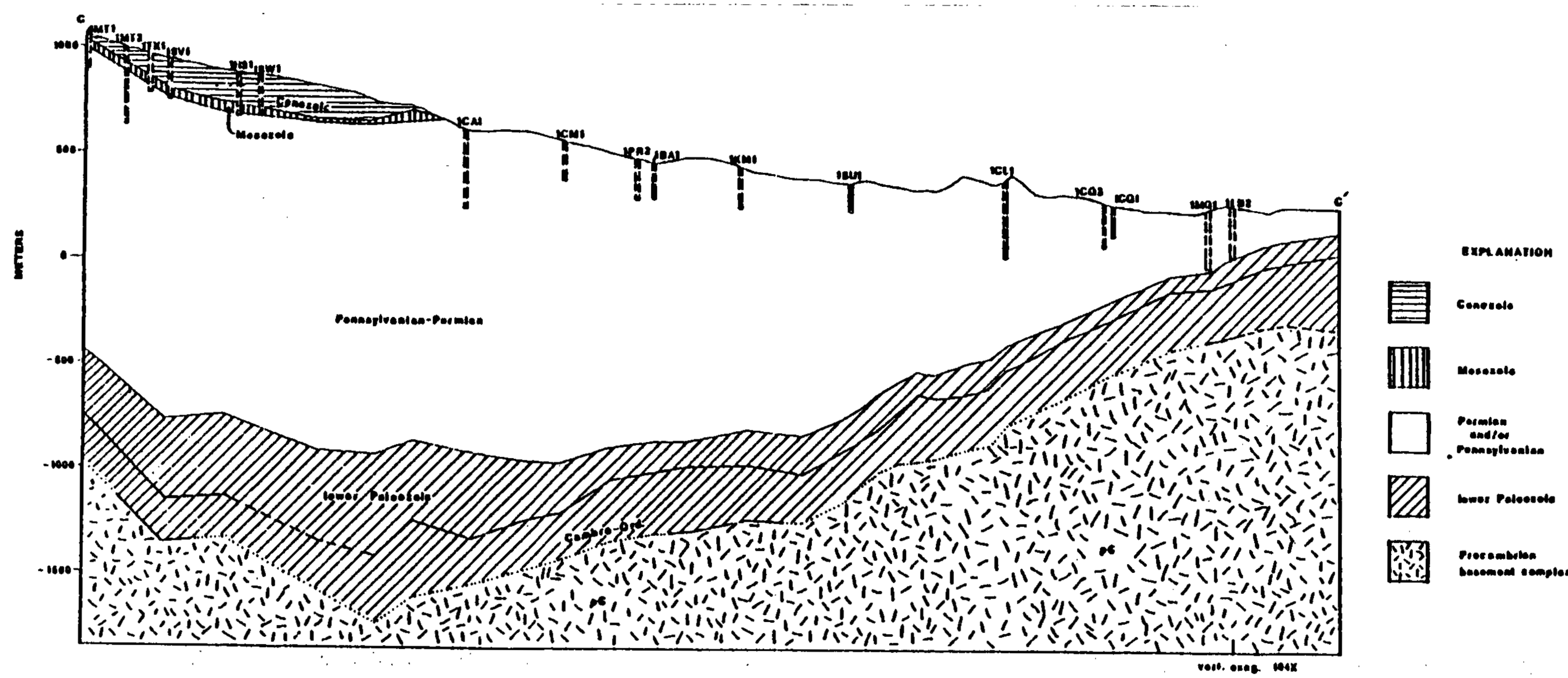


FIGURE 2-12a

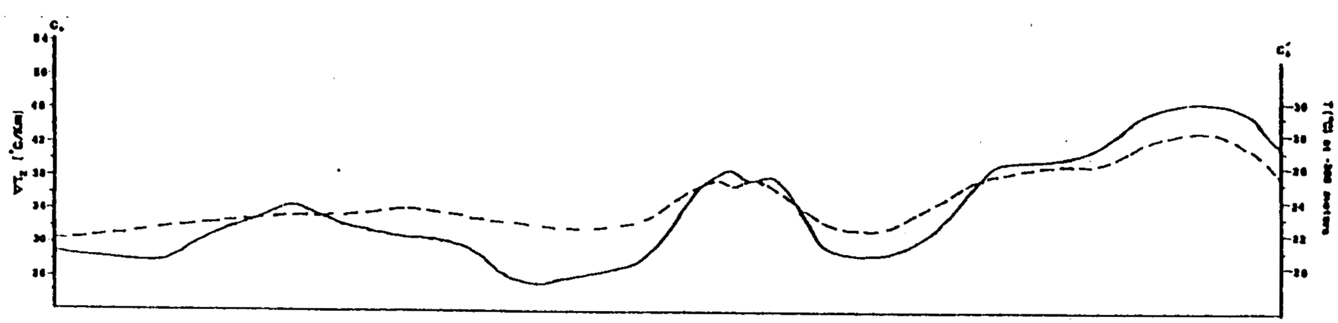


FIGURE 2-12b

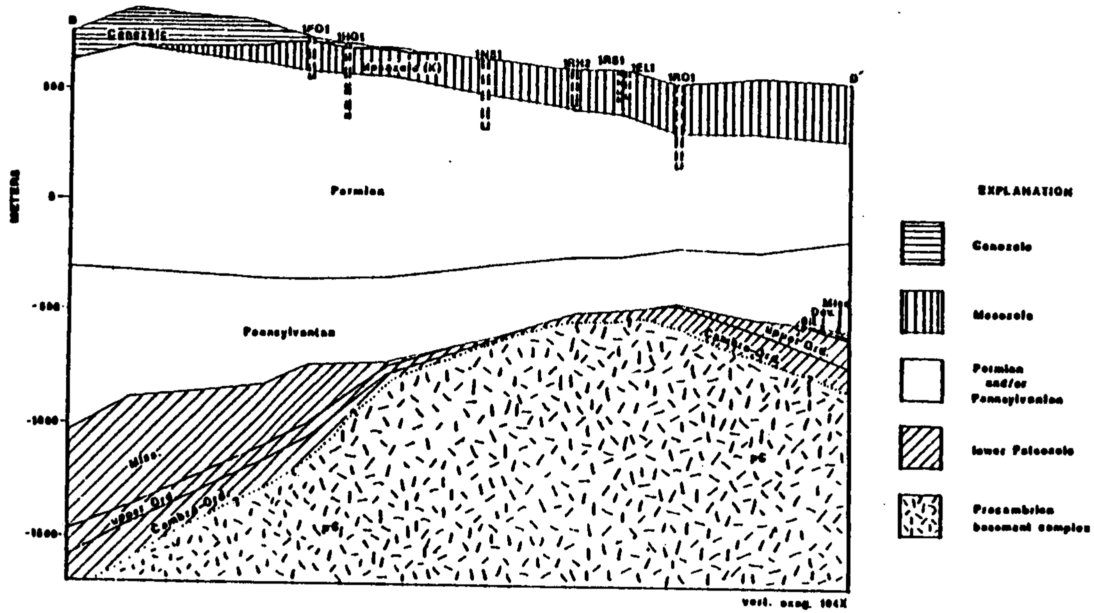


FIGURE 2-13a

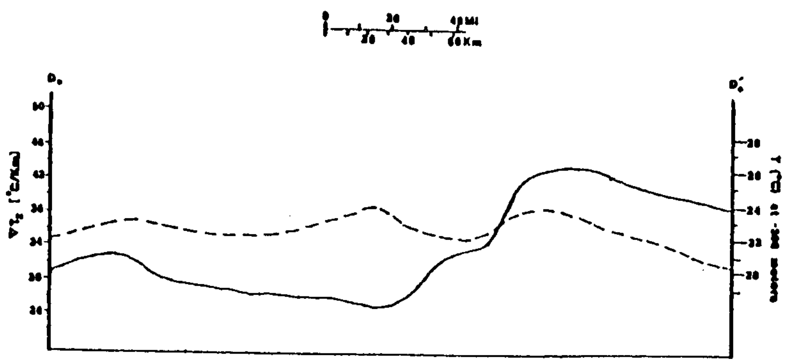


FIGURE 2-13b

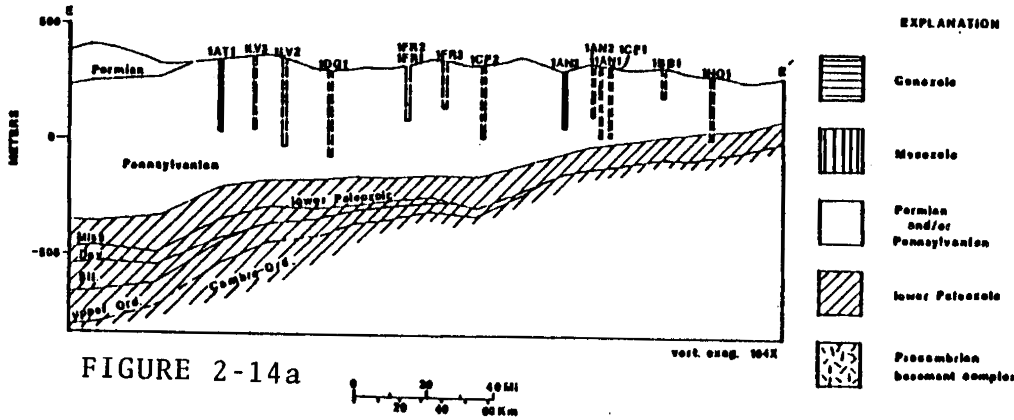


FIGURE 2-14a

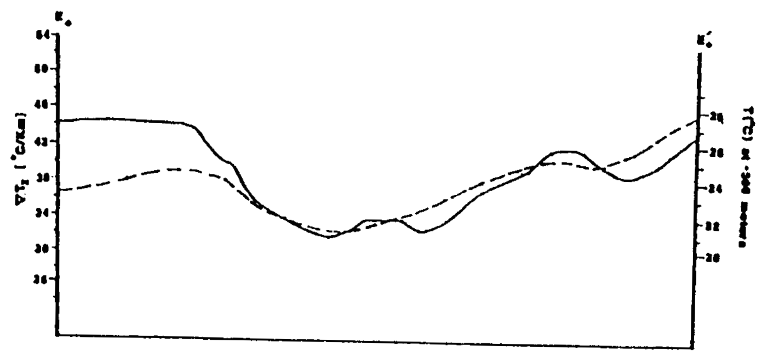


FIGURE 2-14b

PLATE CAPTIONS

PLATE 2-1: Geothermal gradient map of Kansas. Source data: bottom hole data for wells deeper than 305 meters.

PLATE 2-2: Subsurface temperature distribution in Kansas. Source data: bottom hole data for wells deeper than 305 meters. Datum: 300 meters below ground level.

PLATE 2-3: Geothermal gradient map of Kansas. Source data: bottom hole data for wells deeper than 122 meters.

PLATE 2-4: Geothermal gradient map of Kansas. Source data: thermal logging data for wells deeper than 183 meters.

PLATE 2-5: Subsurface temperature distribution in Kansas. Source data: thermal logging data for wells deeper than 122 meters. Datum: 300 meters below ground level.

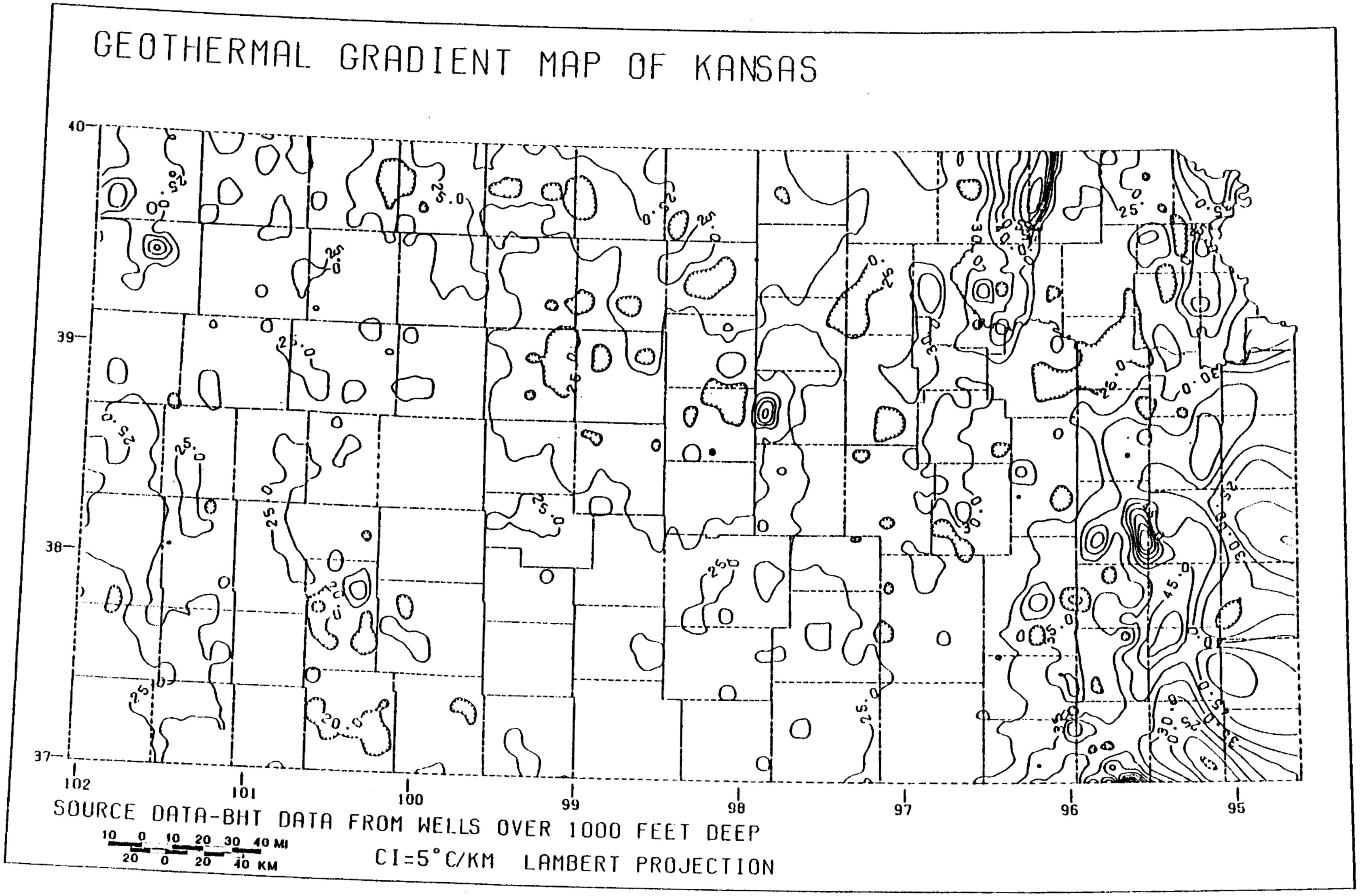
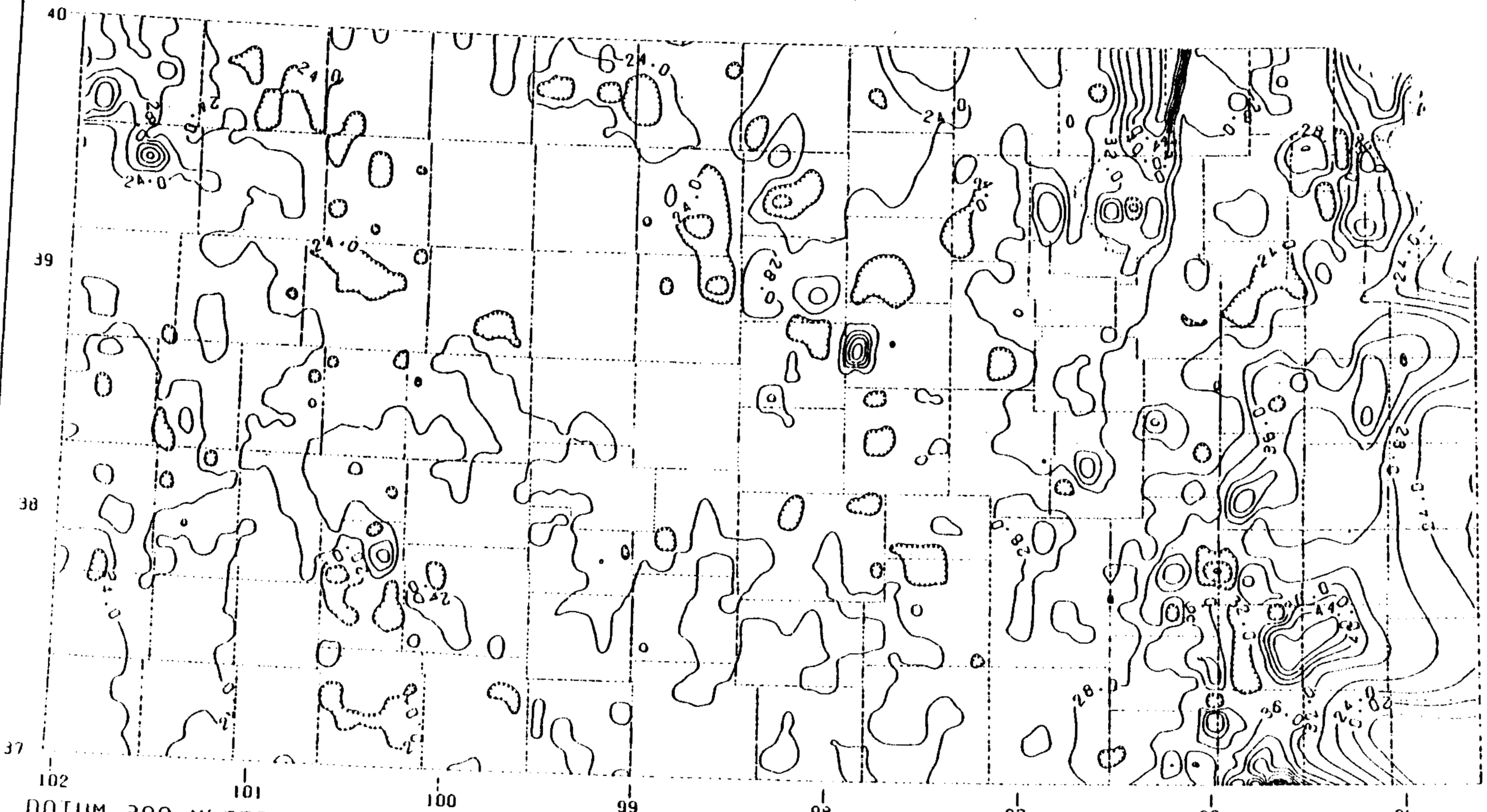

GEOTHERMAL GRADIENT MAP OF KANSAS
40
39
38
37
102
101
100
99
98
97
96
95
SOURCE DATA-BHT DATA FROM WELLS OVER 1000 FEET DEEP
10 0 10 20 30 40 MI
20 0 20 40 KM
CI=5°C/KM LAMBERT PROJECTION

PLATE 2-1

SUBSURFACE TEMERATURE DISTRIBUTION IN KANSAS



DATUM-300 METERS BELOW GROUND LEVEL SOURCE DATA-BHF DATA

10 0 10 20 30 40 MI
20 0 20 40 KM

CI=4° C LAMBERT PROJECTION

PLATE 2-2

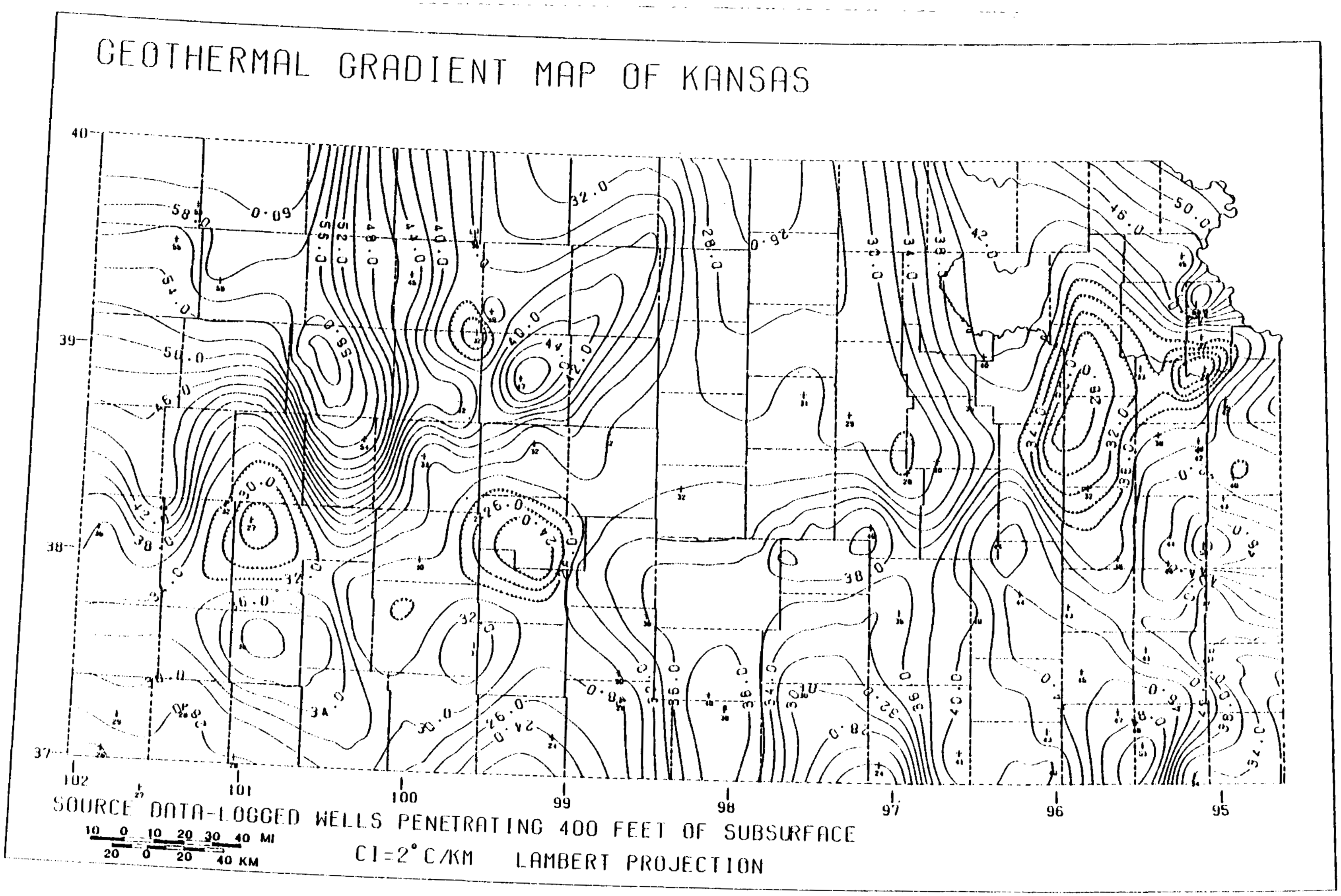

GEOTHERMAL GRADIENT MAP OF KANSAS
40
39
38
37
102
101
100
99
98
97
96
95
SOURCE DATA-LOGGED WELLS PENETRATING 400 FEET OF SUBSURFACE
10 0 10 20 30 40 MI
20 0 20 40 KM
CI=2°C/KM LAMBERT PROJECTION

PLATE 2-3

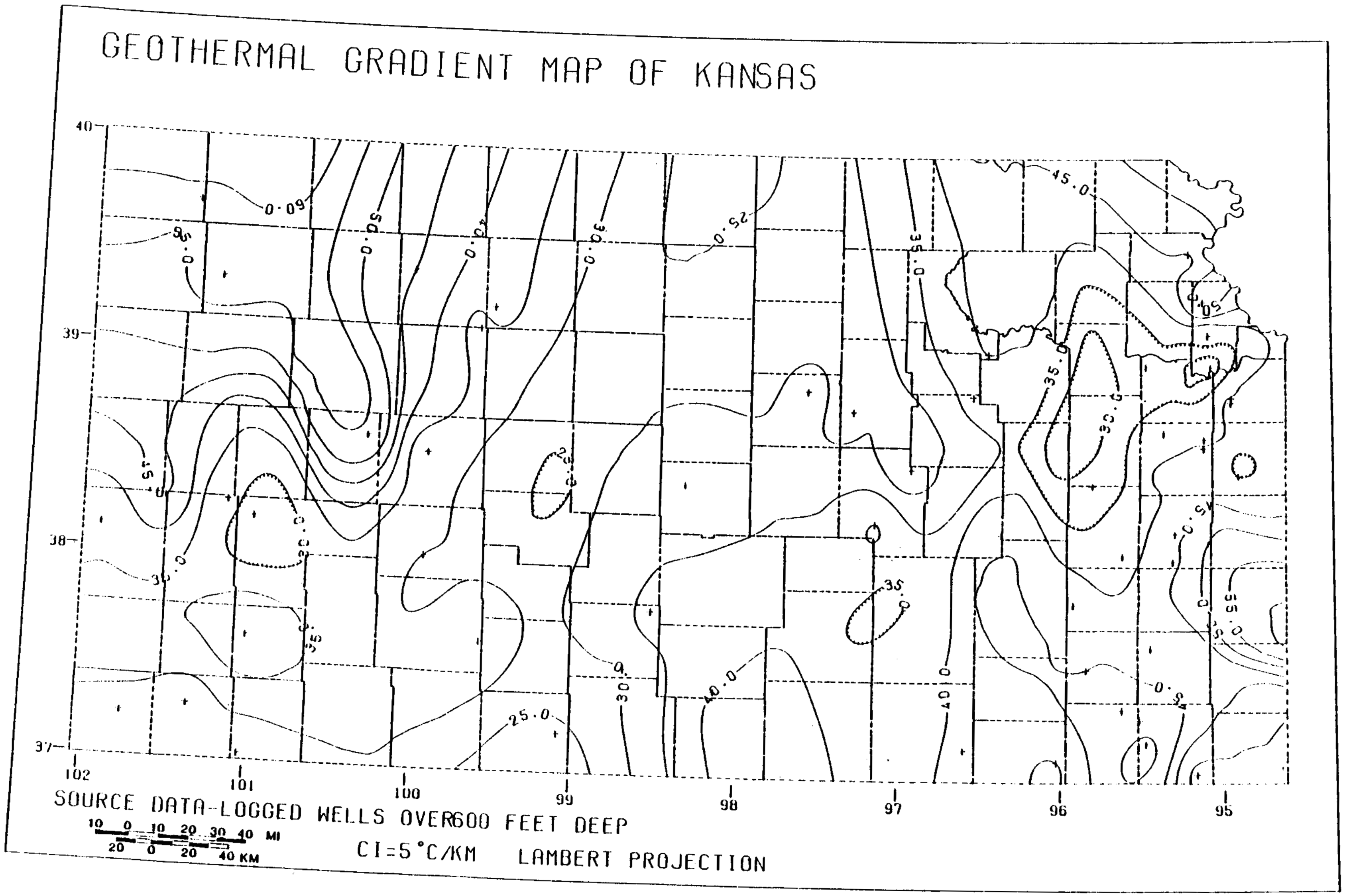

GEOTHERMAL GRADIENT MAP OF KANSAS
40
39
38
37
102
101
100
99
98
97
96
95
60.0
50.0
40.0
30.0
25.0
35.0
45.0
55.0
SOURCE DATA-LOGGED WELLS OVER600 FEET DEEP
10 0 10 20 30 40 MI
20 0 20 40 KM
CI=5°C/KM
LAMBERT PROJECTION

PLATE 2-4

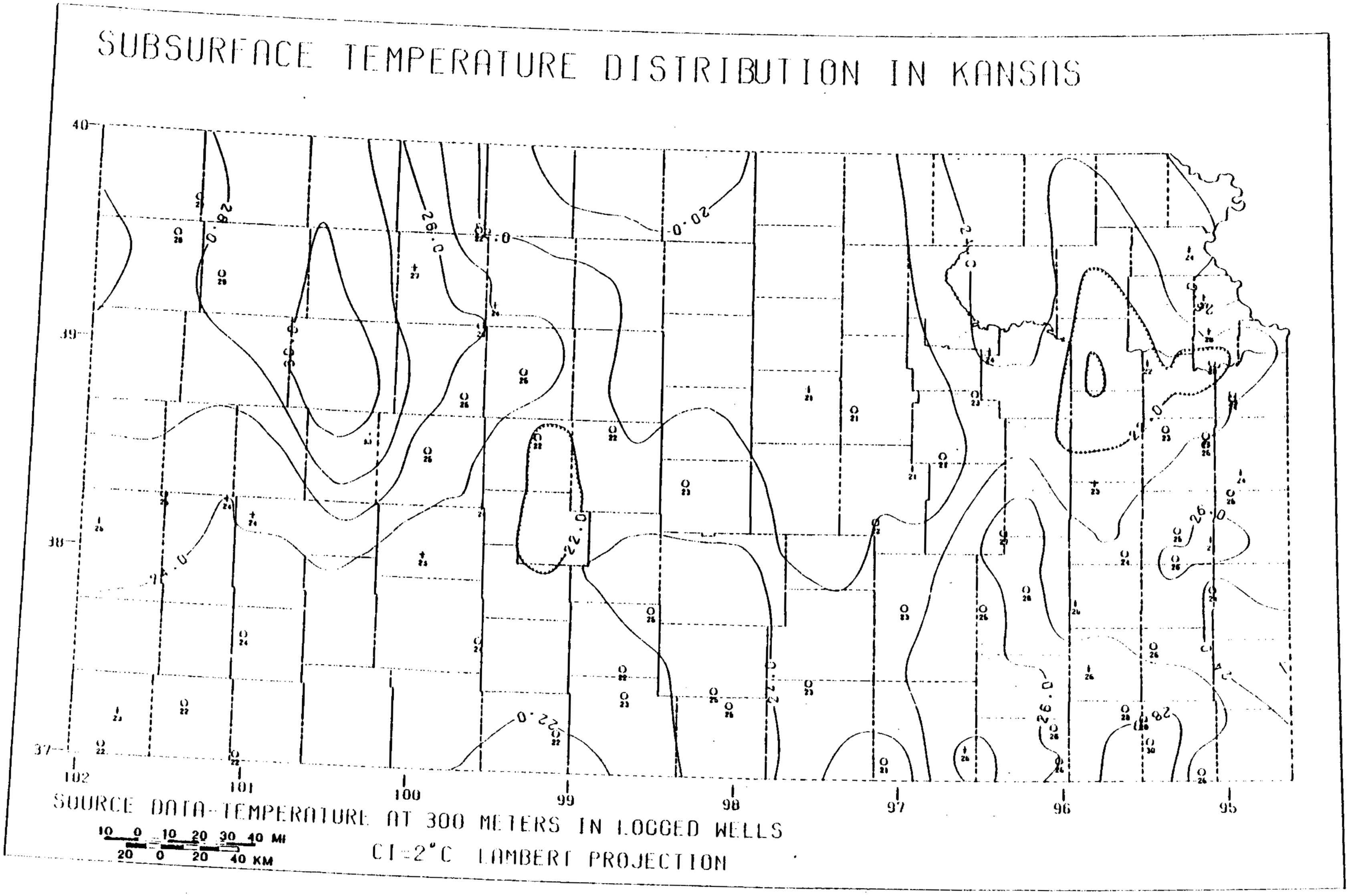

SUBSURFACE TEMPERATURE DISTRIBUTION IN KANSAS
SOURCE DATA-TEMPERATURE AT 300 METERS IN LOGGED WELLS
CI=2°C LAMBERT PROJECTION
10 0 10 20 30 40 MI
20 0 20 40 KM

PLATE 2-5