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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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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 - acquisition 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:

GEOHERMAL 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 sub-surface 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 °C/Km to 55 °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 $1.18 \pm 0.03 \text{ Wm}^{-1}\text{K}^{-1}$. On the high side, evaporite and dolomite units have thermal conductivities of over $4 \text{ Wm}^{-1}\text{K}^{-1}$. 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 Osawatome, 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 (Osawatome I = -20.5° , Big Springs I = 51.5°) 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 Osawatome 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 Osawatome 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.

GEOHERMAL MAPPING OF WESTERN KANSAS BASED ON CHEMICAL GEOHERMOMETERS

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°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°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 ± 10 m.y. ago) at temperatures between 70 and 150 °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 °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 avai-

lable 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 Keweenaw 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 Keweenaw 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 (Steeple, 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).

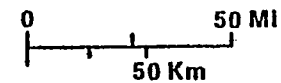
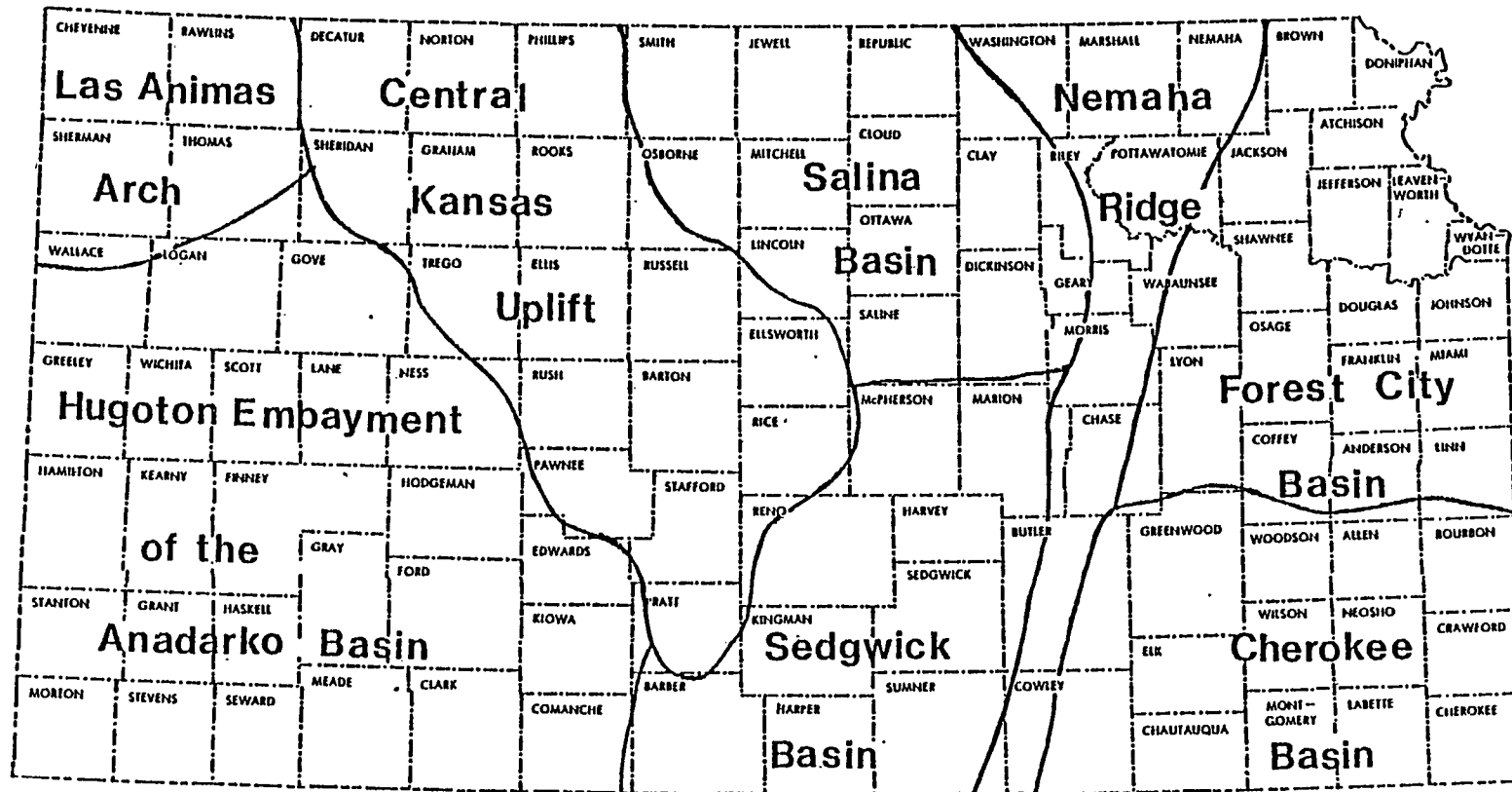
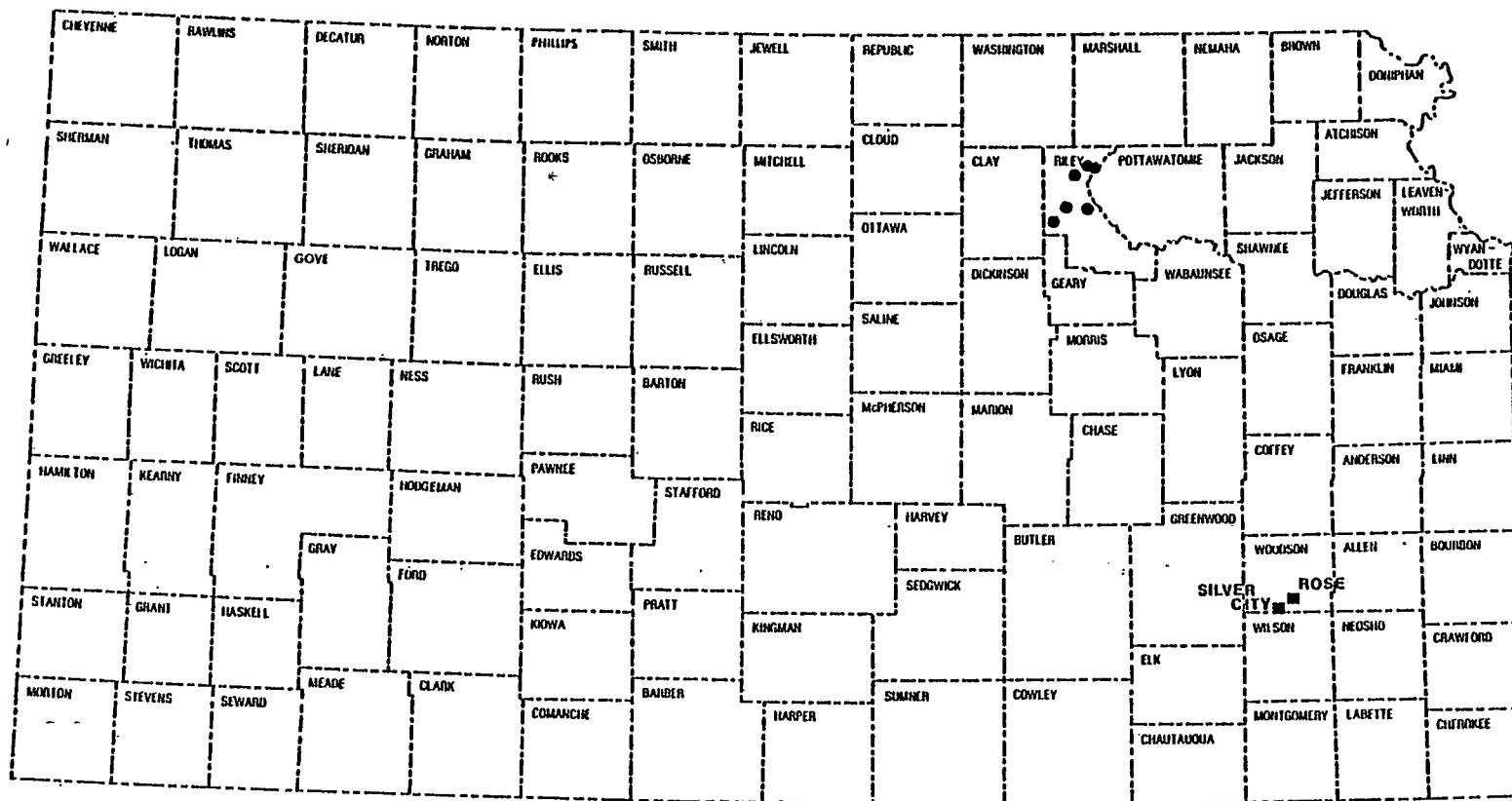


FIGURE 1-1



● RILEY COUNTY KIMBERLITES

■ WOODSON COUNTY PERIDOTITES

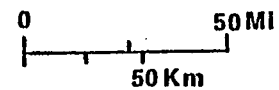


FIGURE 1-2

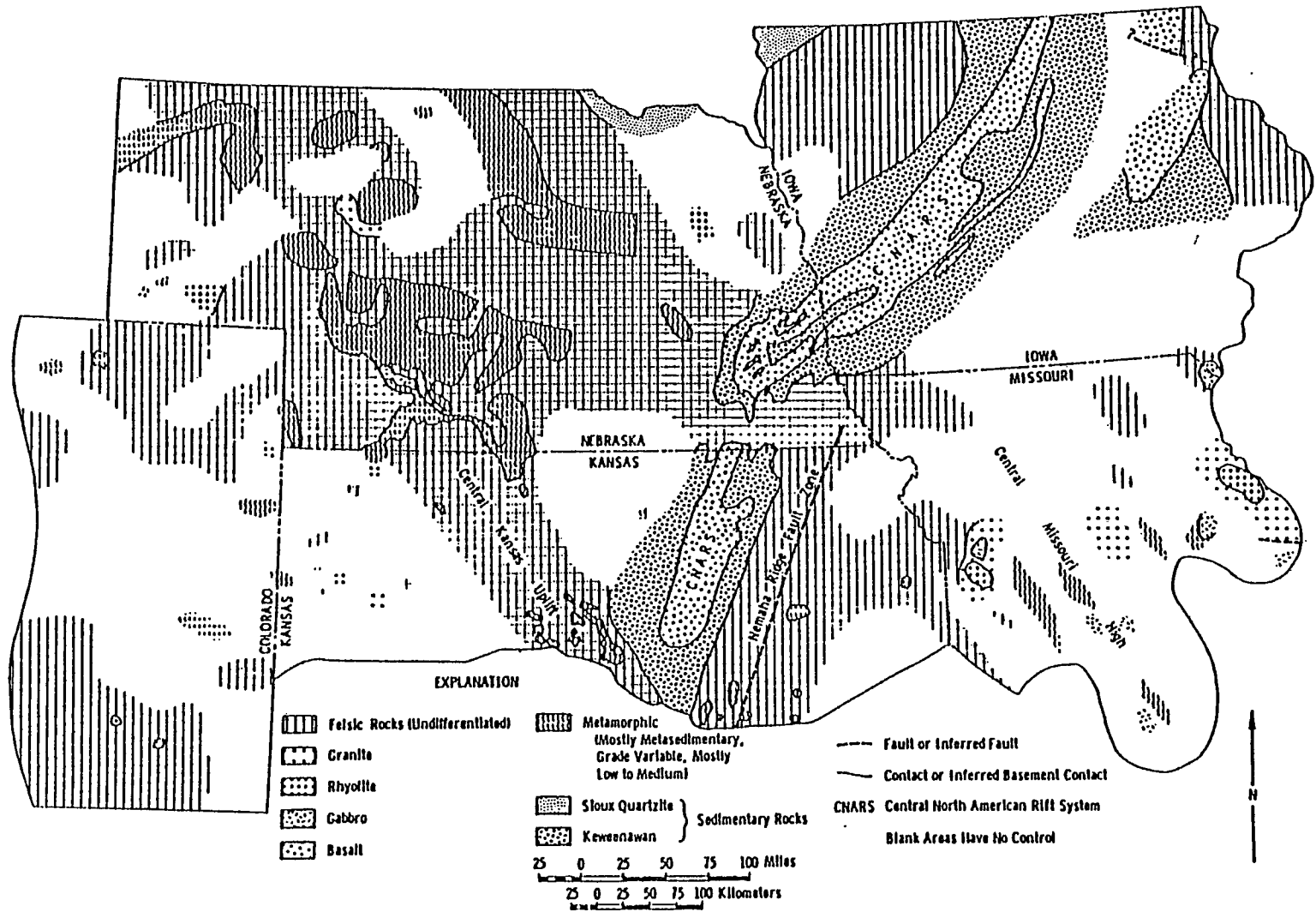


FIGURE 1-3

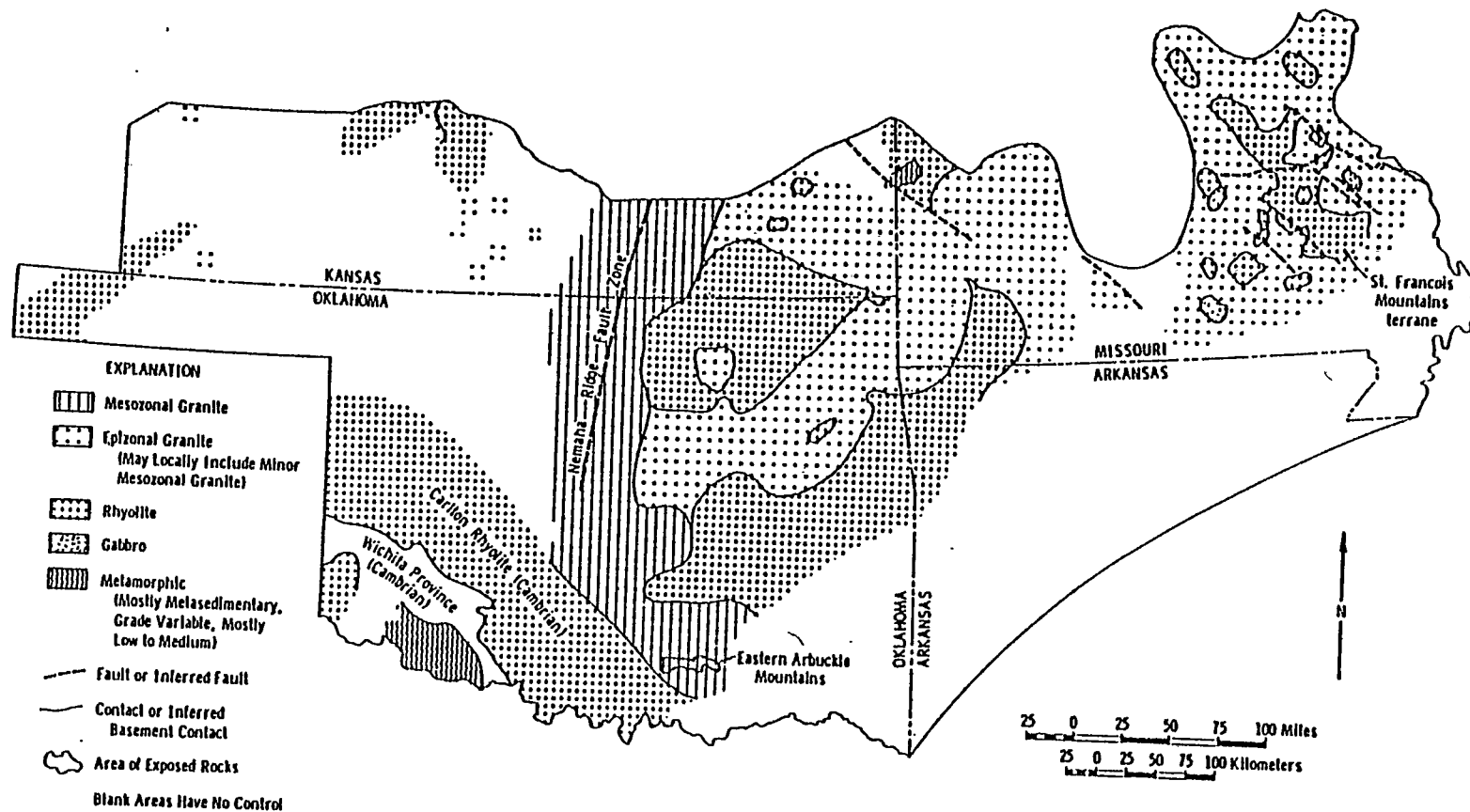


FIGURE 1-4

GEOHERMAL 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 °F at 50 feet below ground level:

$$VT_z = 100[(BHT - 56 \text{ } ^\circ\text{F}) / (TD - 50 \text{ feet})] \quad (\text{Eqn. 2-1})$$

where, VT_z is the magnitude of the vertical component of the geothermal gradient in °F/100 feet

BHT is the bottom hole temperature in °F

TD is the total depth of the well in feet

56 °F and 50 feet are the temperature and depth intercepts, respectively.

(The conversion factor from °F/100 feet to °C/km is 18.23.)

The statewide average annual ambient surface temperature of 12.8 °C (55 °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 °C (56 °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 disturb-

ance 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:

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

where, ∇T_z is the magnitude of the vertical component of the geothermal gradient in $^\circ\text{C}$

300m is the depth datum

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

13.3 $^\circ\text{C}$ 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:

IAN3 - 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 °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 °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 Forma-

tions; 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 approximately 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.

Repeatability of Measurements.

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 reproducible 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/°K, whereas values for granites range from 2.09 to 2.93 W/°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 (Schoepfel 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, Chéyenne 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 delineated here.)

GEOHERMAL 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 °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 °C/km (Plate 2-3). However, in the northern portions of the basin the gradients tend to be somewhat higher (35 to 45 °C/km).

Las Animas Arch.

In this area of northwestern Kansas, extremely high (50 to 60 °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 Mid-continent (specifically in Kansas) to be much lower than reported by pre-

vious workers (Garland and Lennox, 1962; Combs and Simmons, 1973; Scatolini, 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 °C/km) but

decrease to 30 to 35 °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 °C/km, while the contour trend indicates that there are geothermal gradients lower than 24 °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 °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 °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 °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 °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 °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 °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 °C/km). Geothermal gradients in the range of 40 to 50 °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 °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 north-eastern 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 $4.9 \mu\text{W}/\text{m}^3$ in hole 1MI1 and $2.4 \mu\text{W}/\text{m}^3$ 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.

GEOHERMAL 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; Schoepel 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 conductiv-

ity. 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_x-A_x' (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_x-B_x' (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_x-C_x' 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_x-C_x' (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_x-D_x' (Figure 2-13, a and b) are essentially normal to the trend of the Central Kansas Uplift. The subsurface temperatures along D_x-D_x' 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_x-B_x' and this suggests that the offset observed on B_x-B_x' is an effect of the computer contouring program.

Finally, sections E-E' and E_x-E_x' (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 °C (After Misener and Beck, 1960). The borehole is assumed to be full of water. For a particular temperature (temperatures from 5 to 20 °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 behavior 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_x-A_x'.
- 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_x-B_x'.
- 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_x-C_x'.
- 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_x-D_x'.
- 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_x-E_x'.

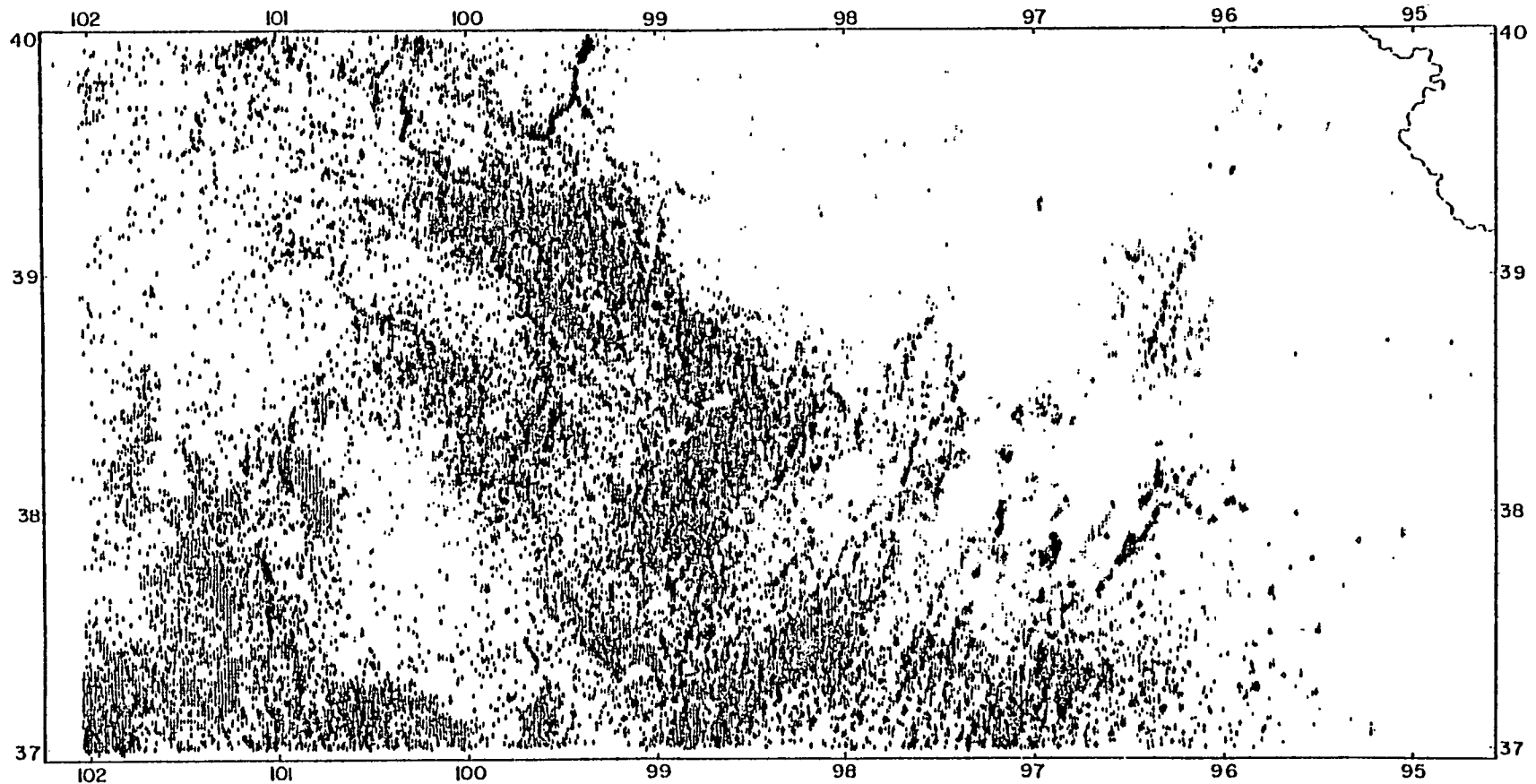


GAMMA-GUARD SIDEWALL NEUTRON LOG

COMPANY CHAMPLIN PETROLEUM COMPANY WELL JOHNSON N-2 FIELD RIVERVIEW County ELLIS State KANSAS	COMPANY <u>CHAMPLIN PETROLEUM COMPANY</u> WELL <u>JOHNSON N-2</u> FIELD <u>RIVERVIEW</u> COUNTY <u>ELLIS</u> STATE <u>KANSAS</u>			
	Location <u>1</u> SE-NE-NW Sec. <u>32</u> Twp. <u>11S</u> Rge. <u>18W</u>		Other Services: <u>CAVL-G-C</u>	
Permanent Datum <u>GROUND LEVEL</u> Elev. <u>2065'</u>		Elev. K.B. <u>2070'</u>		
Log Measured From <u>KELLY BUSHING, 5</u> Ft. Above Perm Datum		D.F. _____		
Drilling Measured From <u>KELLY BUSHING</u>		2 G.L. <u>2065'</u>		
Date	<u>5</u>	<u>6-17-80</u>	<u>6-17-80</u>	<u>6-17-80</u>
Run No.		<u>GAMMA</u>	<u>NEUTRON</u>	<u>GUARD</u>
Depth—Driller		<u>3800'</u>	<u>3800'</u>	<u>3800'</u>
Depth—Welex	<u>3</u>	<u>3800'</u>	<u>3800'</u>	<u>3800'</u>
Btm. Log Inter.		<u>3772.4'</u>	<u>3799'</u>	<u>3786.6'</u>
Top Log Inter.		<u>1800'</u>	<u>1800'</u>	<u>1800'</u>
Casing—Driller		<u>8-5/8@ 245'</u>	<u>8-5/8@ 245'</u>	<u>8-5/8@ 245'</u>
Casing—Welex		<u>8-5/8" @ 245'</u>	<u>8-5/8" @ 245'</u>	<u>8-5/8" @ 245'</u>
Bit Size		<u>7-7/8"</u>	<u>7-7/8"</u>	<u>7-7/8"</u>
Type Fluid in Hole		<u>STARCH</u>	<u>STARCH</u>	<u>STARCH</u>
Dens. Visc.		<u>9.9 143</u>	<u>9.9 143</u>	<u>9.9 143</u>
pH Fluid Loss		<u>6.6 5.6 ml</u>	<u>6.6 16.6 ml</u>	<u>6.6 16.6 ml</u>
Source of Sample		<u>FLOW LINE</u>	<u>FLOW LINE</u>	<u>FLOW LINE</u>
R _m @ Meas. Temp.		<u>.11 @ 92°F</u>	<u>@ °F</u>	<u>@ °F</u>
R _m @ Meas. Temp.		<u>.083 @ 92°F</u>	<u>@ °F</u>	<u>@ °F</u>
R _m @ Meas. Temp.		<u>.165 @ 92°F</u>	<u>@ °F</u>	<u>@ °F</u>
Source R _m R _{xx}		<u>MEASURED</u>	<u> </u>	<u> </u>
R _m @ BHT	<u>4</u>	<u>.092 @ 112°F</u>	<u>@ °F</u>	<u>@ °F</u>
Time Since Circ.	<u>6</u>	<u>2 HOURS</u>	<u> </u>	<u> </u>
Max. Rec. Temp.		<u>112°F @ T.D.</u>	<u>°F @</u>	<u>°F @</u>
Equip. Location		<u>1889 COI BY</u>	<u> </u>	<u> </u>
Recorded By		<u>S. DUDLEY</u>		
Witnessed By		<u>MR. PETE STRUB</u>		

FIGURE 2-1

DATA POINTS FOR GEOTHERMAL GRADIENT MAP OF KANSAS



SOURCE DATA--ALL BHT DATA

FIGURE 2-2

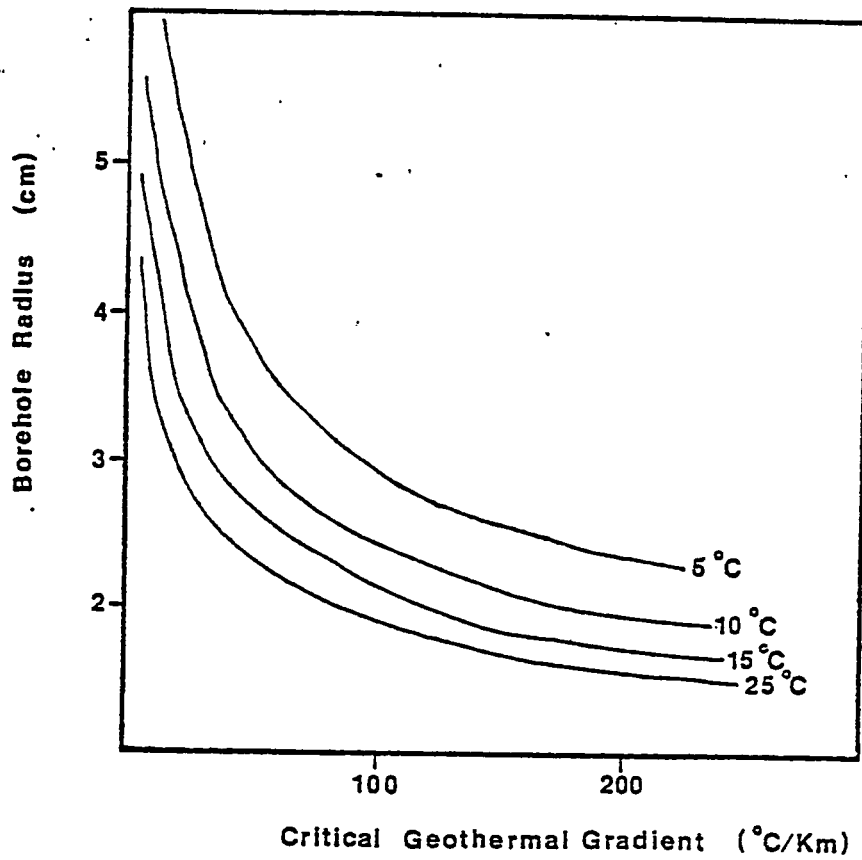


FIGURE 2-4

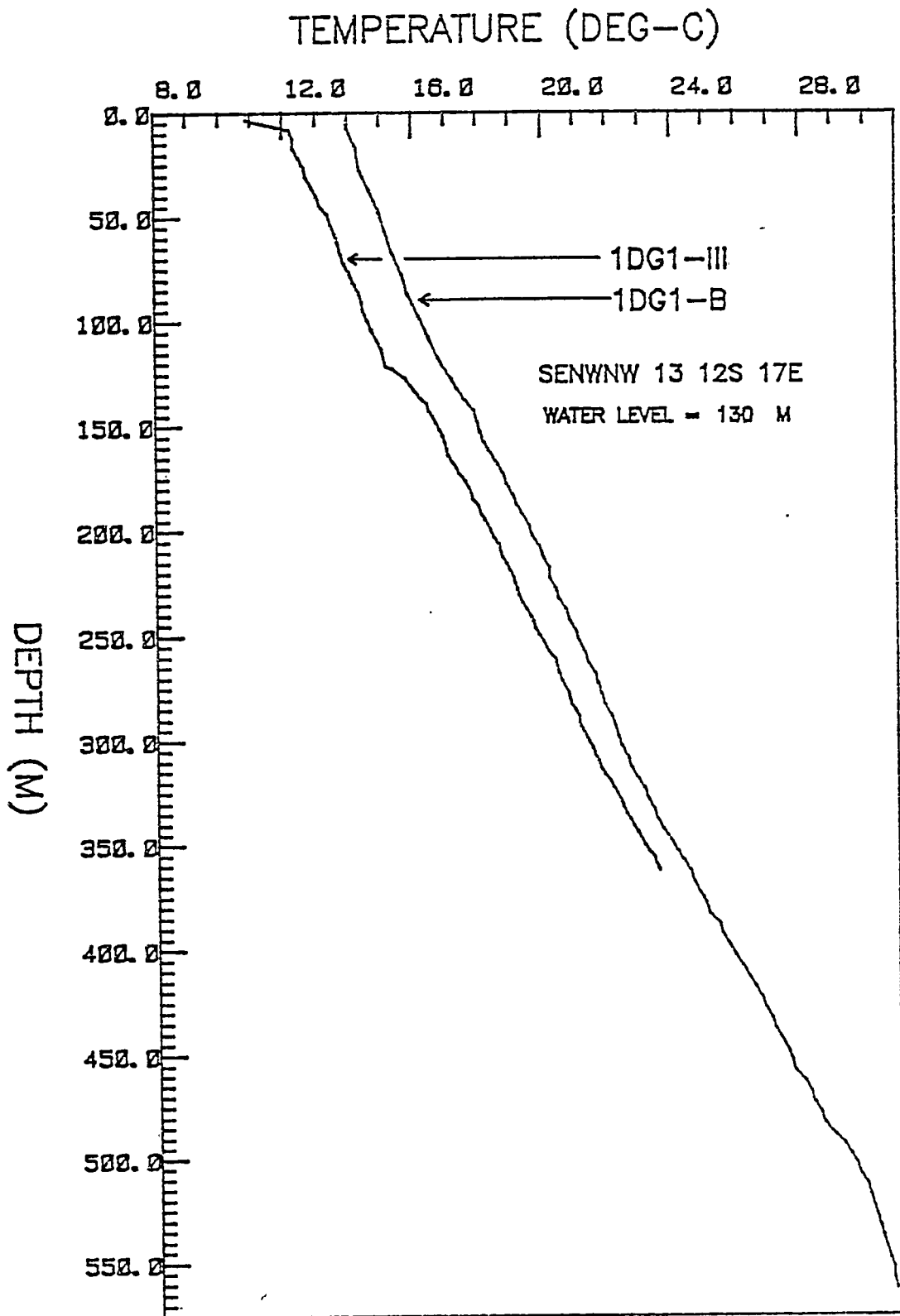


FIGURE 2-5

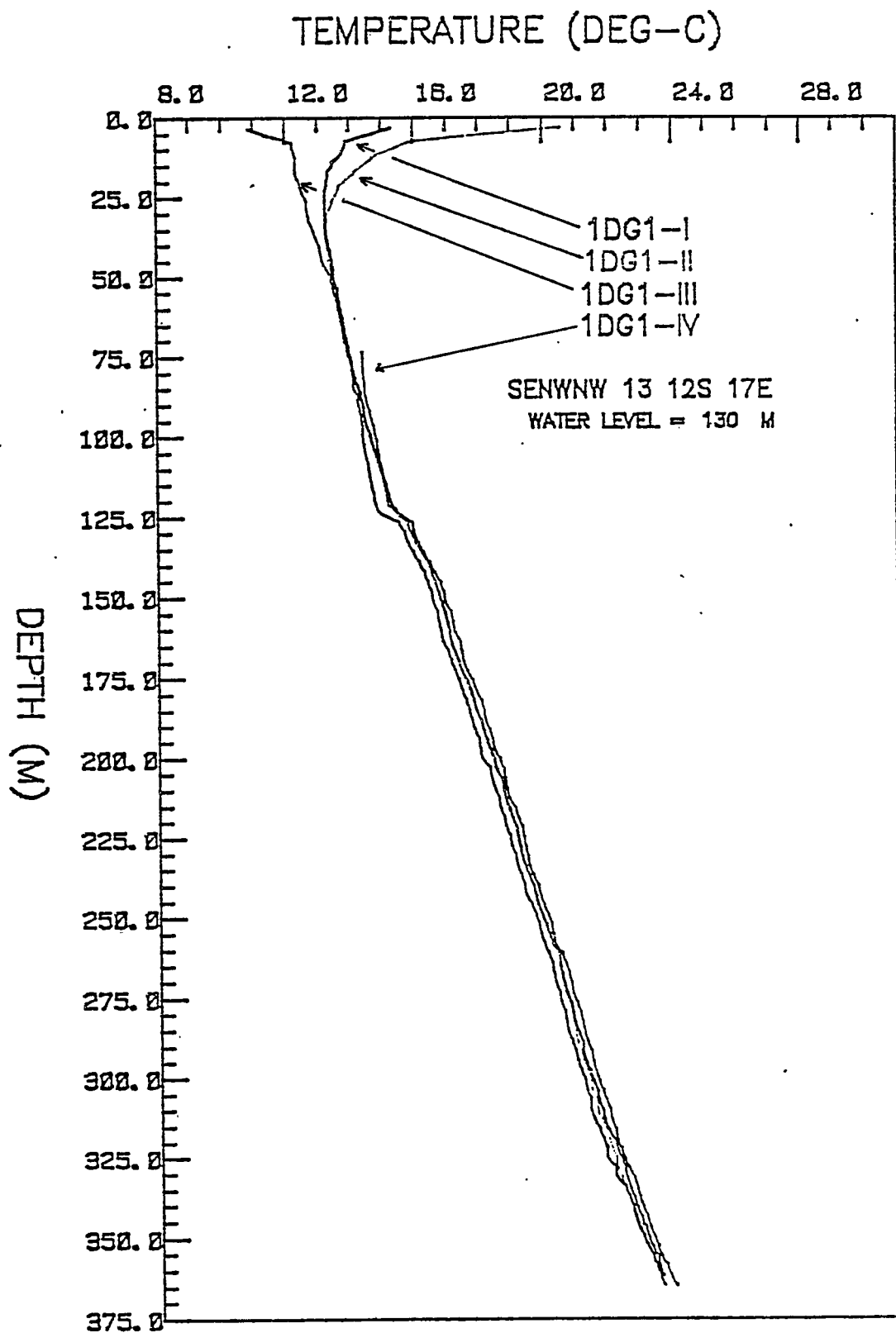
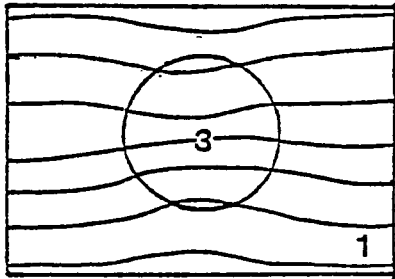
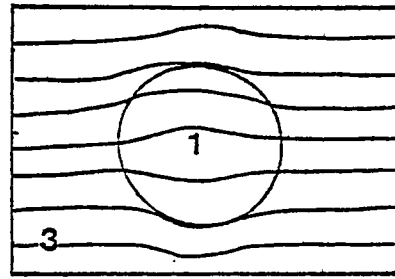


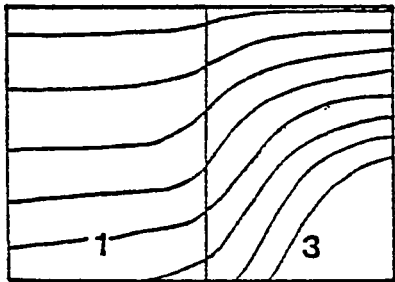
FIGURE 2-6



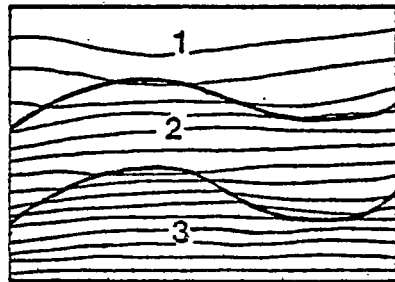
A



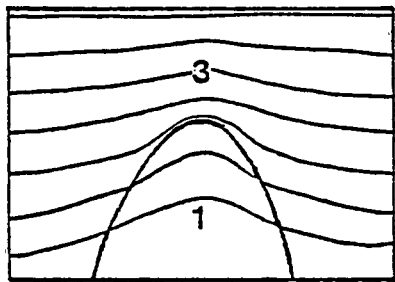
B



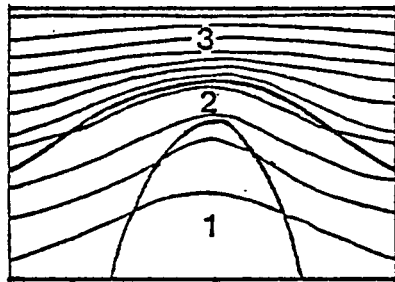
C



D



E



F

1-good

2-medium

3-poor

FIGURE 2-7

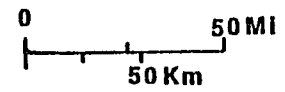
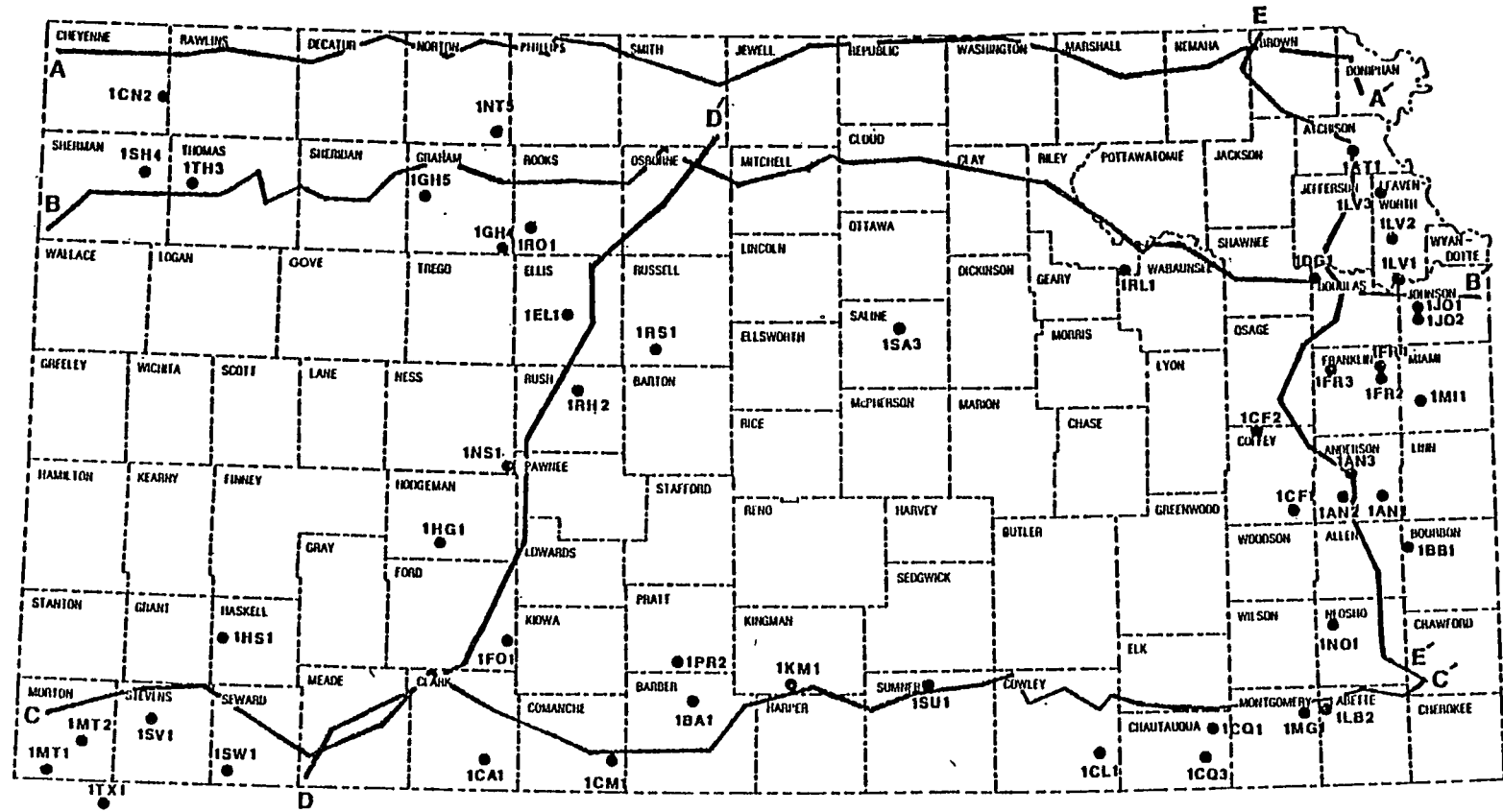


FIGURE 2-8

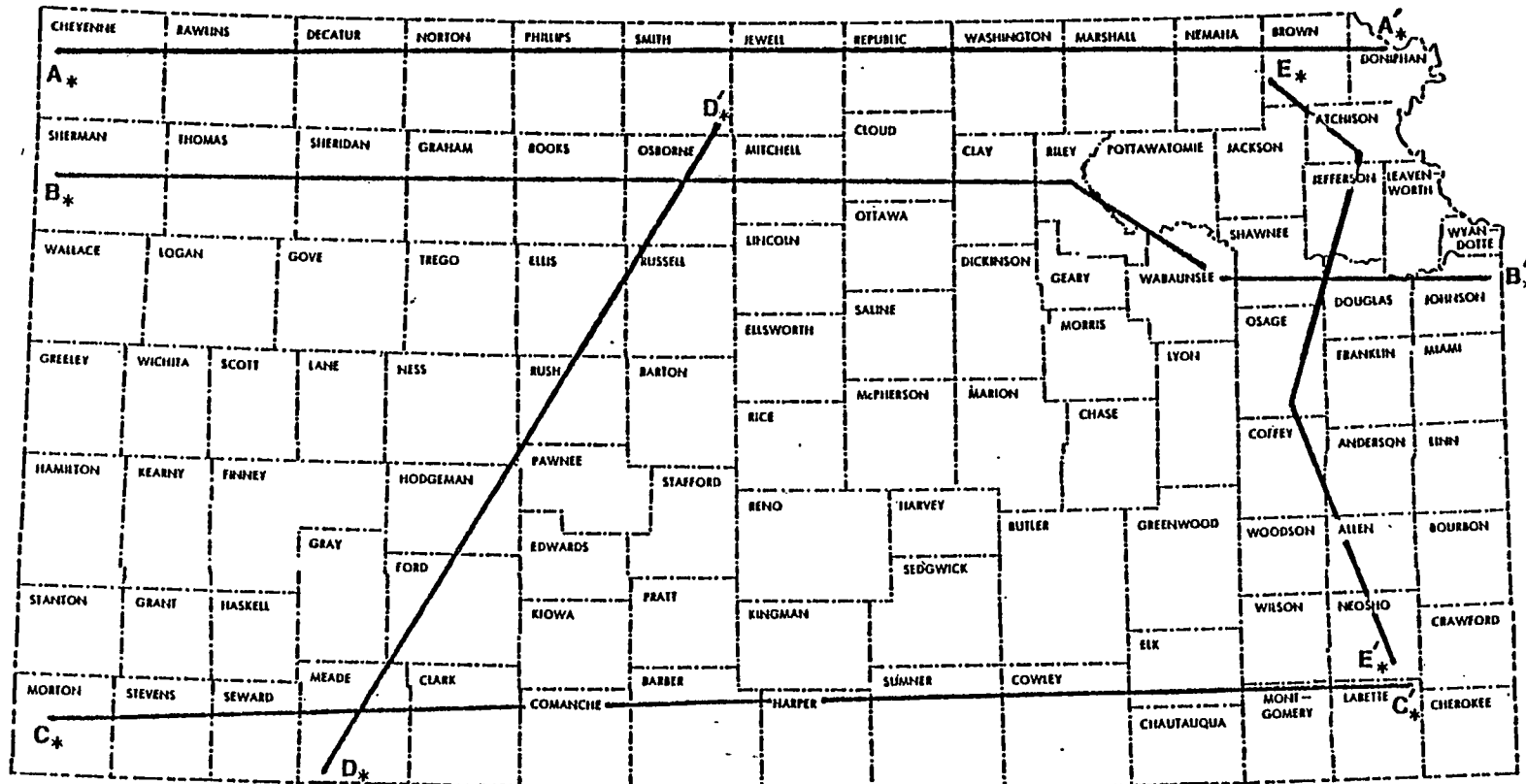


FIGURE 2-9

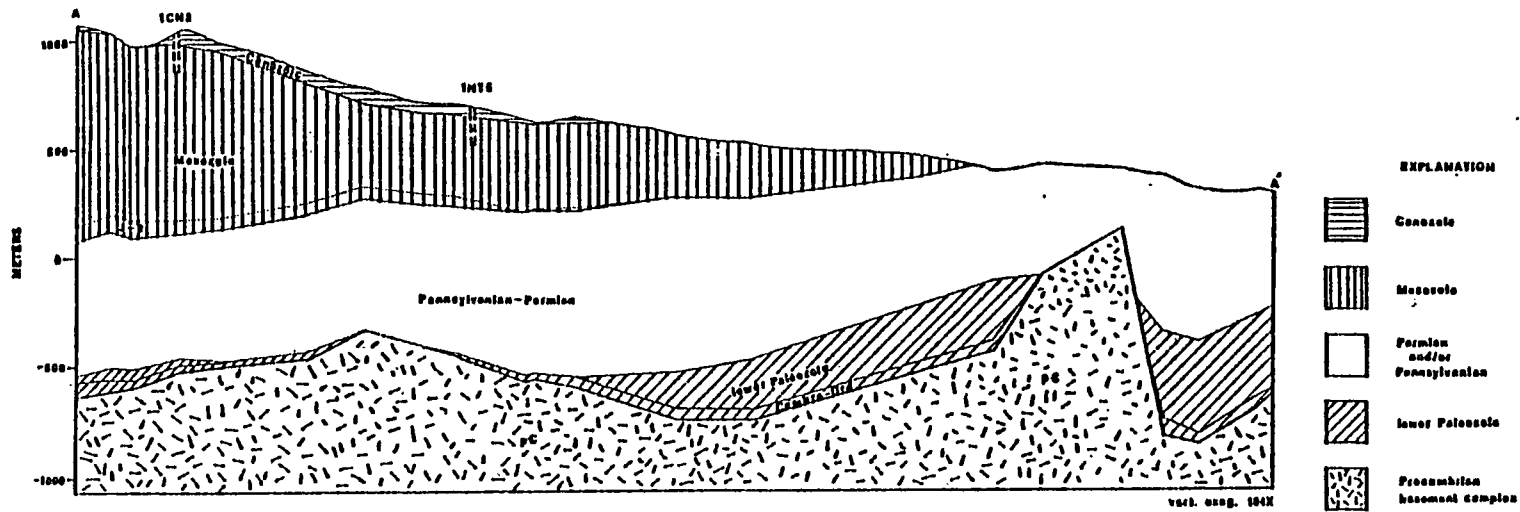


FIGURE 2-10a

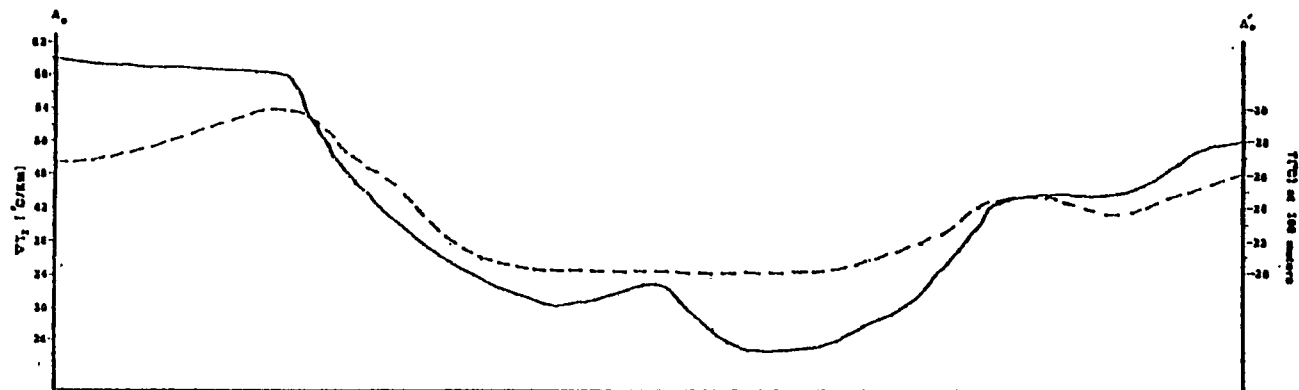
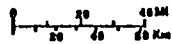


FIGURE 2-10b

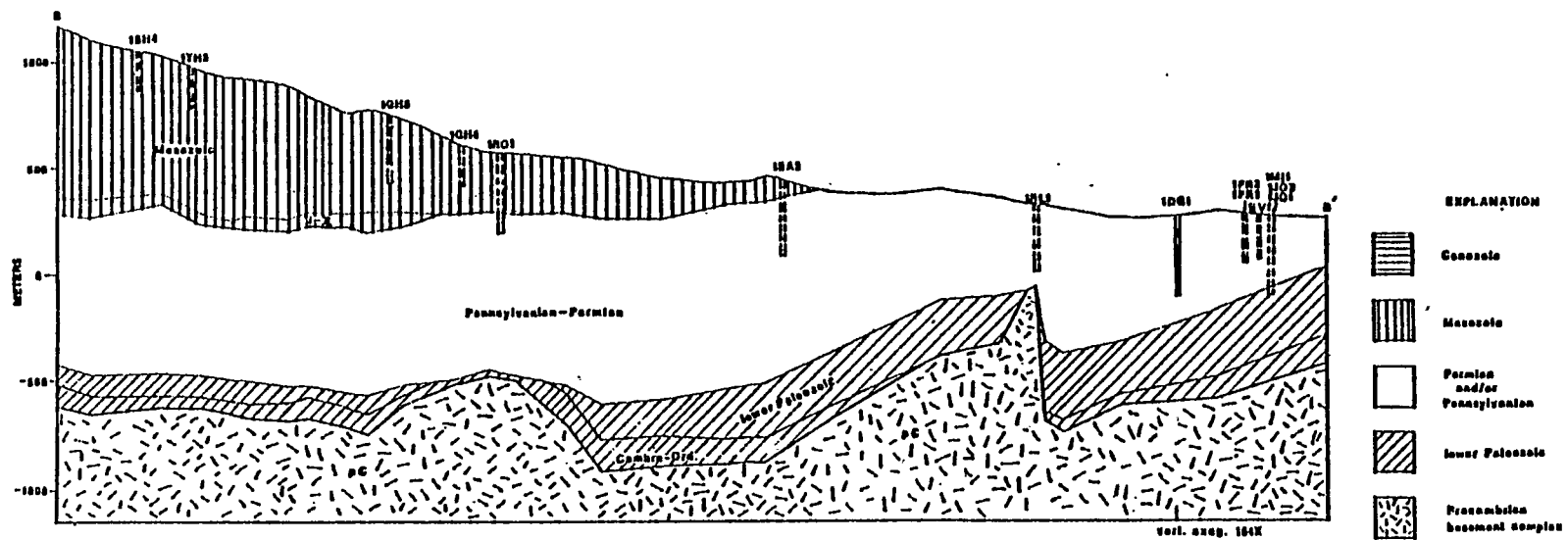


FIGURE 2-11a

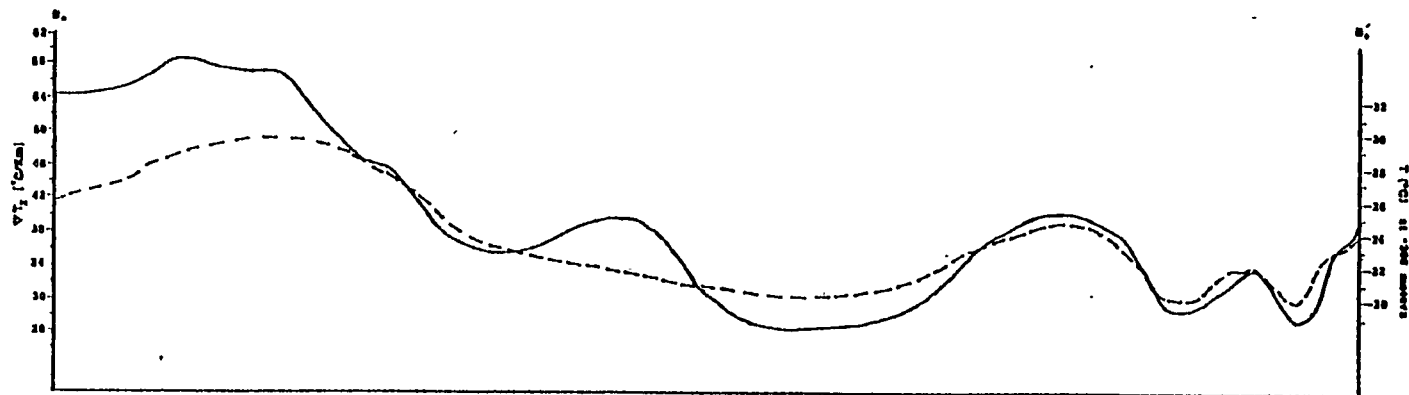
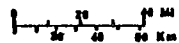


FIGURE 2-11b

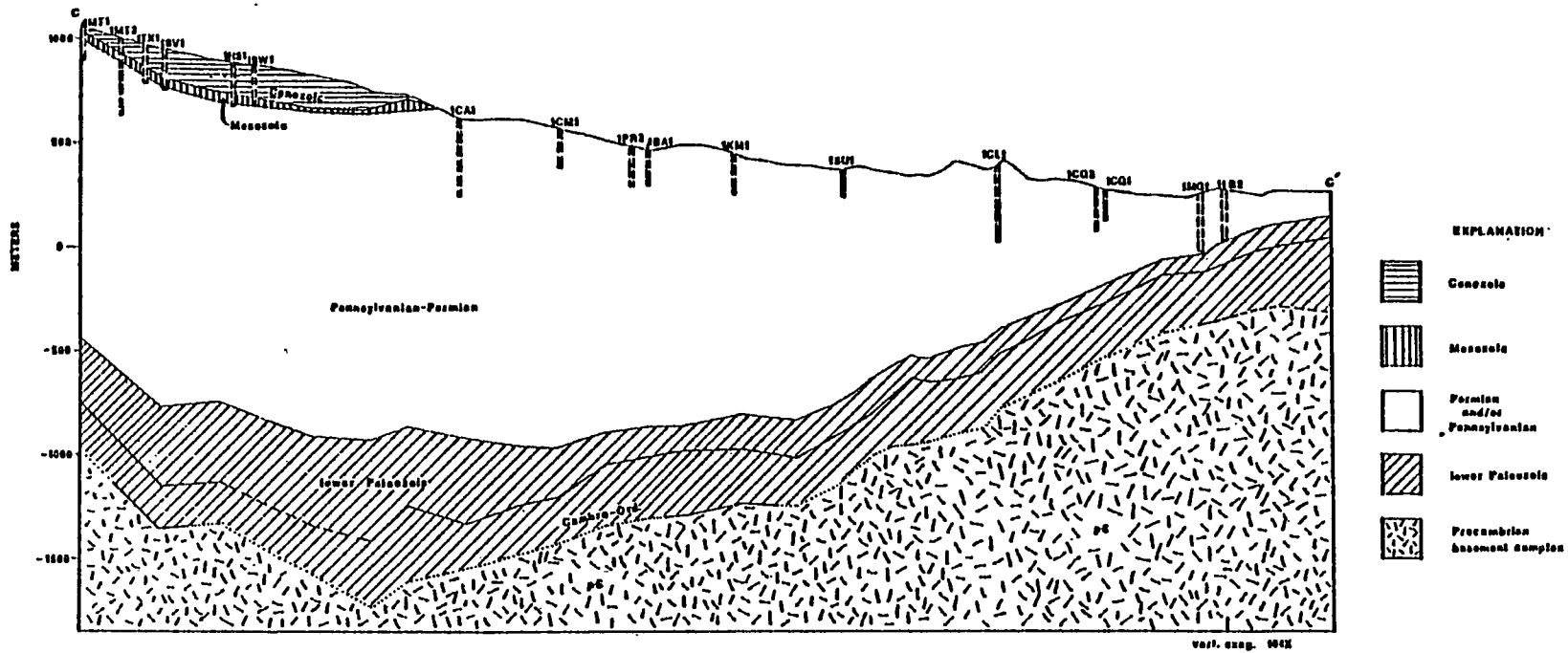


FIGURE 2-12a

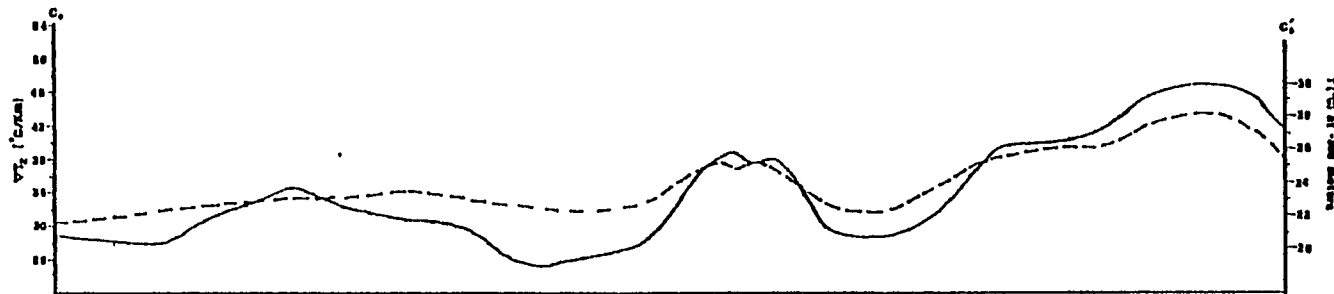
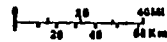


FIGURE 2-12b

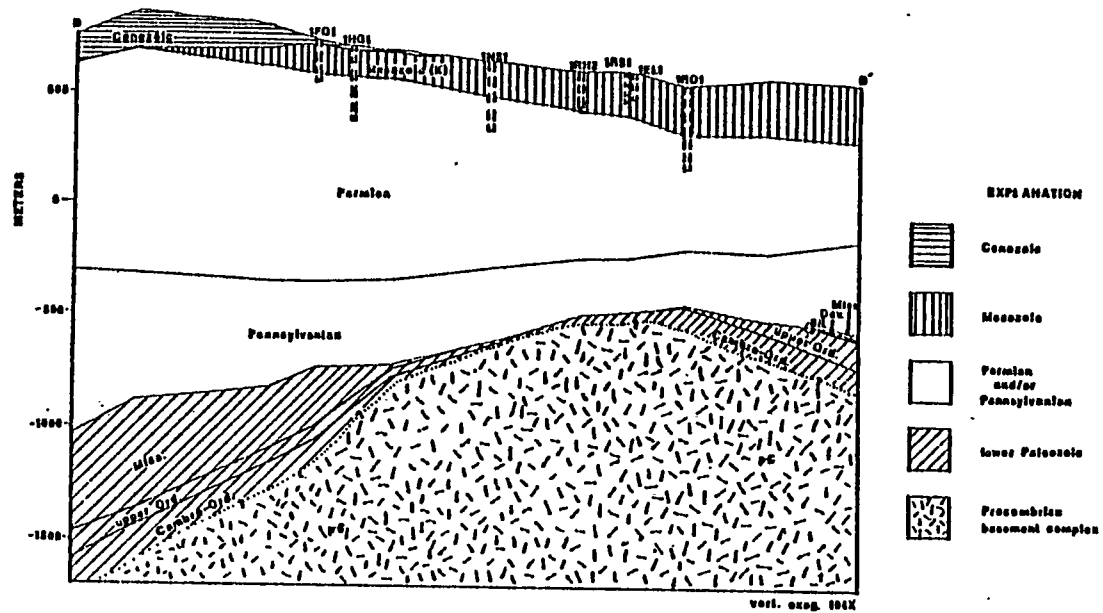


FIGURE 2-13a

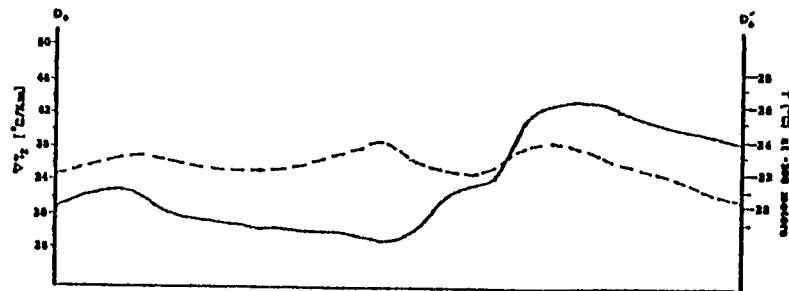
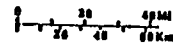


FIGURE 2-13b

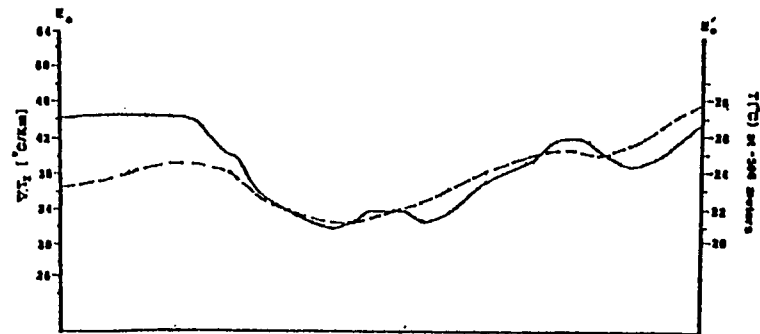
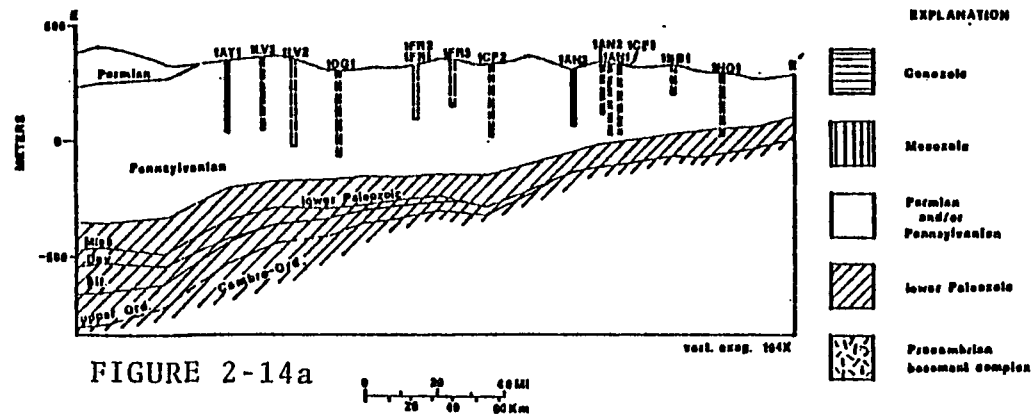
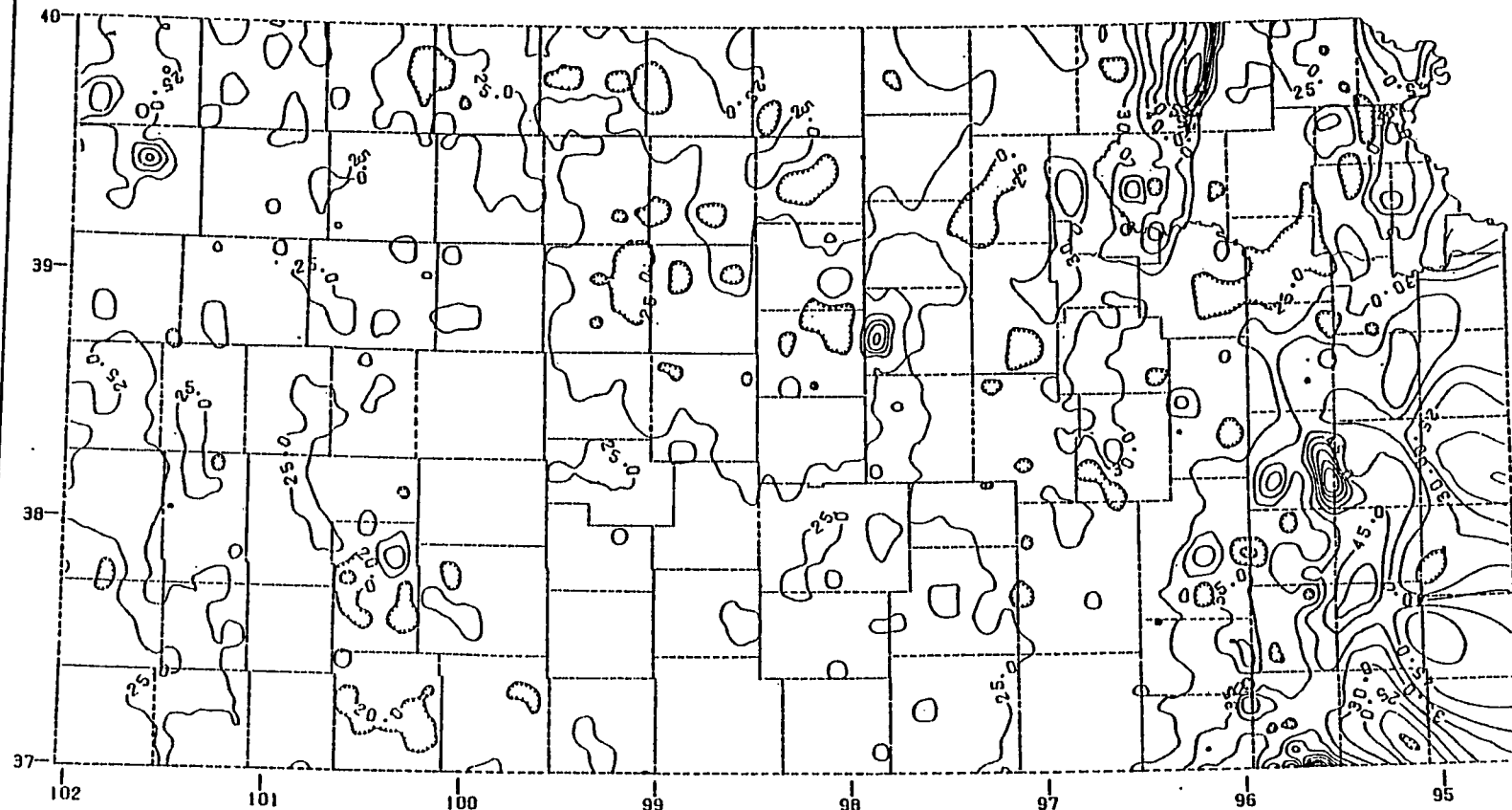


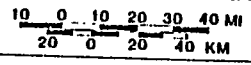
PLATE CAPTIONS

- 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.

GEOHERMAL GRADIENT MAP OF KANSAS



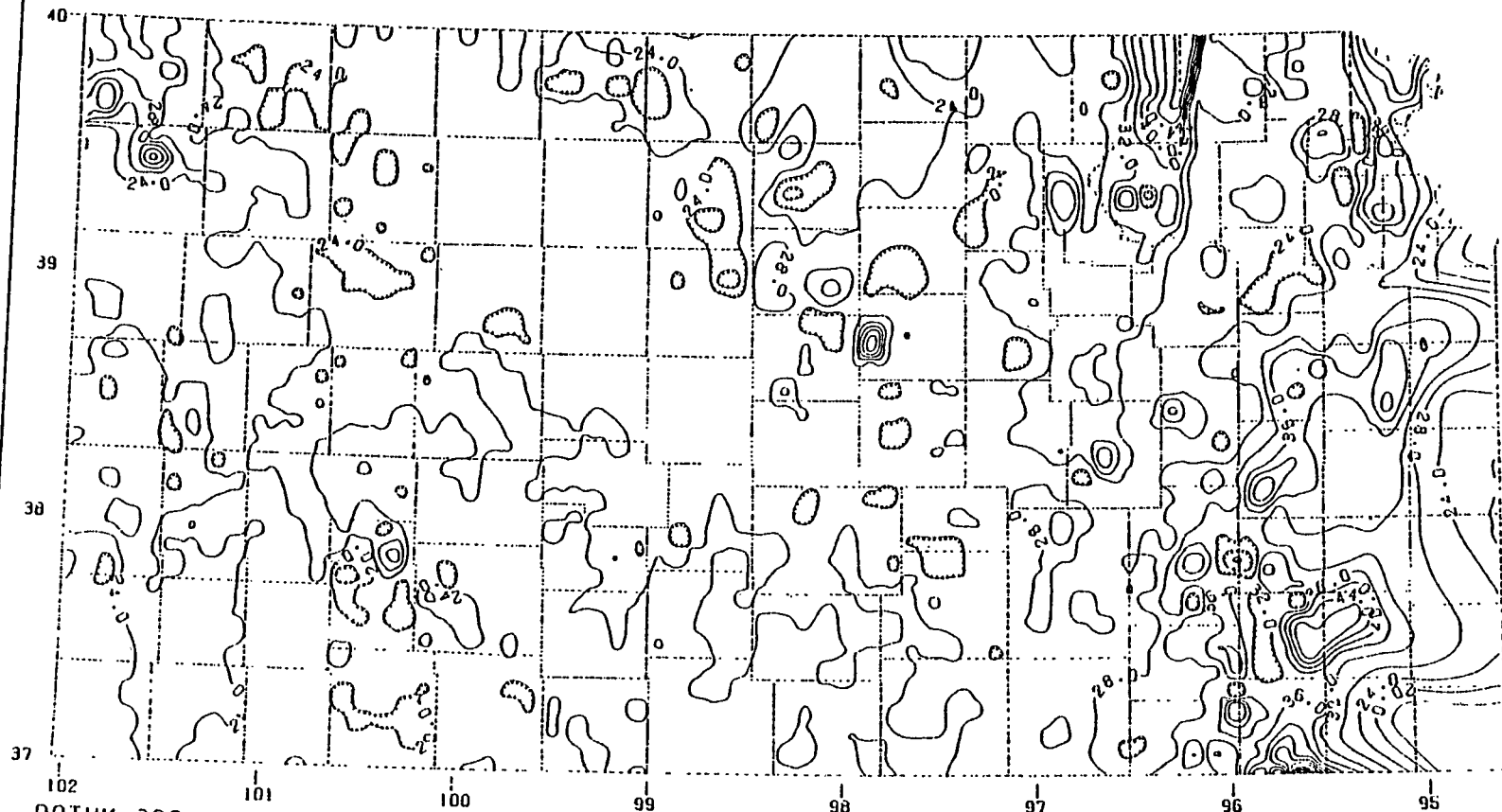
SOURCE DATA-BHT DATA FROM WELLS OVER 1000 FEET DEEP



CI=5°C/KM LAMBERT PROJECTION

PLATE 2-1

SUBSURFACE TEMPERATURE DISTRIBUTION IN KANSAS

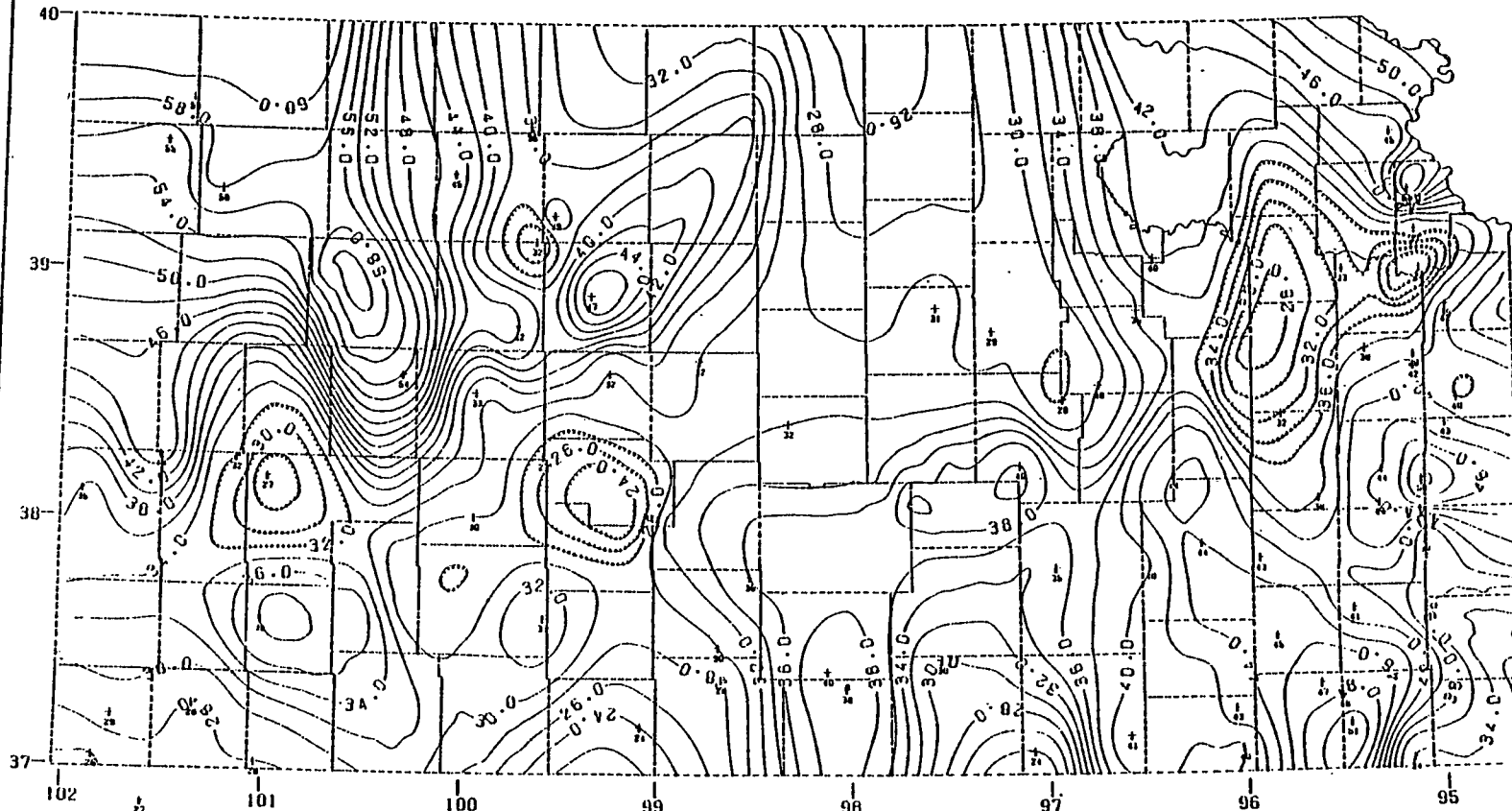


DATUM-300 METERS BELOW GROUND LEVEL SOURCE DATA-BHF DATA
CI=4° C LAMBERT PROJECTION

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

PLATE 2-2

GEOHERMAL GRADIENT MAP OF KANSAS

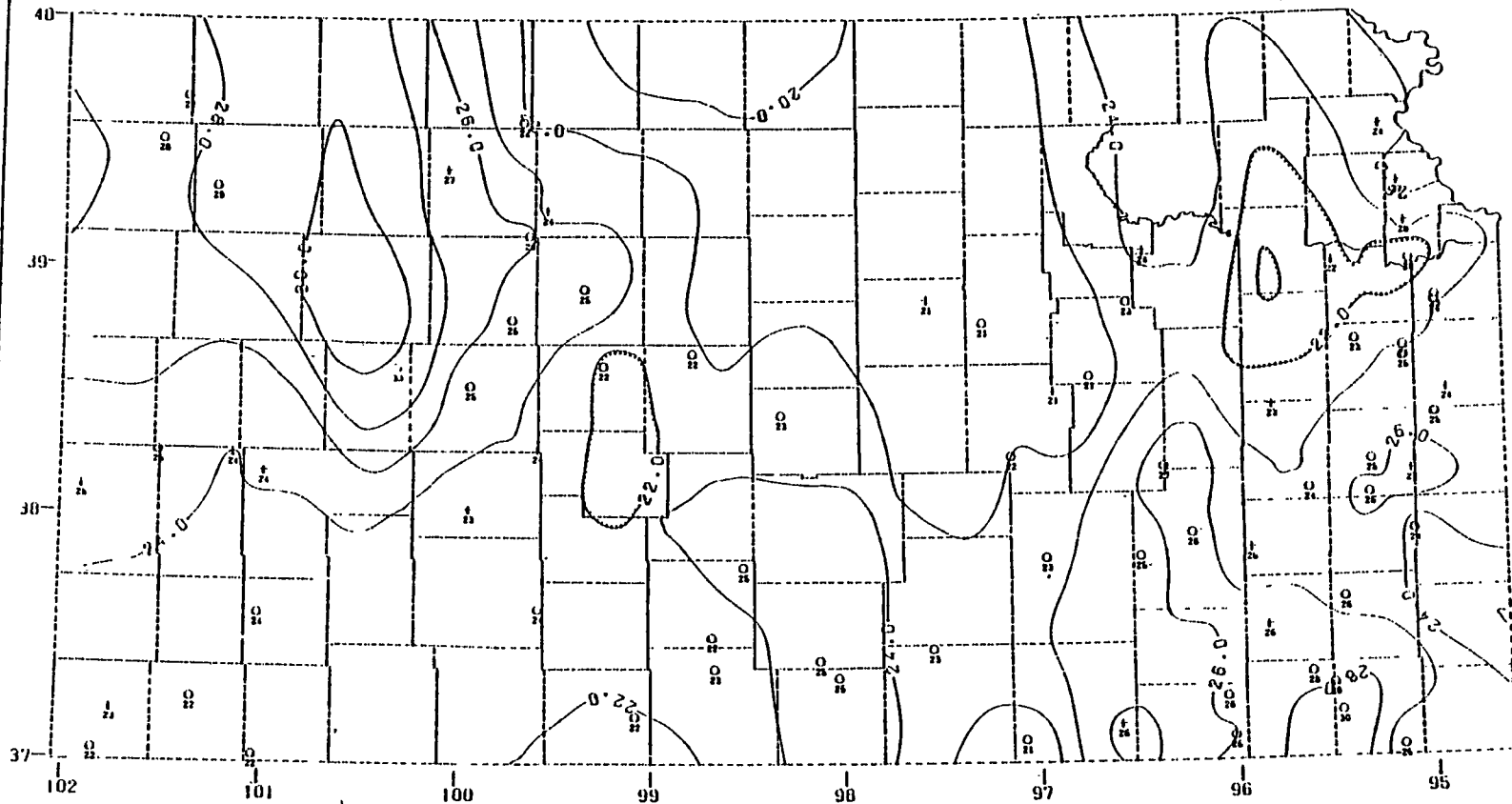


SOURCE DATA—LOGGED WELLS PENETRATING 400 FEET OF SUBSURFACE

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

CI=2° C/KM LAMBERT PROJECTION

SUBSURFACE TEMPERATURE DISTRIBUTION IN KANSAS



SOURCE DATA-TEMPERATURE AT 300 METERS IN LOGGED WELLS

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

1°C = 2°F LAMBERT PROJECTION

KGS
OF
82-22

HEAT FLOW AND GEOTHERMAL POTENTIAL OF KANSAS

by

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INTRODUCTION

At the present time there are only two published heat flow measurements available for the State of Kansas. A value of 63 mWm^{-2} was measured near the central part of the state at Lyons, Kansas (Sass et al, 1971a) and a value of $59+ \text{ mWm}^{-2}$ was estimated for a site near Syracuse by Birch (1947). In addition a heat flow value of 59 mWm^{-2} was published by Roy et al (1968b) for a site in extreme northeastern Oklahoma near the Kansas border. On a regional basis the eastern part of Kansas should be part of the Central Stable Region, an area of the North American continent characterized by a single linear relation between heat flow and heat production (Roy et al, 1968a). In this area, unless heat flow values are disturbed, they are directly related to the heat production of the basement underlying the site where the heat flow measurement was made.

There is a suggestion from regional data that heat flow may increase toward the west in the Great Plains province and that the high heat flow characteristic of the southern Rocky Mountains may extend east of the mountains some distance (Blackwell, 1969; Combs and Simmons, 1973; Lachenbruch

and Sass, 1977; Blackwell, 1978). Extensive thermal studies are in progress in the State of Nebraska but the results are preliminary at this time (Gosnold, 1980). Heat flow values may be quite high in the western part of the state. Swanberg and Morgan (1979) published a heat flow map for the United States based on a correlation of heat flow and silica water temperatures. In this map they have a data gap for the State of Kansas, but extrapolation from data outside the state implies that the heat flow may be greater than 65 mWm^{-2} in the western part of the state and less than 65 mWm^{-2} in the eastern part of the state. While no heat flow measurements were made as part of this study in western Kansas in the area presumed to be characterized by heat flow above that characteristic of the Central Stable Region the data presented here do bear on the heat flow values in the Great Plains and this topic will be discussed in a subsequent section.

The plan of the U.S. Geological Survey and Kansas Geological Survey to drill four deep hydrologic tests in Kansas prompted Dr. Don Steeples to propose a geothermal study in these wells; this study has been carried out by the authors of this report. These wells offer a unique opportunity to make detailed and accurate heat flow measurements in Kansas. These wells were drilled through the Arbuckle Group to within a few feet of basement and two of the holes were deepened on into the basement and core samples collected of the basement rock. Because of the depth of the four holes and because of the fact that they have been cased through most of their depth and left undisturbed to reach temperature equilibrium, it is possible to get highly accurate, stable temperature measurements through the complete sedimentary section. This opportunity does not arise very often in the Midcontinent

in spite of the fact that thousands of wells have been drilled there, because most of the holes were drilled for petroleum exploration and are not available for equilibrium temperature studies. Water wells are usually somewhat shallower and thus do not cut nearly as thick a section or approach the basement; furthermore, possible circulation effects may disturb the temperatures within the wells. In addition an extensive suite of geophysical logs were obtained for each of the holes (gamma-ray, travel time, density, neutron porosity, electric, etc.) and cuttings were collected at frequent intervals. The holes which were drilled to the Arbuckle Group or deeper by the U.S. Geological Survey and the Kansas Geological Survey are 12S/2W-32CCC, 18S/23E-18DCD and 31S/20E-22CAC*. In addition 5 other holes were logged as part of this study. For these holes cutting samples and geophysical logs are not available, but the additional holes offer useful supplementary information on the temperature regime in other parts of Kansas.

MEASUREMENT TECHNIQUES

The holes were logged to a maximum depth of 1045 m with a truck mounted logging system or to 565 m with a portable hand operated equipment. Most of the holes were logged with a digital recording system attached to the output of the volt meter attached to a thermistor probe and the output of a digital depth encoder. Temperatures were calculated from the measured resistance values and gradients were calculated using the two data sets. Temperatures were measured to the nearest 0.001°C at depth intervals of 1 m, allowing a

* Referred to by Department of Transportation County Code in Stavnes, Chapter 2; by county in Yarger, Chapter 5; and by town near where hole is located Kodama, Chapter 6.

very detailed look at gradients in the sedimentary section. Logging rates were quite slow, 4 m per minute, so that equilibrium temperatures were obtained. Roy et al (1968b) and many subsequent authors have illustrated the detail which can be obtained in sedimentary rocks using such continuously recording equipment. The detailed temperature measurements are listed in Appendix I along with temperature-depth curves for each hole logged.

Thermal conductivity measurements were made on cuttings from three of the holes drilled by the U.S and Kansas Geological Surveys. These results are given in Appendix II. Only cuttings were available for the sedimentary section so the measurements were made using the chip technique of Sass et al (1971b). Core samples were available from basement rock at two of the sites and heat production and thermal conductivity were measured on the core samples. These data will be discussed below. Heat production measurements were made using a 256 channel gamma-ray pulse-height analysis system (Gosnold, 1976). Core sample thermal conductivity measurements were made using conventional divided-bar techniques (Roy et al, 1968b). A major problem arose in the use of the chip technique to measure thermal conductivities for some of the units in the sedimentary section. Because of the strong anisotropy of the layered silicates making up the shales it proved impossible to obtain the correct in situ thermal conductivity values of the shales using cutting samples. In preparing the cylinders with the mixture of water and cuttings it appears that many of the fragments of shale will end up randomly orientated whereas of course in the ground the orientation is strongly preferred. The result is that the calculated in situ conductivity is far too high; this point is discussed in much more detail below.

In the tables showing interval thermal conductivity values, these

values have been corrected for temperature effects in the deeper parts of the holes. These effects approach $0.15 \text{ Wm}^{-1}\text{K}^{-1}$ for the bottom part of hole 13S/2W-32CCC (Robertson, 1975).

GEOHERMAL GRADIENTS

Geothermal gradients were obtained in 10 relatively deep holes (375 - 1045 m) throughout the eastern 2/3 of the State of Kansas. In all of these holes the temperatures as a function of depth show a very close relationship to lithologic variations. Because of this correlation and the typically thin individual beds characteristic of the Pennsylvanian section cut by most of the holes, it is very difficult to generalize the results. The hole locations and pertinent information are shown in Table 3-1 and on Figure 3-1, a generalized index map of Kansas. The holes will be individually discussed proceeding in order from northwest to southeast. All of the data have been plotted on the same depth, temperature and gradient scales to facilitate comparisons from hole to hole. The deeper holes have been plotted on two depth scales, 0-600 and 500-1100 m to increase the resolution and allow full page plots of the shallower holes on the same scale as the deeper holes. Bar graphs of gradient are shown for each hole. For the most detailed logs, which were digitally recorded, temperatures are plotted at 2 m intervals.

Figure 3-2 shows a detailed temperature-depth curve and bar graph of gradient for hole 9S/20W-27BDC in Rooks County. This hole was logged to the end of our cable at 1045 m. The upper part of the hole cuts Cretaceous rocks overlying a relatively thick Permian section. The units which are most clearly identifiable on the temperature-depth and gradient plots in

Figures 3-2a and 3-2b are the shales. The water table was just above 100 m and the first reliable gradients are below 105 m. There a section 60 m thick between 105 m and 165 m has a mean gradient of $50.5 \pm 0.3^{\circ}\text{C}/\text{km}$. Below that section the gradient drops to approximately $37.5 \pm 0.5^{\circ}\text{C}/\text{km}$ to a depth of 221 m at which point the gradient drops to values generally less than $30^{\circ}\text{C}/\text{km}$, which continue to the bottom of the hole. The only exception is a zone of higher gradient between 300-340 m and a few local intervals of higher gradient between 900 and 1000 m. The Cretaceous-Permian unconformity is at a depth of about 450 m and the Pennsylvanian-Permian contact is at a depth of approximately 900 m in this hole. The mean gradient in the Cretaceous section (105-450 m) is $27.3 \pm 1.8^{\circ}\text{C}/\text{km}$. In the Permian section (450-900 m) the mean gradient is $24.2 \pm 0.3^{\circ}\text{C}/\text{km}$ and in the Pennsylvanian section (900-1045 m) the mean gradient is $33.6 \pm 0.3^{\circ}\text{C}/\text{km}$. In the Pennsylvanian section the gradients are variable ranging from $45^{\circ}\text{C}/\text{km}$ in the predominantly shale units to $25^{\circ}\text{C}/\text{km}$ in the more limestone-rich units. Temperatures are somewhat lower in this hole than in most of the other holes logged, either because of a higher thermal conductivity for the Permian section, which includes more sandstone and evaporite deposits than the Pennsylvanian, or because of a lower heat flow at this site than at the remainder of the sites. The thermal conductivity hypothesis is favored.

Hole 12S/17E-13BBD, although drilled into Precambrian basement at a depth of 910 m, was logged only to a depth of 565 m. A second attempt was made to log the hole to total depth, but it was being used by the U.S. Geological Survey and was inaccessible. The temperature-depth data and a bar graph of gradient for this hole are shown in Figure 3-3. The gradient in

the Pennsylvanian section between 120 m and 521 m ranges from 25°C/km to just over 40°C/km and averages $32.1 \pm 1.0^\circ\text{C}/\text{km}$. In the Pre-Pennsylvanian carbonate section below 520 m (to 565 m) the mean gradient is $17.1 \pm 0.1^\circ\text{C}/\text{km}$.

Temperature-depth curves and bar graphs of gradient for hole 13S/12W-32CCC are shown in Figure 3-4. This hole was drilled for the U.S. and Kansas Geological Surveys to a depth of 1117 m and was logged to a depth of 1044 m. The stratigraphic section in the upper part of this hole is similar to hole 12S/17E-13BBD; however, temperature data from the deeper section were also obtained. When this hole was logged an injection test had recently been completed, and in the bottom part of the hole the temperatures were unstable, apparently because of this test. The gradients averaged over 15 m intervals are fairly characteristic of those in the rock (Figure 3-4c), but the 2 m interval gradients are very variable as the hole tends toward equilibrium. Some of the injected fluid may have entered the formation around 920 m resulting in the very low gradients in that section of the hole. The mean gradient between 100 and 280 m in the Permian section is $28.5 \pm 0.6^\circ\text{C}/\text{km}$. The mean gradient in the Pennsylvanian section (280-792 m) is $31.9 \pm 0.6^\circ\text{C}/\text{km}$. Below 792 m in the Pre-Pennsylvanian section the units are more monolithic and there is a good correlation between lithology and gradient (Figure 3-4c). The section of high gradient between 558-598 m corresponds to the Lawrence Shale. The gradient in this section is $48.6 \pm 0.1^\circ\text{C}/\text{km}$. The mean gradient between 736 and 796 m in the Cherokee Shale is $36.9 \pm 0.2^\circ\text{C}/\text{km}$ while the mean gradient in the Chattanooga Shale between 862 and 912 m is $52.1 \pm 0.1^\circ\text{C}/\text{km}$. The mean gradient in the limestone units ranges from 15 to 25°C/km. This hole was logged just into the Arbuckle Group (top at 1026 m). The detailed

geology and heat flow for this hole will be discussed in the following section.

Hole 18S/23E-18DCD was also one of the holes drilled for the U.S. and Kansas Geological Surveys. At the time of the first logging it had collapsed at 395 m and we were unable to go deeper; during a second attempt to log the hole, the hole was inaccessible due to muddy conditions of the surrounding field. We intend to relog this hole when conditions allow. The temperature-depth curve and a bar graph of gradient are shown in Figure 3-5. This hole shows generally high gradients, ranging between 37 and 57°C/km and averaging 51.08 ± 1.2 °C/km, between 100 m and 220 m, the Mississippian-Pennsylvanian contact. The gradient drops abruptly to average 22.7 ± 0.7 °C/km in the remainder of the hole, with the exception of a 15 m section in the Chattanooga Shale. The average gradient in the Chattanooga Shale (360-375 m) is 52.5 ± 0.1 °C/km. There is a negative gradient section near the bottom of the hole which reflects a drilling or injection disturbance. The mean gradient for the bottom of the hole below the Chattanooga Shale is only 14.5°C/km although it is poorly determined. This section is predominantly dolomite as discussed in the section on heat flow. The hole was drilled into basement and bottomed at 666 m. Basement thermal conductivity and heat production data are discussed below.

Hole 19S/8W-26 was logged and the data presented by Sass et al (1971a). The temperature-depth and gradient data are shown in Figure 3-6; this hole was drilled in Permian age rocks with the section of the hole between 220 and 305 m in salt deposits. Because of the high thermal conductivity of the salt a low gradient of only 14°C/km is observed within this interval.

Three holes were logged along a more or less east-west section in

the south central part of the state, holes 25S/4E-34DAD, 25S/8E-36ACC and 25S/13E-24ADD. These holes are predominantly in Pennsylvanian age rocks and have the highest temperatures in the 400-500 m depth range observed in any of the holes logged. In large part the high temperatures are due to the greater abundance of shale of low thermal conductivity in the geologic section encountered in these holes. The temperature-depth curves and bar graphs of gradient for the first two holes are shown in Figures 3-7a and 3-7b and 3-8. The mean gradient for hole 25S/4E-34DAD between 200 and 737 m is $35.6 \pm 0.6^{\circ}\text{C}/\text{km}$. The gradients for 25S/4E-34DAD are quite variable; this hole was an abandoned oil well and some of the irregularity may be related to past production effects. The character of the gradient variations changes abruptly at 310 m. At this point a ball of mud or some other material apparently attached itself to the probe severely lengthening the time constant of the probe and resulting in the marked change in behavior. The fluid level in hole 25S/8E-36ACC was at 195 m and logging did not begin until below that depth. The mean gradient for that hole is $38.0 \pm 0.4^{\circ}\text{C}/\text{km}$ between 200 and 390 m.

A temperature-depth curve and a gradient bar graph for hole 25S/13E-24ADD are shown in Figure 3-9. In this hole there is a variation of 10-20 m interval gradients from about 25 to $55^{\circ}\text{C}/\text{km}$. From a comparison with the gamma-ray log it is clear that these high gradients are closely correlated with sections of the hole which have higher gamma-ray activity, i.e., the shale sections. The sections of lower gamma-ray activity are predominantly limestone although there may be some sandstone represented by lower gamma-ray activity as well. The contacts between the shales and limestones appear

quite sharp on the gamma-ray log above 150 m and not so sharp on the temperature log below 150 m. This may be due to mud collecting on the probe and increasing the time constant, because this long time constant type behavior is not observed in the other holes logged (except hole 25S/4E-34DAD, see above) or in the upper part of this hole. The mean gradient for the hole between 40-441 m is $42.2 \pm 0.9^{\circ}\text{C}/\text{km}$.

The only water well logged was hole 30S/24E-2DDD. This hole was logged to a depth of 340 m. The temperature and gradient data are shown in Figure 3-10. Because the hole is an abandoned water well the gradients may be disturbed by water circulation. From the shape of the temperature-depth curve there appears to be borehole upflow between the bottom and about 220 m. Not much is known of the section in this hole, but it is probably predominantly carbonate. The temperatures are quite low probably because it is one of the holes furthest to the east where the Pennsylvanian section is thinnest. The mean gradient between 105 and 340 m is $19.7 \pm 1.6^{\circ}\text{C}/\text{km}$.

Extensive data are available for hole 31S/20E-22CAC, one of the holes drilled by the U.S. and Kansas Geological Surveys. This hole was logged to the drilled depth of 550 m. The results are shown in Figure 3-11. The gradients between 95 m and 205 m are quite high, averaging $53.4 \pm 1.5^{\circ}\text{C}/\text{km}$. Below 205 m the gradients average less than $20^{\circ}\text{C}/\text{km}$. The 205 m depth is the contact of the Pennsylvanian section with the predominantly limestone-dolomite section of Mississippian and older age. At the bottom of the hole there are two negative temperature excursions which are related either to drilling, to injection or to some small water flow existing in the hole previous to drilling. Because of the thinness of the high thermal conduc-

tivity section, temperatures at depth are relatively low in this hole.

Using the data obtained directly from the logs a table of temperatures at various depths was prepared and is shown in Table 3-2. Temperatures are shown at depths of 400, 500, 750 and 1000 m where available. Extrapolations have not been made except for very short depth intervals. Where extrapolations have been made the numbers are given in parentheses. Most of the holes were logged to a depth of 400 m but only about 2/3 of them are logged to a depth of 500 m. A contour map of temperature at 500 m is shown in Figure 3-12. At this depth temperatures are highest in the southern third of the state except along the Missouri border. Temperature differences approach 6°C at a depth of 500 m. The mean surface temperature for almost all of the stations is between 13 and 15°C and thus the mean gradients to 500 m range from approximately 40°C/km in the areas of highest temperature to only 28°C/km in the north-central portion of the state. However, these gradients cannot necessarily be projected to greater depths. It is clear that vertical gradient variations are due to lithology and so very large variations in gradient will occur with depth. Furthermore there may be variations of heat flow related to other factors such as basement radioactivity. In order to evaluate some of these other variations, heat flow values were calculated for several of the holes. These heat flow values are discussed in the following section.

HEAT FLOW

Heat flow values have been calculated for the four holes drilled by the U.S. and Kansas Geological Surveys. Thermal conductivity measurements were made on cutting samples collected from 3 of the 4 holes. The detailed results

of the measurements are contained in Appendix II. Suites of geophysical logs were run in all four of the holes, so log data were available to calculate the average in situ porosity for correction of the bulk thermal conductivity to the in situ thermal conductivity. The gradient segments chosen for averaging were selected from comparison of the temperature-depth logs discussed in the previous section to the geophysical logs and the geological analysis of cuttings from the wells.

In most cases there is very good correlation between the gradient and lithology, although in the Pennsylvanian section there is such a rapid vertical variation of lithology that in most cases the temperature data are not detailed enough to be identified with the individual units. This rapid vertical variation leads to difficulty in calculating heat flow because it is almost impossible to isolate intervals composed only of one lithology over which heat flow values can be reliably calculated. Where temperatures were measured in the Mississippian and older carbonate section, the thicker monolithic units are suitable for heat flow calculations and the most reliable values come from these sections of the drill holes. The data for interval gradient, harmonic average thermal conductivity, and heat flow for each of the four holes are shown in Tables 3-3 through 3-6. Generalized lithology for each of the intervals is also listed. In general the mean gradients in the carbonate sections of all the holes are almost identical, averaging 20 to 21°C/km in sections which are predominantly limestone and 14 to 17°C/km in sections which include dolomite. Gradients in the predominantly shale sections range from 35 to 53°C/km.

The results of interval geothermal gradient and heat flow calculations

for hole 12S/17E-13BBD are shown in Table 3-3. Unfortunately only a short section of temperature data in the carbonate section, below 520 m, is available and thus the gradient is poorly determined. Consequently the heat flow calculated for that interval, 48 mWm^{-2} , is poorly determined. The heat flow values calculated in the upper section of the hole are much higher. This situation is discussed in the following paragraphs.

The results for hole 13S/20W-32CCC are shown in Table 3-4. Heat flow values calculated for the various carbonate sections range from $49\text{-}60 \text{ mWm}^{-2}$ and average 57 mWm^{-2} . As was the case for hole 12S/17E-13BBD the heat flow values in the upper sections of the hole are significantly higher. However, in hole 13S/20W-32CCC the Chattanooga Shale has a gradient of 52.2°C/km and an apparent heat flow of 124 mWm^{-2} , between carbonate units with gradients of 17 and 20°C/km and heat flow values of $49\text{-}60 \text{ mWm}^{-2}$. The Sylvan Shale section has a gradient of 46°C/km and an apparent heat flow of 98 mWm^{-2} with the carbonate units on either side having gradients of 17.3 and 21.0°C/km and heat flow values 49 and 58 mWm^{-2} . Since the heat flow is the same on either side of these two shale units the only conclusion that is consistent with the data is that the thermal conductivity of the Chattanooga Shale is about $1.1 - 1.2 \text{ Wm}^{-1}\text{K}^{-1}$ and the conductivity of the Sylvan Shale is about $1.3 \text{ Wm}^{-1}\text{K}^{-1}$. The data for hole 18S/23E-18DCD are shown in Table 3-5. The heat flow calculated for the carbonate section is 60 mWm^{-2} . The gradients in the Cherokee Shale and Chattanooga Shale are 52°C/km and the directly calculated heat flow values are over 110 mWm^{-2} . The heat flow on either side of the Chattanooga Shale is identical. If the true thermal conductivity for these two units is $1.15 \pm 0.5 \text{ Wm}^{-1}\text{K}^{-1}$ then the heat flow in the shale

units would be the same as in the carbonate units.

The data for hole 31S/20E-22CAC are shown in Table 3-6. Thermal conductivity measurements were made on samples from the Arbuckle Group. The rock is a dense dolomite with a high thermal conductivity so that even though a large interval (290-550 m) has a low gradient, the heat flow is the highest (by only 3 per cent) of all the values obtained. The gradients are slightly higher in the limestone section of the hole above the dolomite, and much higher (by a factor of 4) in the Cherokee Shale. The inferred thermal conductivity of the shale is shown in parentheses. The gradients in the Arbuckle section are exactly the same in this hole and in two holes discussed by Roy et al (1968b; see Decker and Roy, 1974), near Picher Oklahoma, about 50 km to the southeast. The heat flow values are also similar so that apparently the Arbuckle thermal conductivity is very similar in both holes. The heat flow for the holes discussed by Roy et al (1968b) was based on thermal conductivity measurements of core samples from Precambrian basement rocks.

On the basis of this analysis there would appear to be only minor variation of heat flow between the four holes. The mean value for all the carbonate sections ranges from 48-60 mWm^{-2} . However, if heat flow values are calculated from thermal conductivity measurements on cuttings from the Pre-Pennsylvanian shale sections or from the Pennsylvanian units in each hole then an extremely different picture of the heat flow is obtained. Typical cuttings determined thermal conductivities for the shale sections, assuming porosity measured in situ of 10 \pm 5 per cent, are 1.8 to 2.25 $\text{Wm}^{-1}\text{K}^{-1}$. These values taken together with typical gradients of 45 to 55 $^{\circ}\text{C}/\text{km}$ imply

heat flow values in the shale sequences of 100 mWm^{-2} or greater. These values are in clear contradiction to the heat flow values obtained in the carbonate units.

There are two possibilities for the differences in heat flow in different lithologies. It is possible there is a difference in heat flow between the upper and lower parts of the drill holes. One of the reasons for drilling the wells was to investigate possible fluid flow on the Arbuckle aquifer and slow fluid motions could change the heat flow values above the aquifer and also effecting heat flow values below the aquifer. The second possibility is that the thermal conductivity of the shales is misestimated by the chip technique. We will examine these two hypotheses in order.

According to the first hypothesis there should be a change in heat flow associated with the contact between the relatively impermeable shale section and the lower, more permeable dominately carbonate section. There are several arguments against this hypothesis. The first of these is that for two of the holes which cut fairly thick sequences of Pennsylvanian strata the variation in geothermal gradients within the Pennsylvanian section ranges from $25^{\circ}\text{C}/\text{km}$ to $50^{\circ}\text{C}/\text{km}$. The lower values appear to be in sections which have a higher proportion of limestone than the sections with higher gradient. These gradient values are about 20 per cent higher than those in the Pre-Pennsylvanian carbonate section. Since most of the limestones in the Pennsylvanian section are very thin, however, most of these intervals probably include some shale. The second major argument against the water flow hypothesis is the interbedding of the shale and carbonate

units with their varying gradients.

The conclusion of this discussion is that the range of thermal conductivity for at least some of the shales encountered in the holes is between 1.1 and 1.3 $\text{Wm}^{-1}\text{K}^{-1}$. Thus there is an approximate ratio of 2.5:1 between the thermal conductivity of the limestone and shale and up to 4:1 between the thermal conductivity of dolomite and shale. Corresponding ratios of gradients in the various units are observed.

An examination of the chip technique of thermal conductivity measurements indicates that it is not surprising that the shale conductivity will be in error. Since small fragments of shale are packed into a hollow cylinder some of them may be on end and all of them are finite in length, therefore conduction along the grains in the high conductivity directions may be important. It is very difficult to measure thermal conductivity on core samples of shales as well and perusal of the literature indicates in fact, adequate thermal conductivity measurements for the shale may not exist. It is difficult to measure shale thermal conductivity on the divided-bar using core samples because of the fissility of the shale. The anisotropy makes needle probe measurements of dubious value. In heat flow studies in the Midcontinent previous investigators have estimated the conductivity of the shale sections between 1.55 and 1.85 $\text{Wm}^{-1}\text{K}^{-1}$ (Garland and Lennox, 1962; Combs and Simmons, 1973; Scattolini, 1978). Judge and Beck (1973) encountered the problem in a study of heat flow in the Western Ontario Basin where the rocks range in age from Precambrian to Mississippian. They found heat flow values 60 per cent too high in the Ordovician shale section (Collingwood Formation). If a value of 1.1 $\text{Wm}^{-1}\text{K}^{-1}$ is assumed, as deter-

mined above for the lower Paleozoic shales in this study, the heat flow in the Collingwood Formation is the same as in the remainder of the units they studied (dominantly limestone and dolomite). Thus the shale thermal conductivity values in the literature are significantly in error. One implication is that the heat flow in the Great Plains may not be as high as has been estimated in the past. In particular the zone of high heat flow extending out into the Great Plains north of the Black Hills (Lachenbruch and Sass, 1977; Blackwell, 1978) may not in fact, exist. Furthermore, the correlation of silica values of groundwater and heat flow for the Midcontinent may be instead a correlation of silica values and mean geothermal gradient.

Thus in spite of the large amount of high quality temperature data, the conventional heat flow values for the four holes must be based on only small sections of the hole and large sections of the hole cannot be used for heat flow determinations by conventional heat flow techniques. In the next section we will investigate the use of well log parameters in conjunction with the temperature data in order to more completely evaluate the best heat flow values for these four holes.

CALCULATING OF HEAT FLOW UTILIZING WELL LOGGING PARAMETERS

Because of the difficulties of evaluating the mean thermal conductivity in the shale sections and in sections with very rapidly varying thermal conductivity it would be useful to have other techniques to evaluate these sections. Since four of the holes had available extensive geophysical well logs suites the use of these data to assist in calculation of the heat flow values was investigated. It has been demonstrated in a number of studies that of various physical properties such as density,

porosity and velocity, velocity is most directly useful in estimating thermal conductivity (Goss and Combs, 1976; Williams, 1981) so emphasis was placed on use of the velocity and gamma-ray logs. The gamma-ray activity in these holes is relatively directly related to the amount of shale. Typical gamma-ray counts for the shale sections are about 100 ± 25 API units, whereas in the carbonate sections gamma-ray values are 25 ± 5 API units. If the primary control on the thermal conductivity is the mixing of only two lithologies then it should be possible to obtain a good correlation between gamma-ray activity and the gradient.

A series of bar graphs of temperature gradient, gamma-ray activity and velocity for the four wells drilled for the U.S. and Kansas Geological Surveys are shown in Figures 3-13, 3-14, 3-15 and 3-17. For holes logged with the digital equipment, gradient graphs are plotted using a running 2 m average except for hole 13S/2W-32CCC where a 15 point running average was used because of the problems discussed above. In addition the gradient data from hole 25S/13E-24ADD are accompanied by a gamma-ray log from a nearby hole (Figure 3-16). The geophysical logs are based on a 0.5 m digitization of paper copies at a 5 inches = 100 feet scale. The values plotted are 3 m running averages. Detailed evaluation of individual figures illustrates an almost point by point correlation between various regions of high gamma-ray activity, low velocity and high geothermal gradient from the sections of the holes below 100 to 150 m.

The bottom part (500-1045 m) of hole 13S/2W-32CCC shows the clearest correlation because the units are the thickest and the most cleanly separated. There is a very clear correlation between gradients, gamma-ray activity and velocity in the Lawrence, Cherokee, Chattanooga and Sylvan shales

and the interlayered carbonate sections. In hole 18S/23E-18DCD there is a very good correlation between the carbonate and shale units and in particular the Chattanooga Shale stands out because of the extreme excursion in gradient, gamma-ray activity and travel time in the midst of a predominately carbonate section. The logs from hole 25S/13E-24ADD also show a one for one correlation between areas of high gradient and high gamma-ray activity, however, because of the apparently impaired time constant of the probe, the shale-limestone contacts do not appear as sharp on the thermal log as on the gamma-ray log. There also appears to be an offset of about 5 m between the two logs, either because the logs are not from the same hole or because of the time constant of the temperature probe.

In order to quantify these visual relationships, crossplots were prepared between velocity, travel time (inverse of velocity), gamma-ray activity and gradients, there are shown in Figures 3-18 through 3-21. Shown are the least square straight lines fit to crossplots of the data averaged over 10 m intervals in the section of the hole for which both geothermal gradient and geophysical log data are available. In addition to the least square straight line, the scatter of points for each hole is indicated by the corresponding envelope. It is clear that there are very systematic relationships between the four different properties; especially the gamma-ray activity and gradient.

The relationship between gamma-ray activity and geothermal gradient is shown in Figure 3-18. It appears that all of the holes have similar populations of gradient and gamma-ray data. The slopes of three of the holes are almost identical and the lines are offset by approximately $5^{\circ}\text{C}/\text{km}$. The slopes for holes 25S/13E-24ADD and 31S/20E-22CAC are somewhat greater. However, the

calibration of the gamma-ray data for hole 25S/13E-24ADD is uncertain and there may be a time constant difficulty with the temperature log. Based on the least-square-fit straight lines there is a small variation in parameters among the different drill holes. This variation could be due to systematic problems in calibration of the gamma-ray logs, lateral variations in gamma-ray activity, gradient or thermal conductivity in the various units.

In order to evaluate some of these possibilities we can examine the relationship between velocity and geothermal gradient (Figure 3-19). Here again, almost exactly the same array of data is seen, i.e., similar slopes and with about a $10^{\circ}\text{C}/\text{km}$ offset in the lines. However, the total data envelope is not as clearly linear as is the case in Figure 3-18, especially for holes 12S/17E-13BBD and 13S/2W-32CCC. The crossplots of gradient and transit time are shown in Figure 3-20. The envelopes of data points are more linear than in Figure 3-19. Again, the data overlap is almost complete for holes 13S/2W-32CCC, 18S/23E-18DCD and 31S/20E-22CAC while hole 12S/17E-13BBD has a best fit line offset about $5^{\circ}\text{C}/\text{km}$ below the other three lines.

Finally, Figure 3-21 shows a correlation between gamma-ray activity and velocity. The data from holes 12S/17E-13BBD and 13S/2W-32CCC are identical, 31S/20E-22CAC is slightly steeper in slope and 18S/23E-18DCD is displaced by approximately 0.3 km/sec from the other lines. In this case there is almost a complete overlap of all of the data sets and so apparently the same population of gamma-ray and velocity data is present in all of the holes.

The qualitative result of this investigation is that using the three indicators of velocity, gamma-ray activity and transit time results in the same order of results. Hole 12S/17E-13BBD has consistently the lowest grad-

ient by 4-7°C/km. Hole 13S/2W-32CCC has the next lowest gradient by only 2-5°C/km and hole 18S/23E-18DCD has the highest gradient. Gradients from hole 31S/20E-22CAC overlap the data from the last two holes, being closer to hole 18S/23E-18DCD at the high gradient end and closer to hole 13S/2W-32CCC on the low gradient region of each curve. The heat flow values from the Pre-Pennsylvanian carbonate sections of each hole are shown in Table 3-7a. The relative heat flow values are in the same sense as the relative gradients for the whole holes shown in Figures 3-18 to 3-20. The fact that the relative relationships of all of the holes (except 31S/20E-22CAC) are so similar is evidence that the relative heat flow values shown in Table 3-7 are correct, even if the absolute heat flow values are not. Furthermore, the similar relationship between the properties above and below the Mississippian-Pennsylvanian contact is also strong evidence against the possibility that the heat flow is much higher above than below the Mississippian-Pennsylvanian contact. Quantitative heat flow values can be derived from the data shown in the figures. The quantitative analysis of the data shown in Figures 3-18 to 3-20 depends on the number of different lithologies involved. If only shale and limestone are involved than the analysis is relatively simple and fortunately in this case these lithologies predominate. Minor components which may be locally important and cause difficulty in the interpretation are sandstone (higher thermal conductivity for a given velocity than the shale-limestone relationship), dolomite (higher thermal conductivity) and coal or lignite (lower thermal conductivity). Heat flow values were calculated using the relationship between thermal resistance (R_T in cm sec°C/mcal) and transit time (in μsec/foot)

$$R_T = -140 + 4.83t$$

and the relationship

$$T(x) = Q \int_0^x R_T dx.$$

Heat flow (Q) was calculated by a least square straight line fit to $T(x)$ versus the integral values. The results are shown in Table 3-7b. The agreement with the heat flow values in Table 3-7a is within 10 per cent so that the heat flow values using the data from the whole section in each hole are within 10 per cent of the heat flow derived from the carbonate sections alone. There is still a variation in the response of the Pennsylvanian section in holes 12S/17E-13BBD and 13S/2W-32CCC as compared to holes 18S/23E-18DCD and 31S/20E-22CAC in that apparent thermal conductivities are higher for the first two holes than for the second two holes. Either there is a slight change in heat flow at the Pennsylvanian-Mississippian contact ($<5-10 \text{ mWm}^{-2}$) in the second two holes or the lithology of the sections is different. A higher proportion of sandstone in the first two holes or coal in the second two holes (or a combination of both) could also explain the apparent thermal conductivity discrepancy.

The results of the analysis confirm a major conclusion from the previous section-that shale thermal conductivity values are overestimated by the chip technique of measurement-and verify that the heat flow values are the same in the different units if realistic values of thermal conductivity are assumed for the shale sections. The inferred thermal conductivity values, average gradients and thicknesses for the main shale units encountered are shown in Table 3-8. Except for the Cherokee Shale in holes 12S/17E-13BBD

and 13S/2W-32CCC, all values are less than $1.3 \text{ Wm}^{-1}\text{K}^{-1}$ and the average value, excluding the Cherokee Shale in 13S/2W-32CCC is $1.18 \text{ Wm}^{-1}\text{K}^{-1}$. The discrepancy of the Pennsylvanian sections was discussed in the previous paragraph and the results in Table 3-8 emphasize the apparent difference in the lithology of the Cherokee Shale in the two sets of holes.

The conclusions of this section are:

1) The best estimates of heat flow for the carbonate sections are the best estimates for the heat flow of the holes and the results are given in Table 3-7a.

2) Estimation of thermal conductivity from geophysical well log parameters is feasible and such data can be used to predict temperatures as a function of depth in areas where no temperature measurements are available if the heat flow value is assumed.

3) Shale thermal conductivity values have been overestimated in the past, the Paleozoic shales in Kansas have thermal conductivity values of about $1.18 \pm 0.03 \text{ Wm}^{-1}\text{K}^{-1}$.

4) Heat flow values do not vary more than 10 per cent between the Pennsylvanian and Pre-Pennsylvanian sections of the holes in spite of the often very large contrast in mean geothermal gradient, consequently water flow effects on the heat flow data are small or nonexistent.

DISCUSSION

HEAT FLOW AND THE BASEMENT

The heat flow values obtained are shown in Figure 3-22 on a map which includes the simplified geology of the basement rocks in Kansas. If such things as aquifer motions are not affecting the heat flow in the sediments

then the heat flow should be directly related to the radioactivity of the basement rocks (Roy et al, 1968a). There is no relationship obvious with this data set between the heat flow and the basement lithology. However, since the basement lithology is highly generalized and the heat flow data are sparse this result is not particularly surprising. Two of the holes were drilled to basement and heat production values obtained for samples from these sections of the holes. The holes were 12S/17E-13BBD and 18S/23E-18DCD the heat production values are $2.4 \mu\text{Wm}^{-3}$ and $4.9 \mu\text{Wm}^{-3}$, respectively. These data are shown in Figure 3-23 on a heat flow-heat production plot for data from the Central Stable Region of the United States (Roy et al, 1968a). The data from Kansas appear to be consistent with the predictions of this curve and the relatively high values observed in most of Kansas may be attributed to the relatively high heat generation of the basement rocks. Both holes were drilled on basement magnetic anomalies 5-10 km in diameter. These sharp positive anomalies are apparently caused by post-tectonic granite bodies with higher than normal magnetite contents. Thus hole 18S/23E-18DCD may fall below the Q-A line because the zone of high heat production in the basement is small. The background heat production then might be on the order of $3-4 \mu\text{Wm}^{-3}$. A value of $3.2 \mu\text{Wm}^{-3}$ was found by Roy et al (1968a) for the Picher, Oklahoma area near hole 31S/20E-22CAC discussed previously.

It might be anticipated that somewhat lower heat flow values would be observed over the Midcontinent gravity feature which runs through central Kansas. Hole 13S/2W-32CCC is close to this feature, however, the heat flow in that hole does not appear to be significantly below that observed in the other drill holes. Additional studies could allow investigation of the

nature of the Precambrian basement more directly than has been possible in the past, because of the relationship between surface heat flow and basement heat generation. Further detailed studies in holes which do not penetrate basement could be carried out in order to investigate the differences in heat flow and therefore the variations in basement geology. This technique would be of particular use in areas where the basement is too deep to be reached by many drill holes so that basement data are sparse.

HEAT FLOW IN THE SEDIMENTARY SECTION

A number of new techniques and modifications of existing techniques have been applied to evaluation of the geothermal data from Kansas. The available data for four of the holes include a detailed temperature log for a major portion of the sedimentary section, several kinds of geophysical well logs, a geological analysis of the cuttings and the cuttings samples themselves. As a result we have been able to evaluate a number of new techniques and to apply these new techniques to increase the information which we can obtain from the relatively small number of holes available.

Correlation of the geothermal gradient data with the well logging data has allowed recognition of errors apparently existing in previous determinations of shale thermal conductivity values which in turn have caused some errors in estimates of heat flow in the Midcontinent region.

The results demonstrate that the contrast in thermal conductivity between limestone and shale may reach 2.5:1 and the conductivity contrast between shale and dolomite or evaporite deposits may approach 1:4. Using the well log data we have demonstrated that there is no significant variation in heat flow down the length of the boreholes so that the contribution to the surface heat

flow from any aquifer flow in such aquifers as the Arbuckle Group must be less than 5 mWm^{-2} .

GEOHERMAL POTENTIAL

The geothermal "potential" of a particular area depends on a number of different factors. In Kansas the use of geothermal energy will be restricted to lower temperature applications such as heat pumps, thermal assist, and perhaps some direct space heating. In spite of the rather thin sedimentary section it appears that relatively high temperatures exist in the sediments. The temperature map in Figure 3-12 shows an estimate of these temperatures at a depth of 500 m. The lateral and vertical temperature variations will depend primarily on three factors, the heat production of the basement rocks, the presence or absence of slight disturbances of the heat flow by aquifer motions, and the varying lithology. Based on the data discussed in this report the second possible effect on the heat flow and temperature variation seems to be the minor, in the eastern half of the state at least, even though the geothermal gradients vary drastically between the upper and lower parts of several of the holes. This analysis indicates that the heat flow values do not vary because the thermal conductivity offsets the variation in gradient. Therefore there seems to be no evidence for large scale lateral transfer of heat in any of the possible aquifer systems that might exceed 10 per cent of the surface heat flow. Perhaps in western Kansas the water flow effect could be more important although this remains to be proved, it cannot be expected without such proof.

The second major contributor to the variation in temperature is the heat flow, which will be primarily related to the heat production of the

basement rocks. At the present time we have very little information on the distribution of heat production in the basement of Kansas, it will be valuable to make a systematic study of all existing core and cutting samples of the basement in order to determine the uranium, thorium, potassium contents in order to begin a preliminary evaluation of the heat production distribution in the basement. This study will allow a relatively precise estimate of the heat flow at any prospective geothermal use site based on the relationship between heat flow and heat production shown in Figure 3-23.

The third and possibly the most significant contribution to the temperature at depth is the total thermal resistance of the section from the surface to that particular depth i.e., the distribution of thermal conductivity with depth. Several of these holes illustrate the extreme differences in geothermal gradient related to thermal conductivity contrasts. One conclusion which is clear from the results of this study is that in evaluating the temperatures at a particular depth, simple extrapolation of observed data from over one depth to a greater depth is not justified without consideration of the intervening lithology. It has been demonstrated in this paper that good estimates of the mean thermal resistance of the Pennsylvanian and older geologic sections can be obtained from well log data. Utilizing available well log information the thermal resistance of the sedimentary section can be estimated and areas selected for temperature logging which have the highest probability of high temperatures or the same techniques can be used to evaluate the probable temperature at a depth near areas where utilization of the geothermal resource might be contemplated.

In the past few years much attention has been focused on the eastern

United States in order to evaluate geothermal potential there. The evaluation has been based on the concept of radiogenic plutons underlying low thermal conductivity Mesozoic and Cenozoic sedimentary rocks with projected temperatures of 40 to 60°C maximum suggested (Costain et al, 1977). Recognition that the high gradients observed in areas of the Midcontinent are related to a much lower thermal conductivity than has previously been realized, suggests that the radiogenic pluton concept can be applied to the Midcontinent region as well as to the eastern United States. Even though the age of most of the rocks in the Midcontinent is Paleozoic to Mesozoic, the thermal conductivities of the shales do not appear to be any higher, and in fact may be lower, than typical values of similar units of Cenozoic age. Therefore regions of the Midcontinent with relatively thick shale sections have as high or higher geothermal gradients for a given heat flow than those observed in the Atlantic Coastal Plain region. Thus exploration for high radioactivity plutons in the Midcontinent could identify numerous areas of greater potential geothermal energy than have previously been expected. Furthermore, in some of the deep basins in the Midcontinent, thicker sections of sedimentary rocks are available than in the eastern United States. For example, the thick Devonian shales of the Appalachian region and the thick Cretaceous shale of the Great Plains cause very high temperatures to be observed at relatively moderate depths (see for example, Gosnold, 1980). Thus evaluation of the basement rocks of the Midcontinent and the location of potential geothermal targets using gravity, magnetic and temperature data should outline targets more favorable for geothermal energy than those presently outlined in the eastern United States. For example, if a large

region of basement has a heat generation similar to the White Mountain Batholith of New England ($6 \mu\text{Wm}^{-3}$), the predicted heat flow would be about 85 mWm^{-2} and the typical gradients in sections of shale such as those in Kansas would be approximately $70^{\circ}\text{C}/\text{km}$.

In spite of its presence in the Central Stable Region it appears that some areas of the State of Kansas have temperatures high enough to be used as thermal assistance for space heating and perhaps for direct space heating. These temperatures are available in the sedimentary section where possible aquifers exist for production of the required fluid. Additional work can more clearly outline areas in the state of given temperature in particular aquifers so that the total geothermal potential can be determined.

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FIGURE CAPTIONS

- FIGURE 3-1: Index map of sites of published heat flow values (solid circles) and sites of holes discussed in this report (open circles).
- FIGURE 3-2A: Temperature-depth and gradient-depth curves for hole 9S/20W-27BDC. Two-meter gradient intervals are plotted.
- FIGURE 3-2B: Temperature-depth and gradient-depth curves for hole 9S/20W-27BDC. Two-meter gradient intervals are plotted.
- FIGURE 3-3: Temperature-depth and gradient-depth curves for hole 12S/17E-13BBD. Five-meter gradient intervals are plotted.
- FIGURE 3-4A: Temperature-depth and gradient-depth curves for hole 13S/2W-32CCC. Five-meter gradient intervals are plotted.
- FIGURE 3-4B: Temperature-depth and gradient-depth curves for hole 13S/2W-32CCC. Two-meter gradient intervals are plotted.
- FIGURE 3-4C: Temperature-depth and gradient-depth curves for hole 13S/2W-32CCC. Fifteen-meter running average gradient values are plotted.
- FIGURE 3-5: Temperature-depth and gradient-depth curves for hole 18S/23E-18DCD. 2.5 meter gradient intervals are plotted.
- FIGURE 3-6: Temperature-depth and gradient-depth curves for hole 19S/8W-26 (Sass et al, 1971a).
- FIGURE 3-7A: Temperature-depth and gradient-depth curves for hole 25S/4E-34DAD. Two-meter gradient intervals are plotted.
- FIGURE 3-7B: Temperature-depth and gradient-depth curves for hole 25S/4E-34DAD. Two-meter gradient intervals are plotted.
- FIGURE 3-8: Temperature-depth and gradient-depth curves for hole 25S/8E-36ACC. Two-meter gradient intervals are plotted.
- FIGURE 3-9: Temperature-depth and gradient-depth curves for hole 25S/13E-24ADD. Two-meter gradient intervals are plotted.
- FIGURE 3-10: Temperature-depth and gradient-depth curves for hole 30S/24E-2DDD. 2.5 meter gradient intervals are plotted.
- FIGURE 3-11: Temperature-depth and gradient-depth curves for hole 31S/20E-22CAC. Five-meter gradient intervals are plotted.
- FIGURE 3-12: Isotherms at 500 meters. Temperatures are in °C.

- FIGURE 3-13: Comparison of geothermal gradient, gamma-ray activity and P-wave velocity for hole 12S/17E-13BBD. The gamma-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 3-3.
- FIGURE 3-14A: Comparison of geothermal gradient, gamma-ray activity and P-wave velocity for hole 13S/2W-32CCC. The gamma-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 3-4A.
- FIGURE 3-14B: Comparison of geothermal gradient, gamma-ray activity and P-wave velocity for hole 13S/2W-32CCC. The gamma-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient values are fifteen-meter running average values.
- FIGURE 3-15: Comparison of geothermal gradient, gamma-ray activity and P-wave velocity for hole 18S/23E-18DCD. The gamma-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 3-5.
- FIGURE 3-16: Comparison of geothermal gradient and gamma-ray activity for hole 25S/13E-24ADD. The gamma-ray data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient values are three-meter running average values. The gamma-ray log is for hole 25S/13E-24DBB.
- FIGURE 3-17: Comparison of geothermal gradient, gamma-ray activity and P-wave velocity for hole 31S/20E-22CAC. The gamma-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 3-11.
- FIGURE 3-18: Crossplot of 10 m averages of gamma-ray activity and geothermal gradients. Least square straight lines fit to data and range of data are shown for each hole. Data from hole 12S/17E-13BBD are shown as the light solid line, data from hole 13S/2W-32CCC are shown as the heavy solid line, data from hole 18S/23E-18DCD are shown as the dashed line and data from hole 31S/20E-22CAC are shown as the dotted lines.
- FIGURE 3-19: Crossplots of 10 m averages of compressional velocity and geothermal gradient. The key is the same as in Figure 3-18.
- FIGURE 3-20: Crossplot of 10 m averages transit time ($\mu\text{sec}/\text{ft}$) and geothermal gradient. Least square straight lines fit to data and range of data are shown for each hole. Data from hole 12S/17E-13BBD are shown as the light solid line, data from hole 13S/2W-32CCC are shown as the heavy solid line, data from hole 18S/23E-18DCD are shown as the dashed line and data from hole 31S/20E-22CAC are shown and the dotted lines.
- FIGURE 3-21: Crossplot of 10 m averages of gamma-ray activity and compressional velocity. The key is the same as in Figure 3-20.

FIGURE 3-22: Generalized basement rock lithology map (from Bickford, et al, 1979). Key: dot pattern-mesozonal granitic rocks; diagonal ruling-rhyolite; dashes-Precambrian sedimentary rocks; v's-mafic intrusive rocks; +'s-epizonal granitic rocks. Heat flow values shown in mWm^{-2} .

FIGURE 3-23: Plot of heat flow versus heat generation for the Midcontinent. Line, and data from Levasy, Missouri and Picher, Oklahoma from Roy et al (1968a).

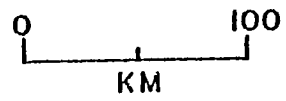
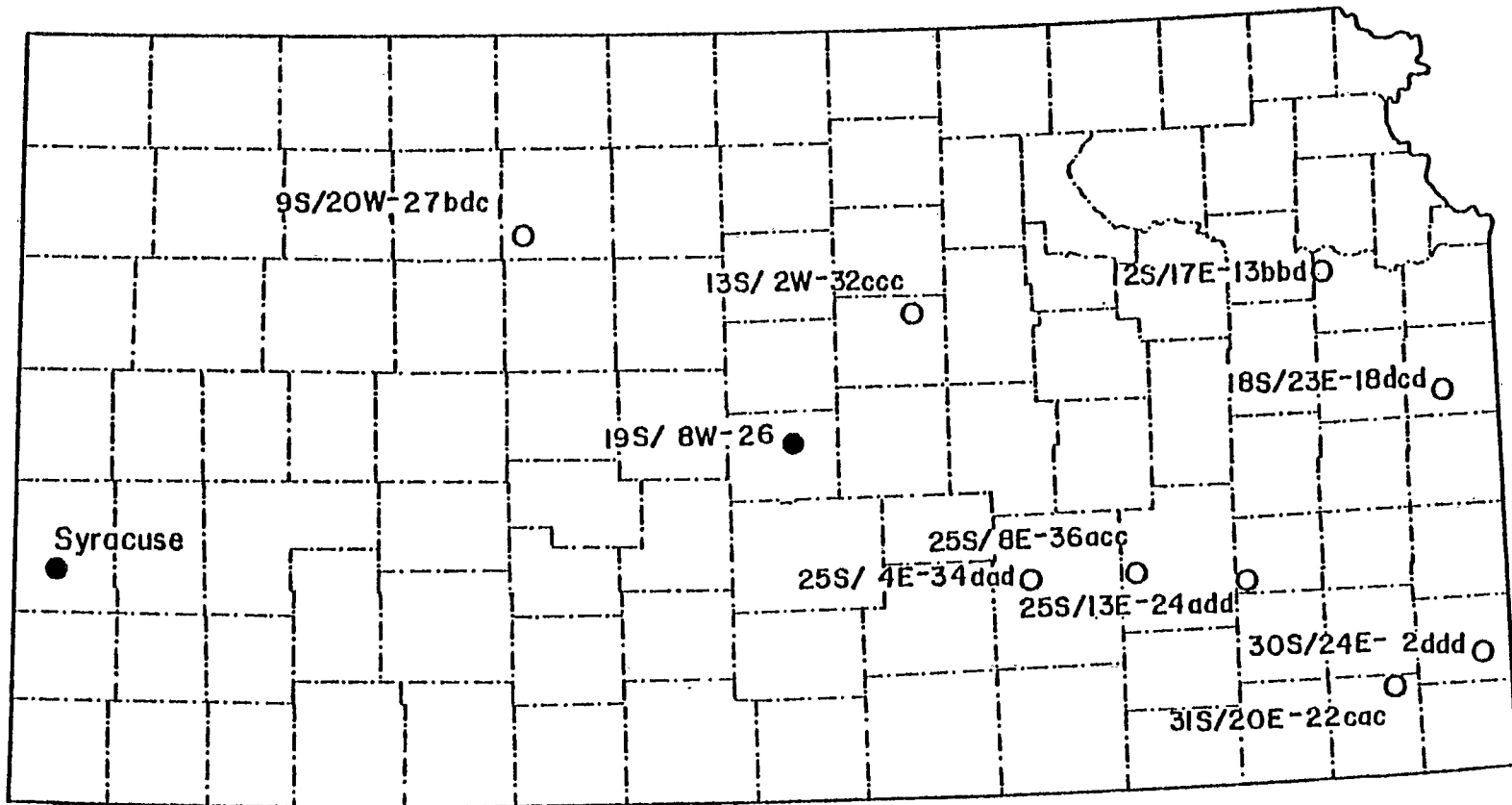


FIGURE 3-1

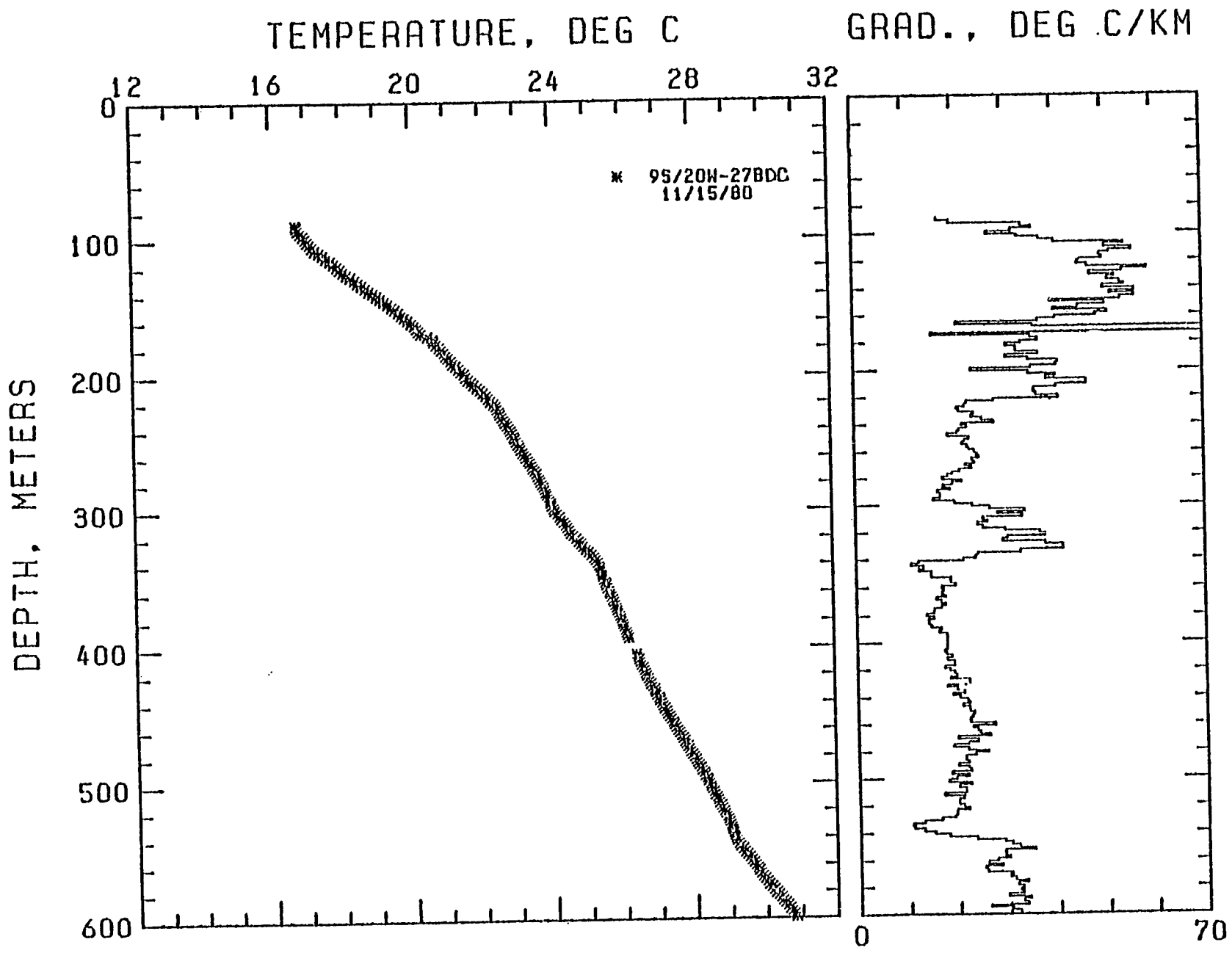


FIGURE 3-2A

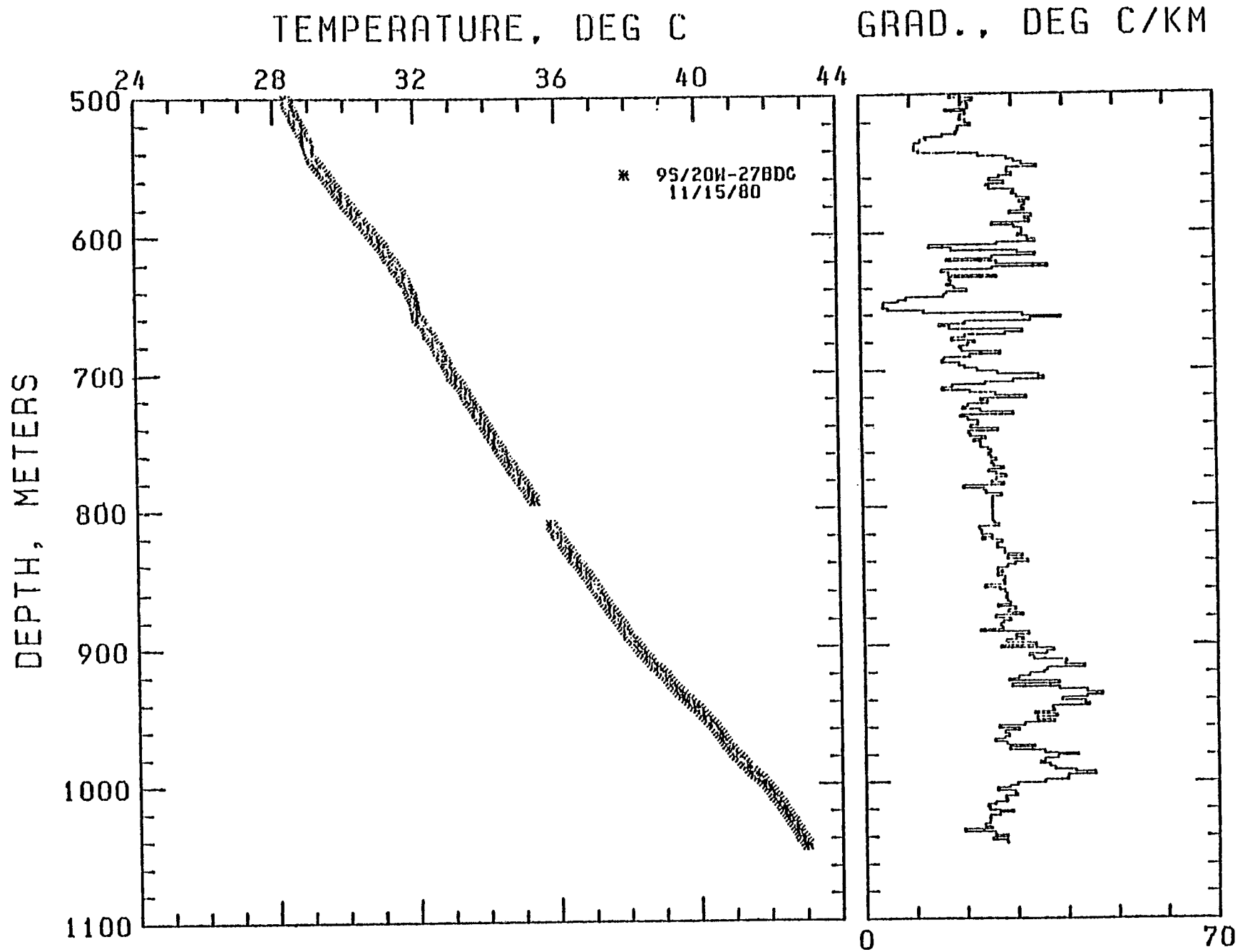


FIGURE 3-2B

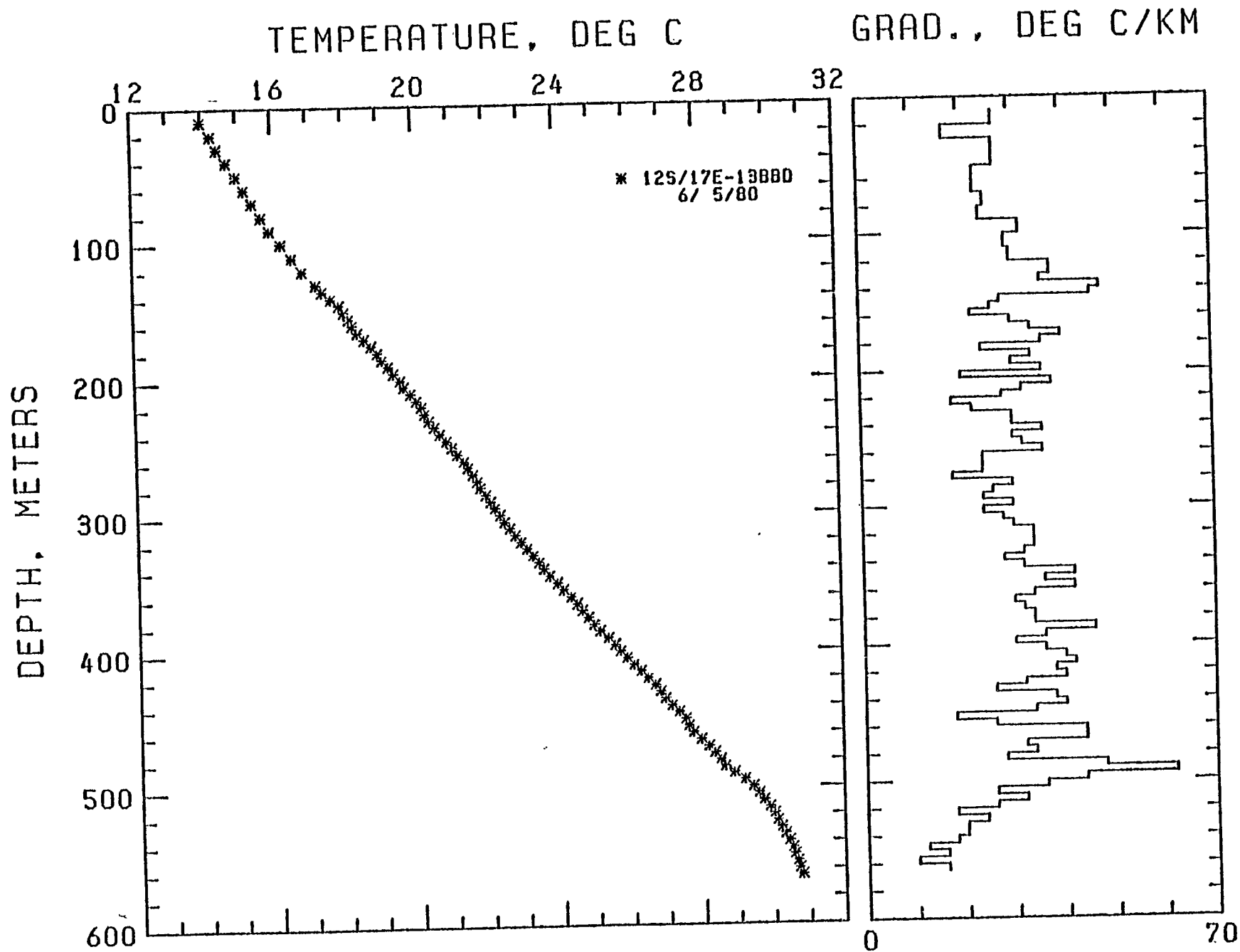


FIGURE 3-3

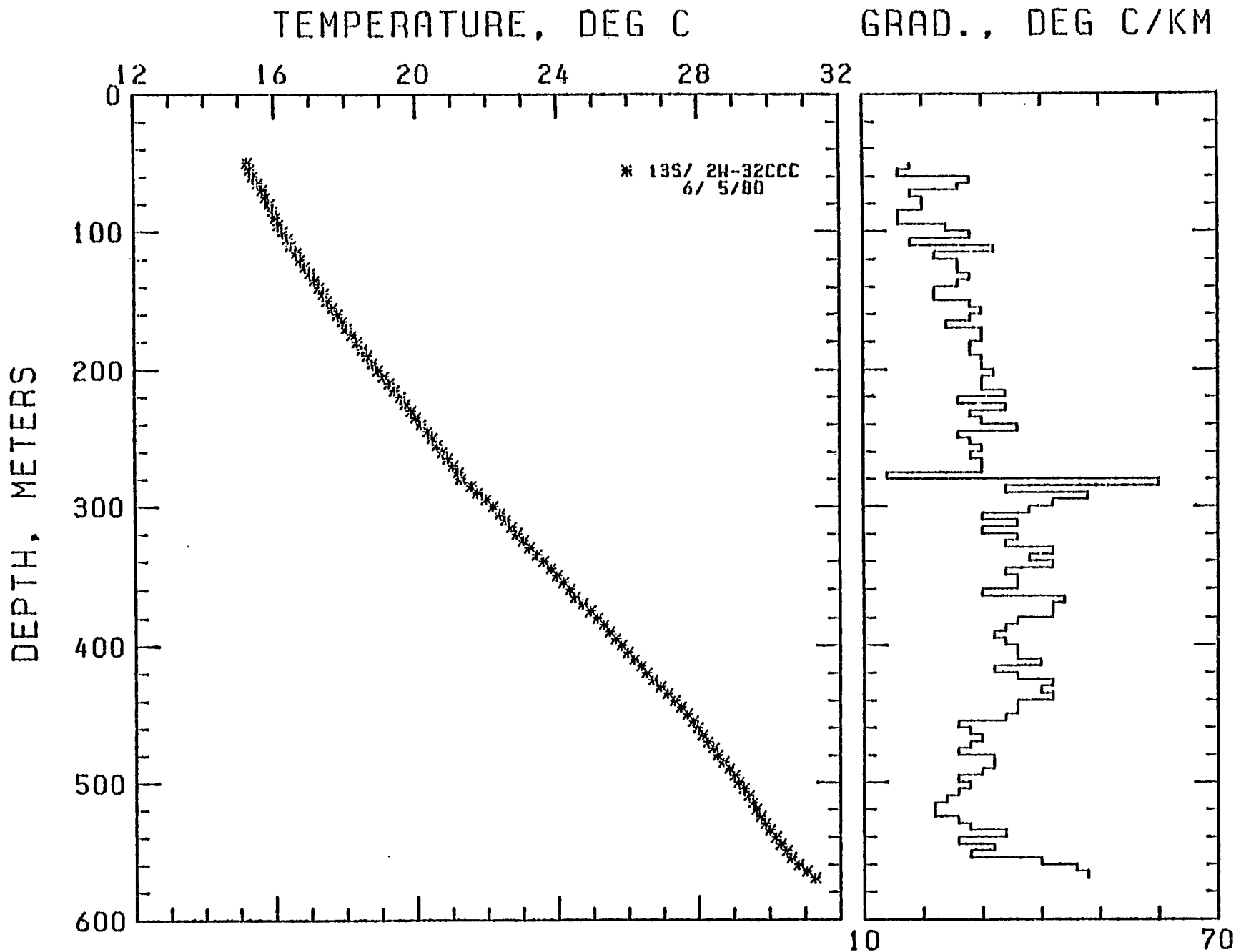


FIGURE 3-4A

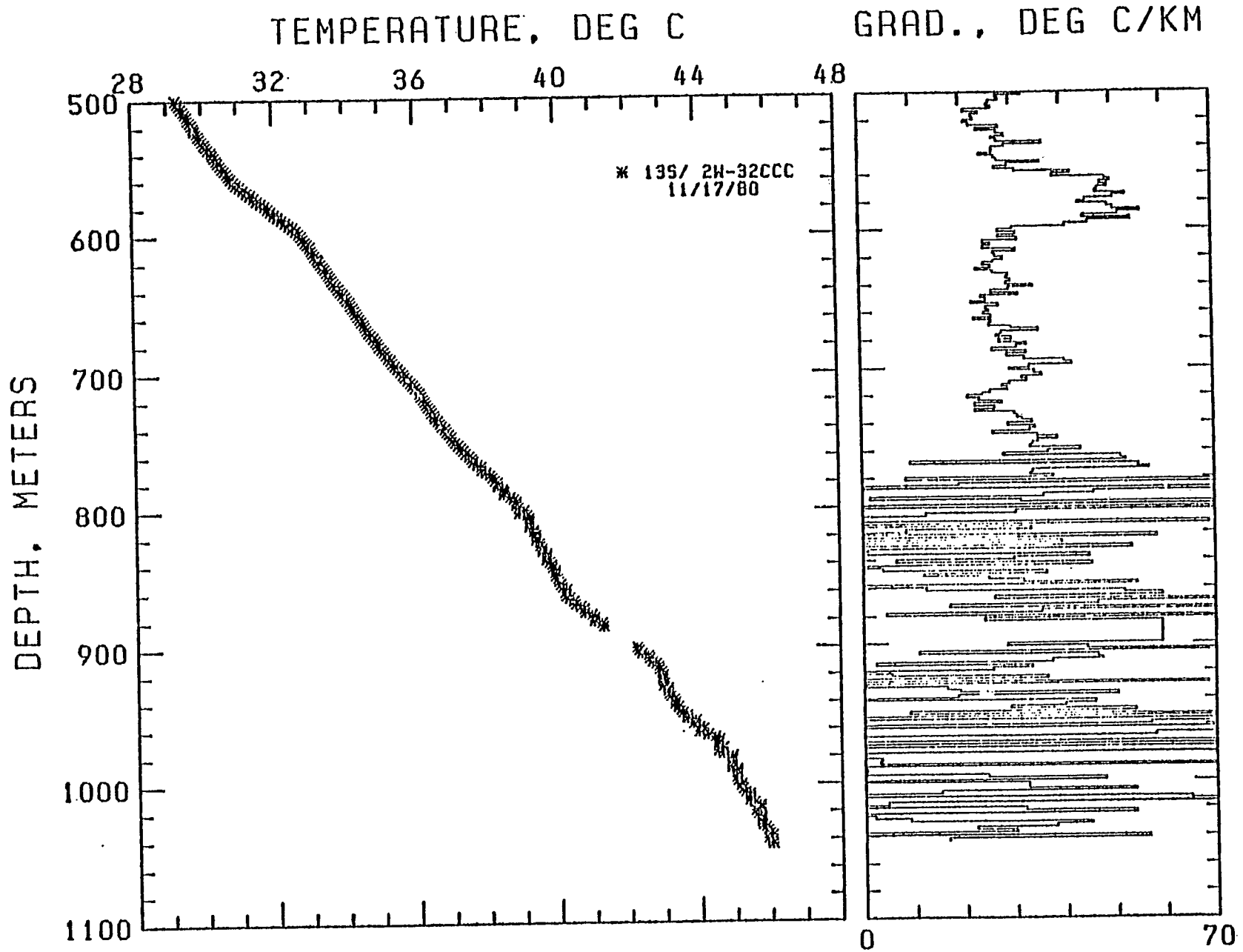


FIGURE 3-4B

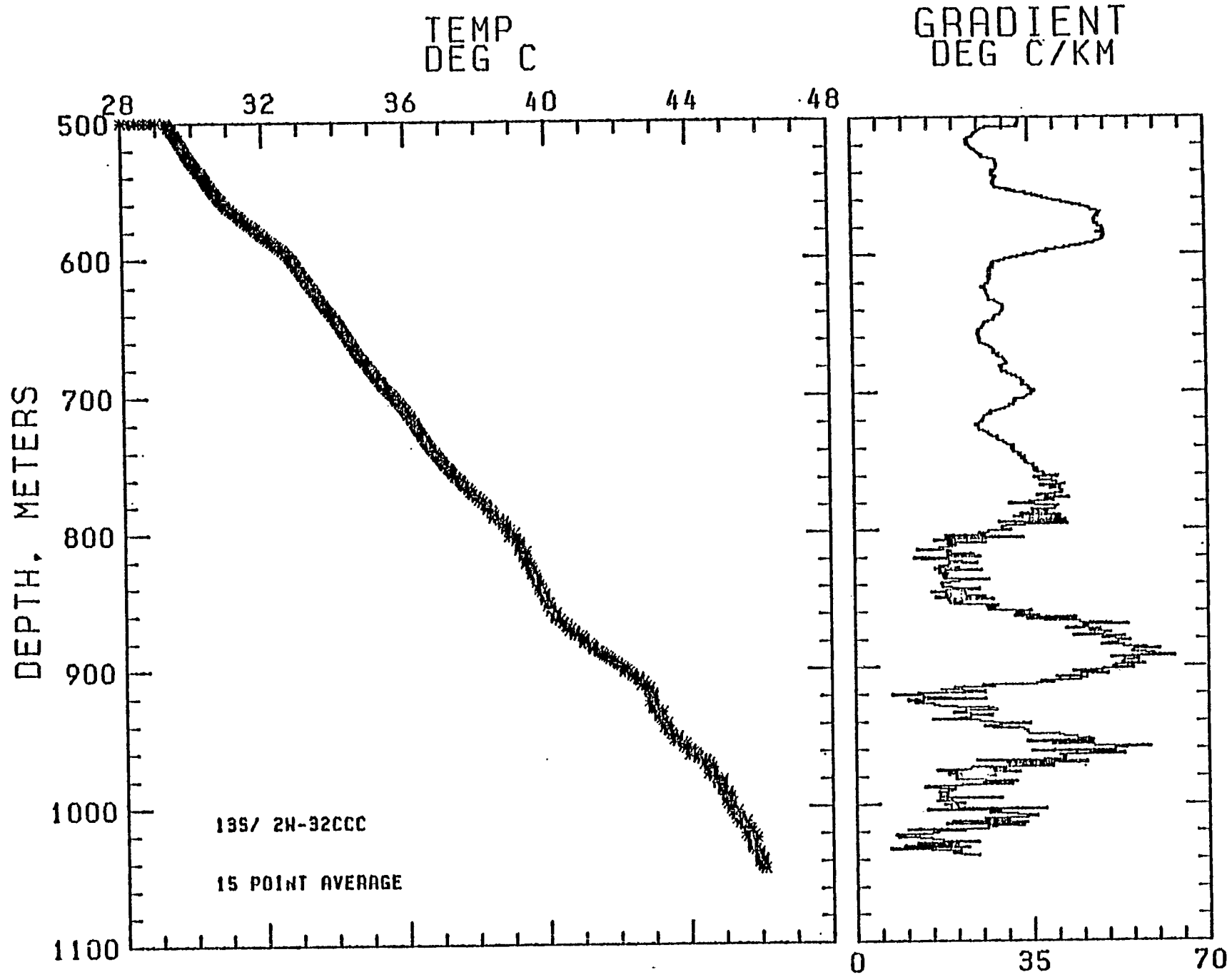


FIGURE 3-4C

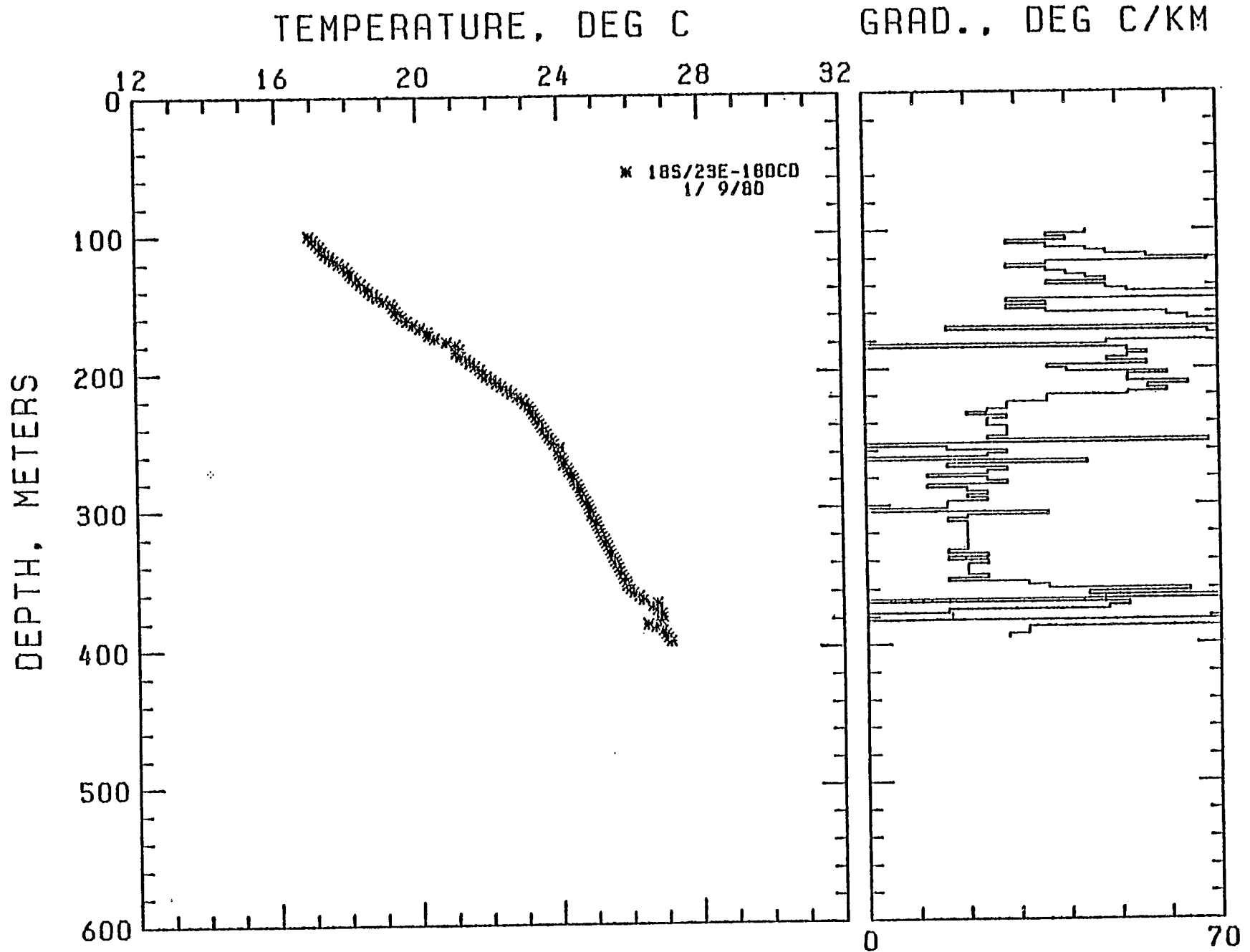


FIGURE 3-5

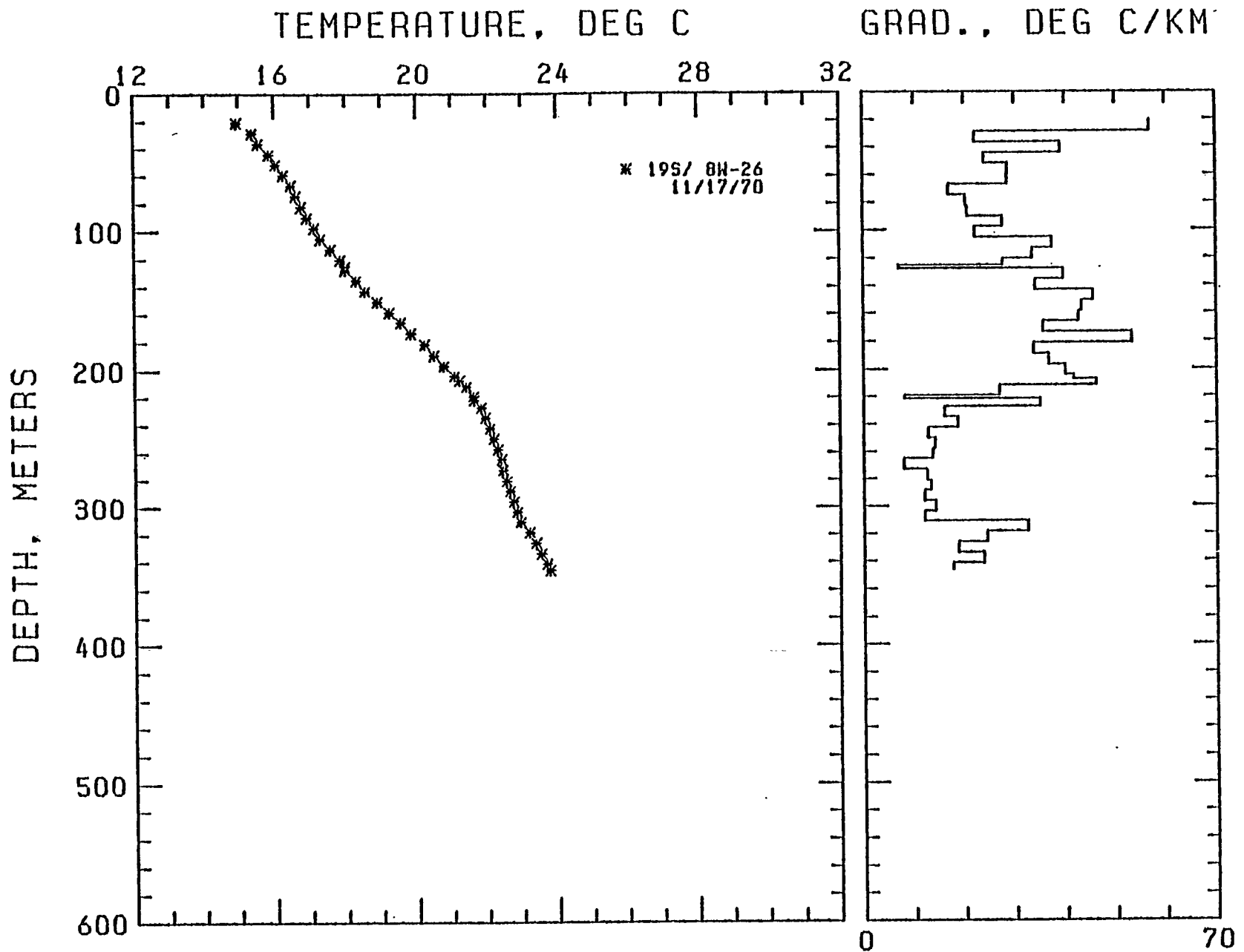


FIGURE 3-6

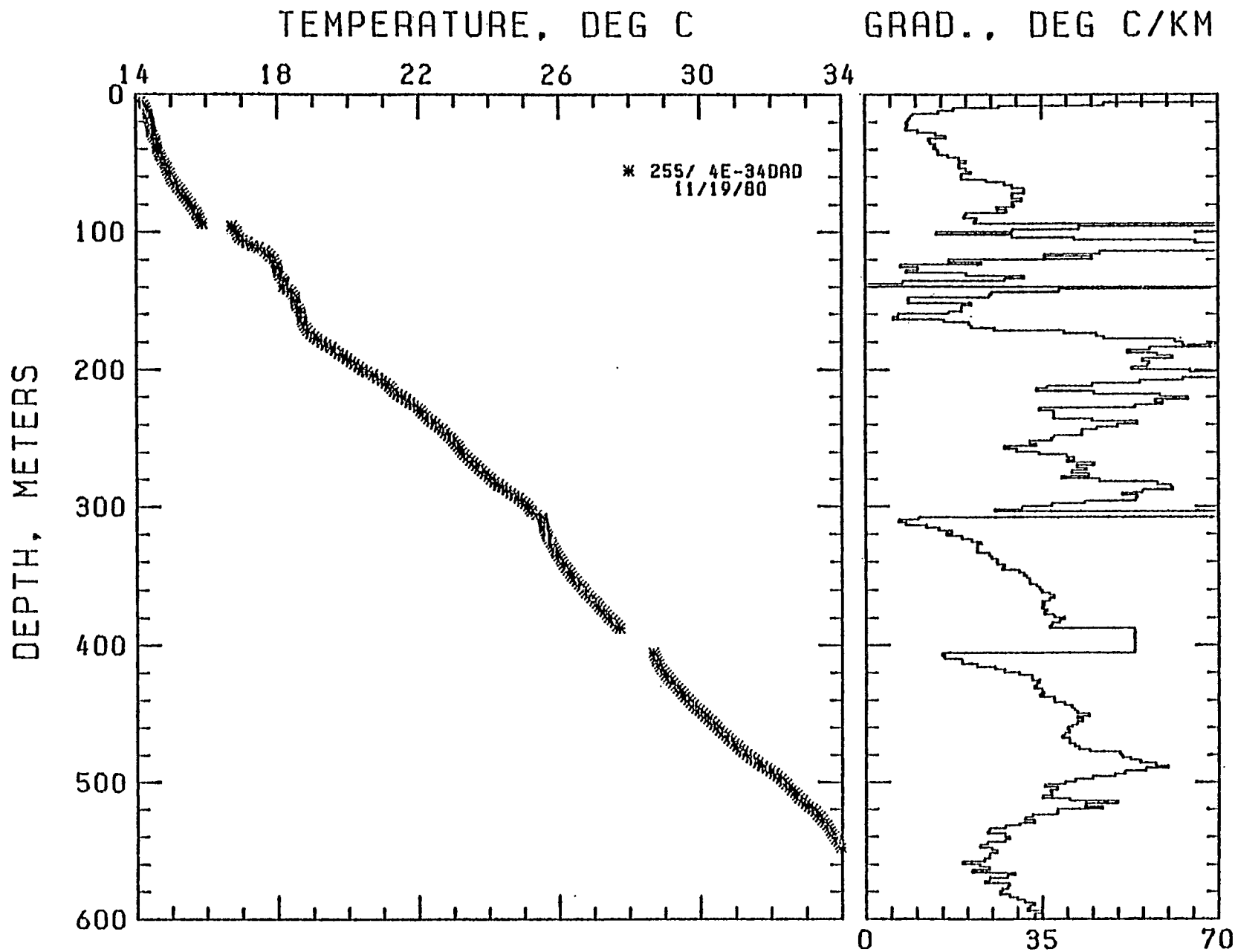


FIGURE 3-7A

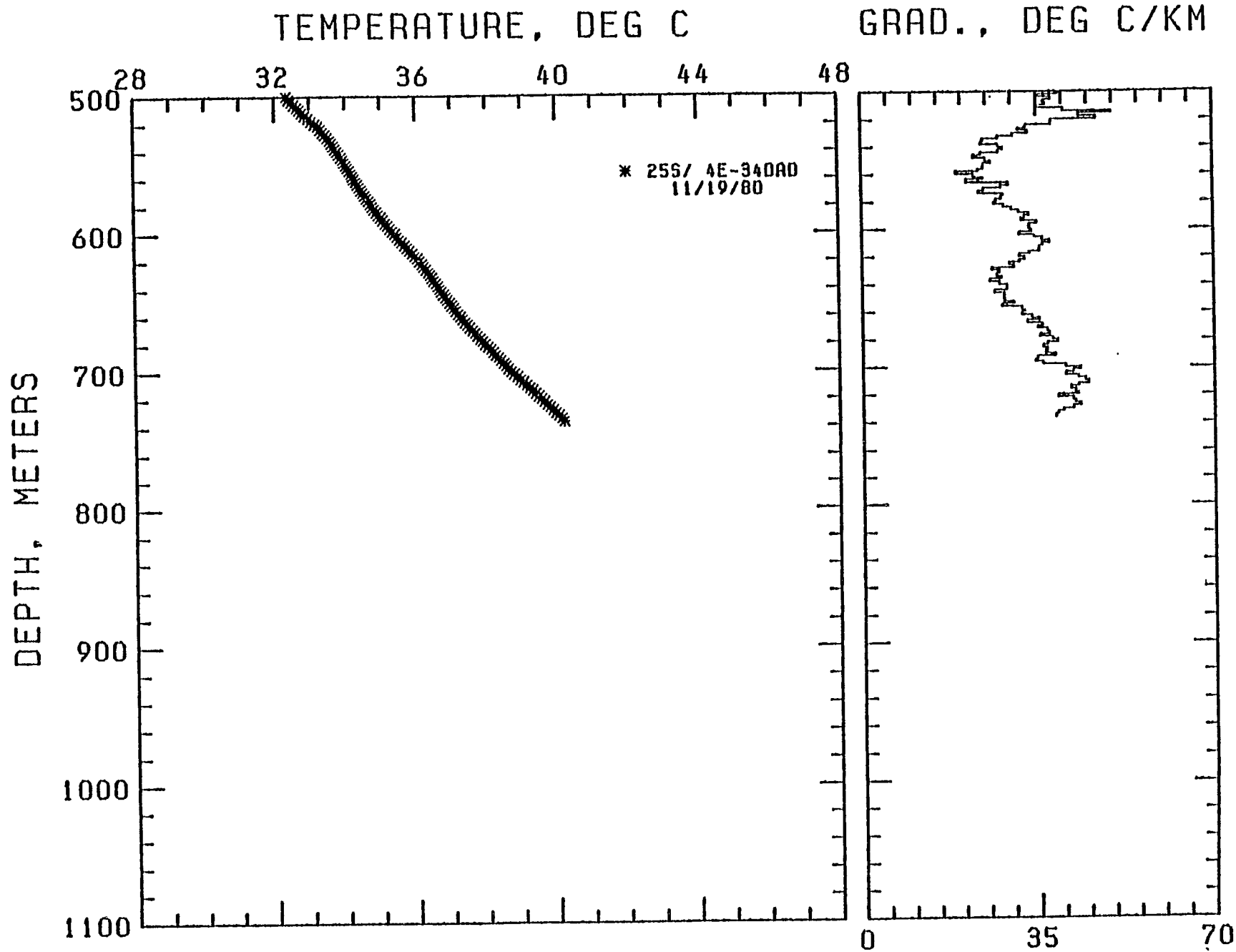


FIGURE 3-7B

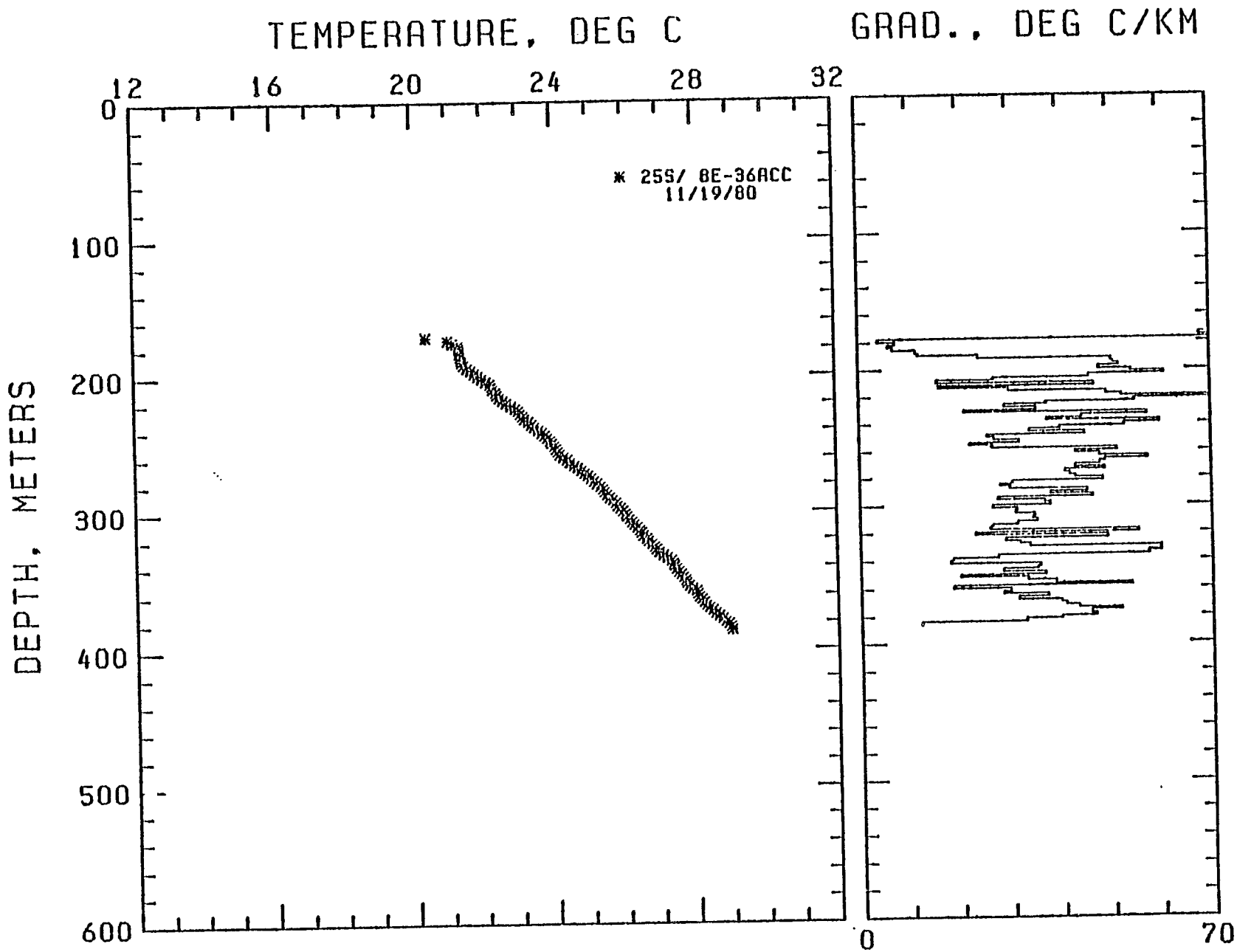


FIGURE 3-8

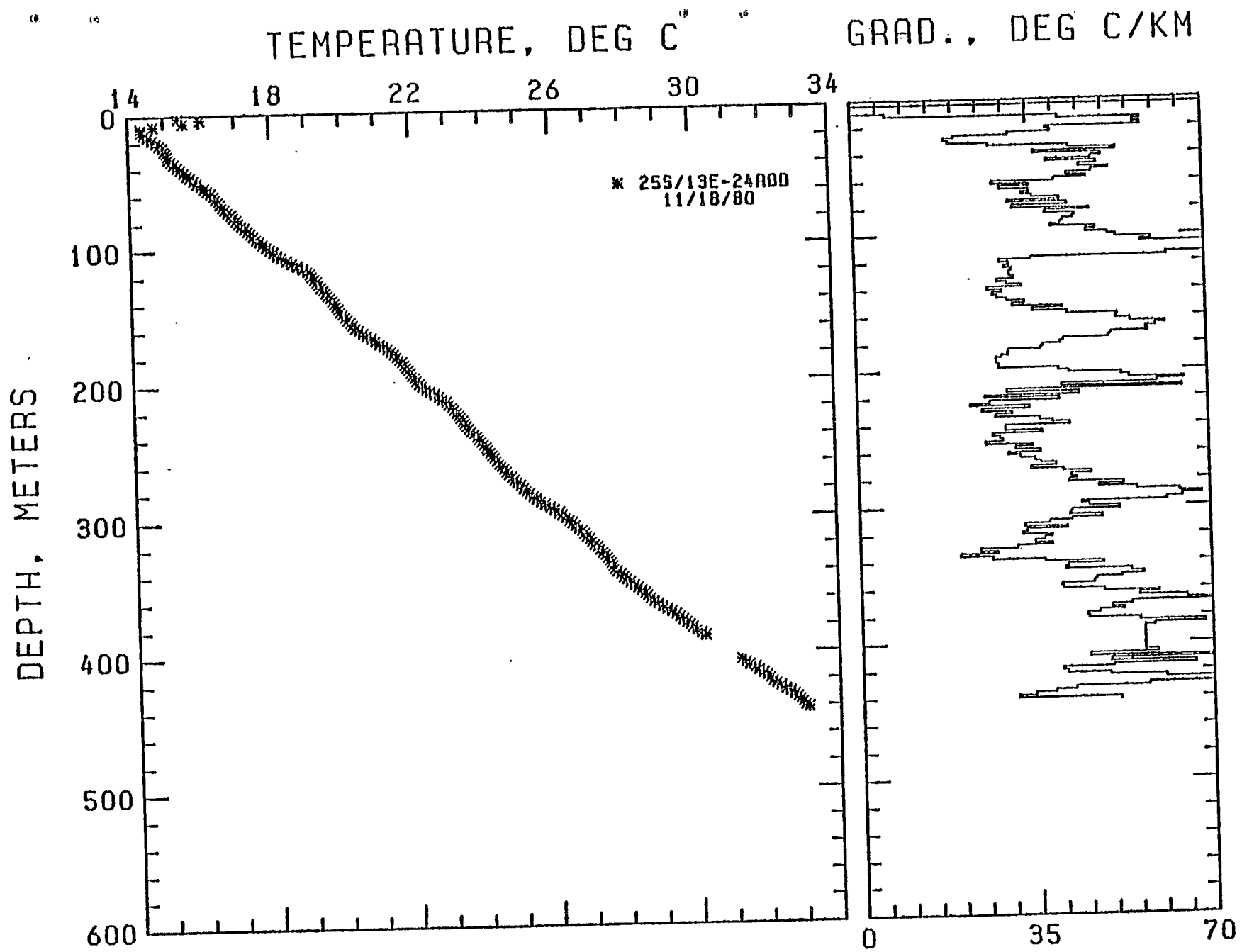


FIGURE 3-9

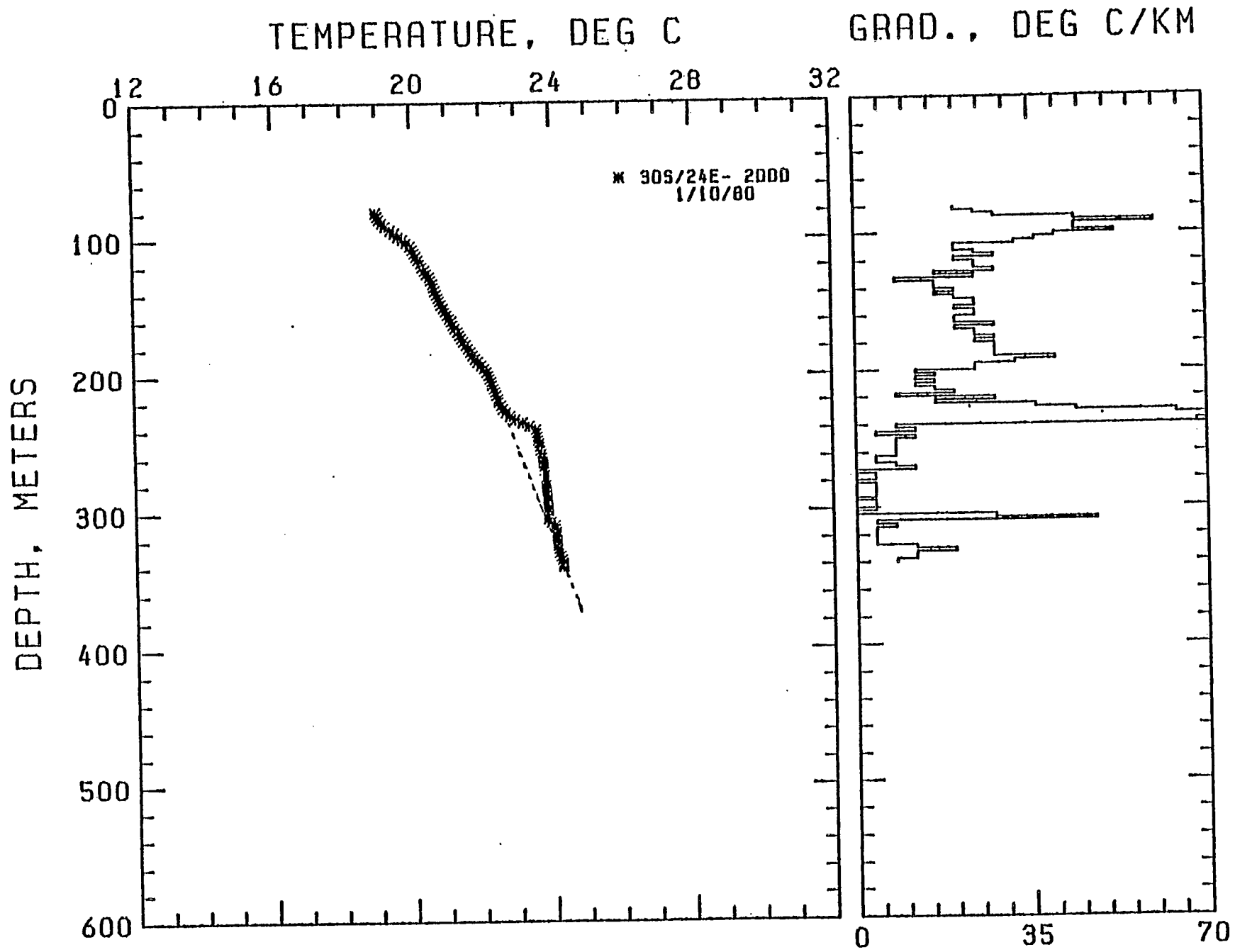


FIGURE 3-10

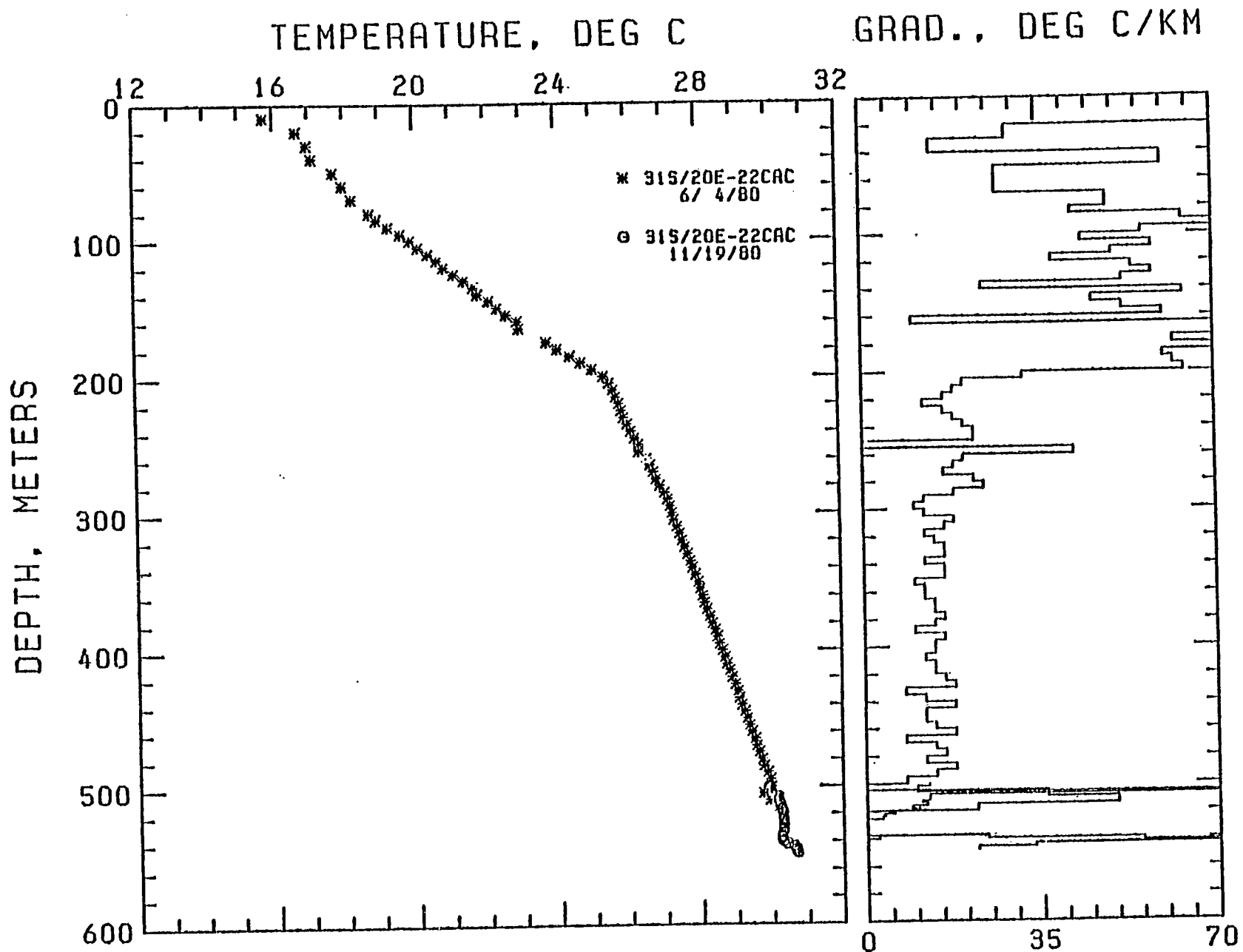


FIGURE 3-11

TEMPERATURES AT 500 METERS

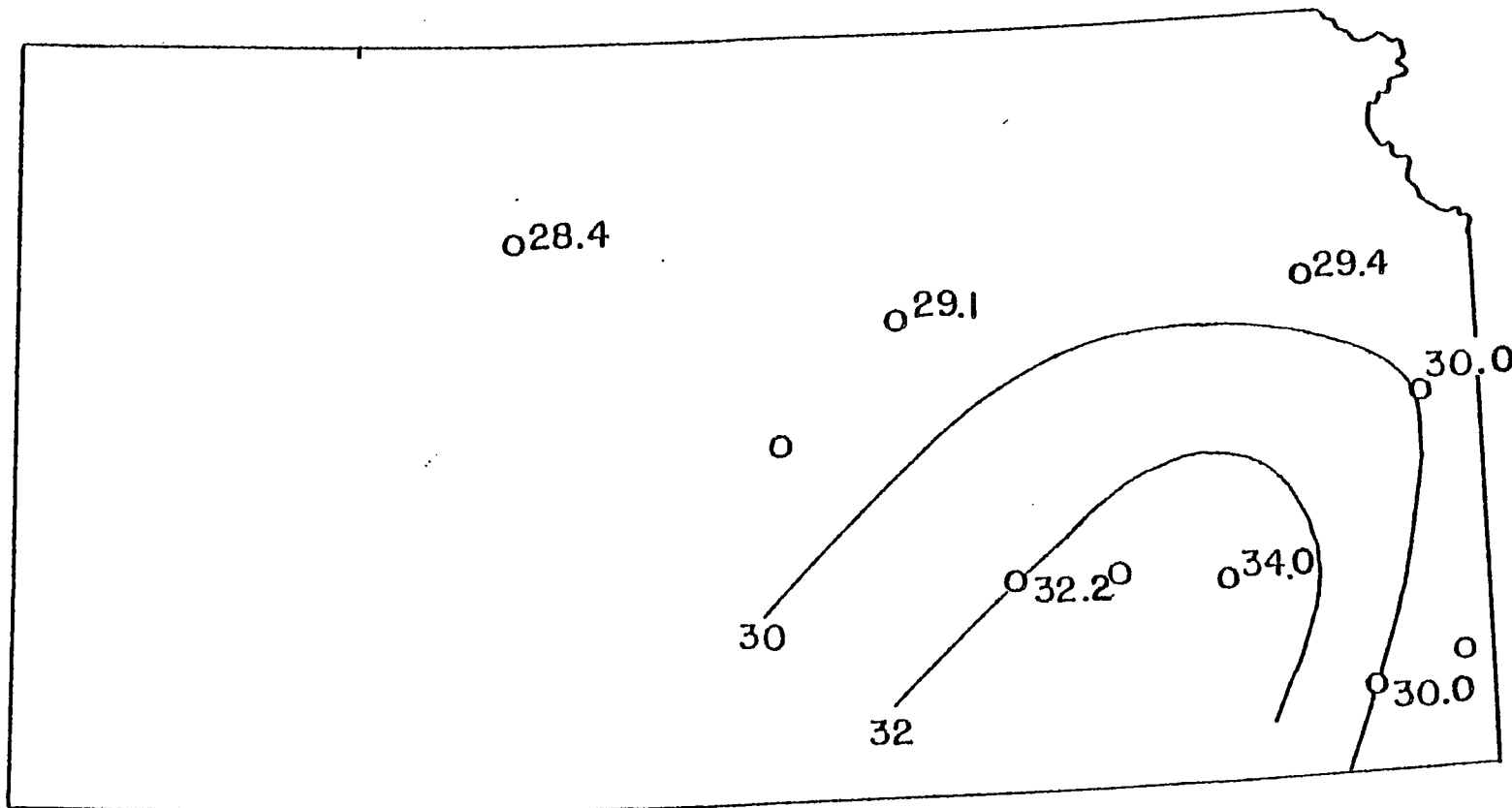


FIGURE 3-12

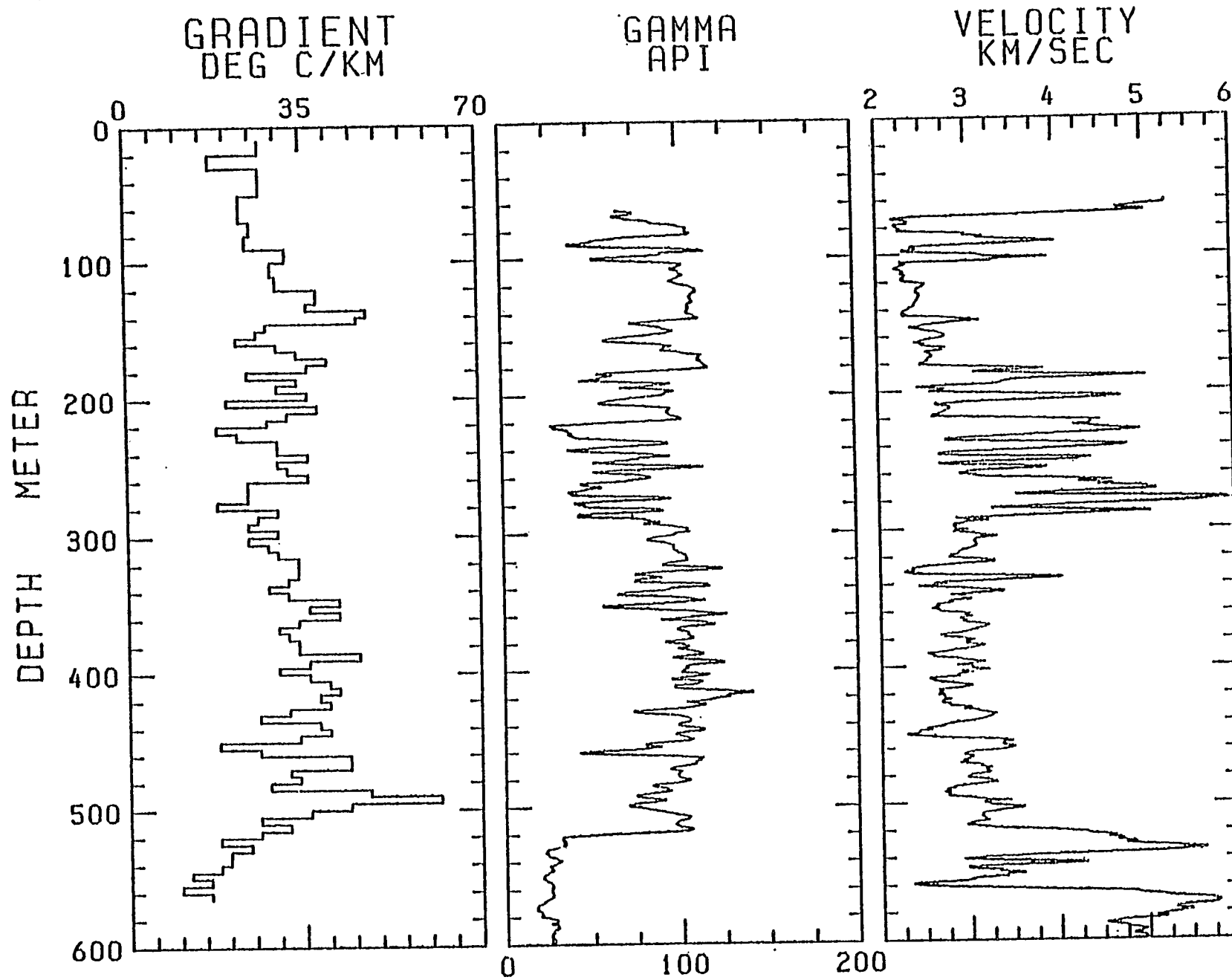


FIGURE 3-13

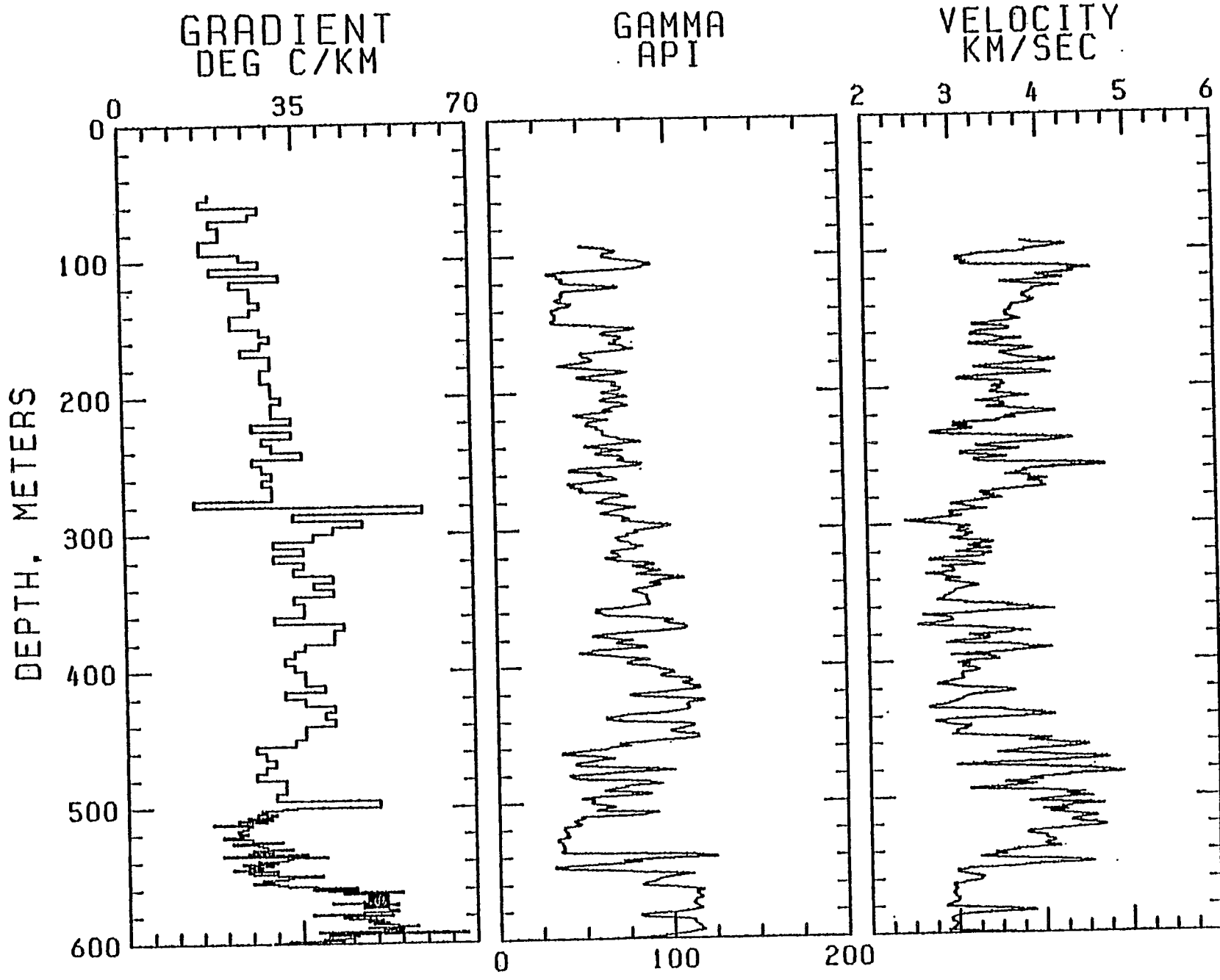


FIGURE 3-14A

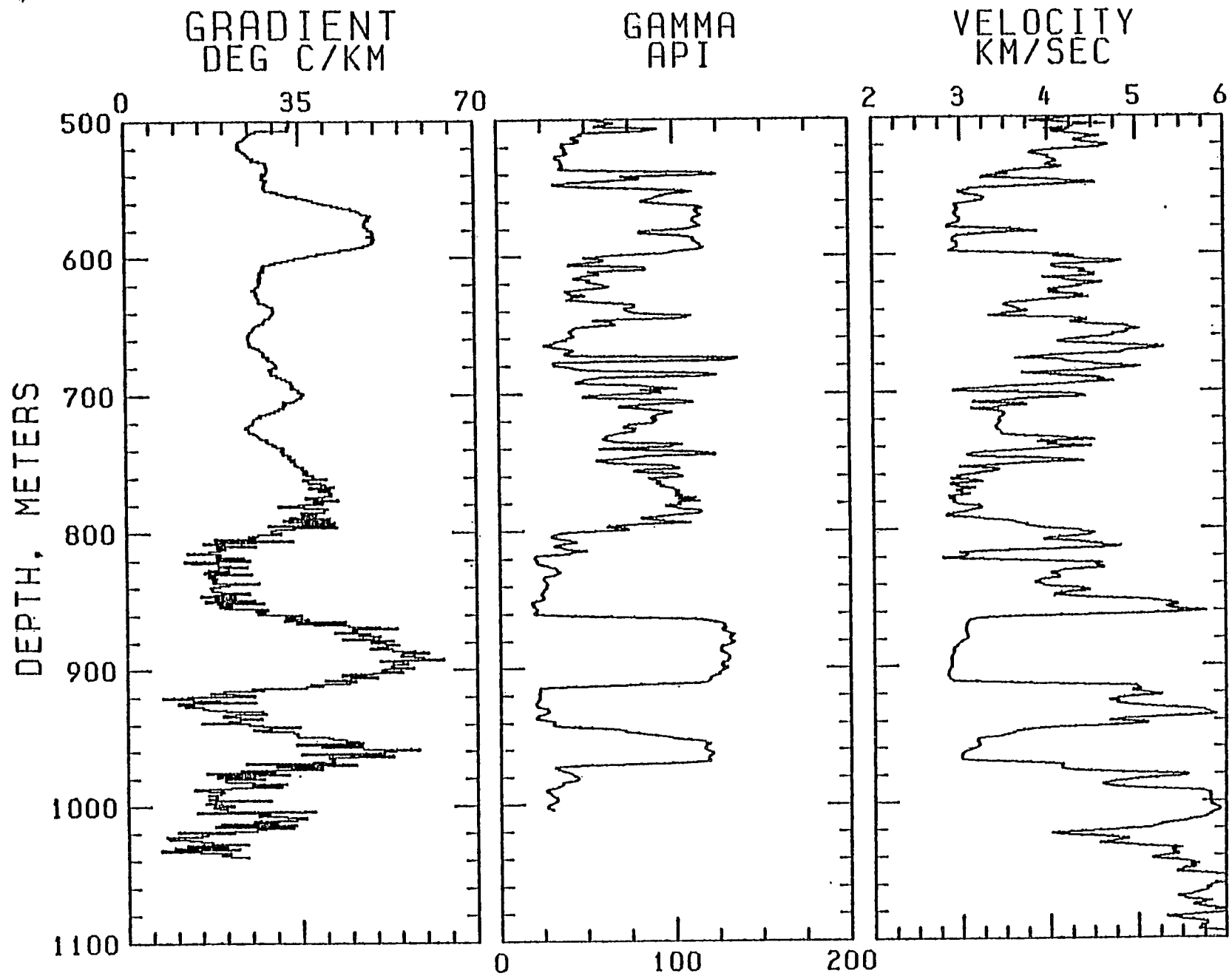


FIGURE 3-14B

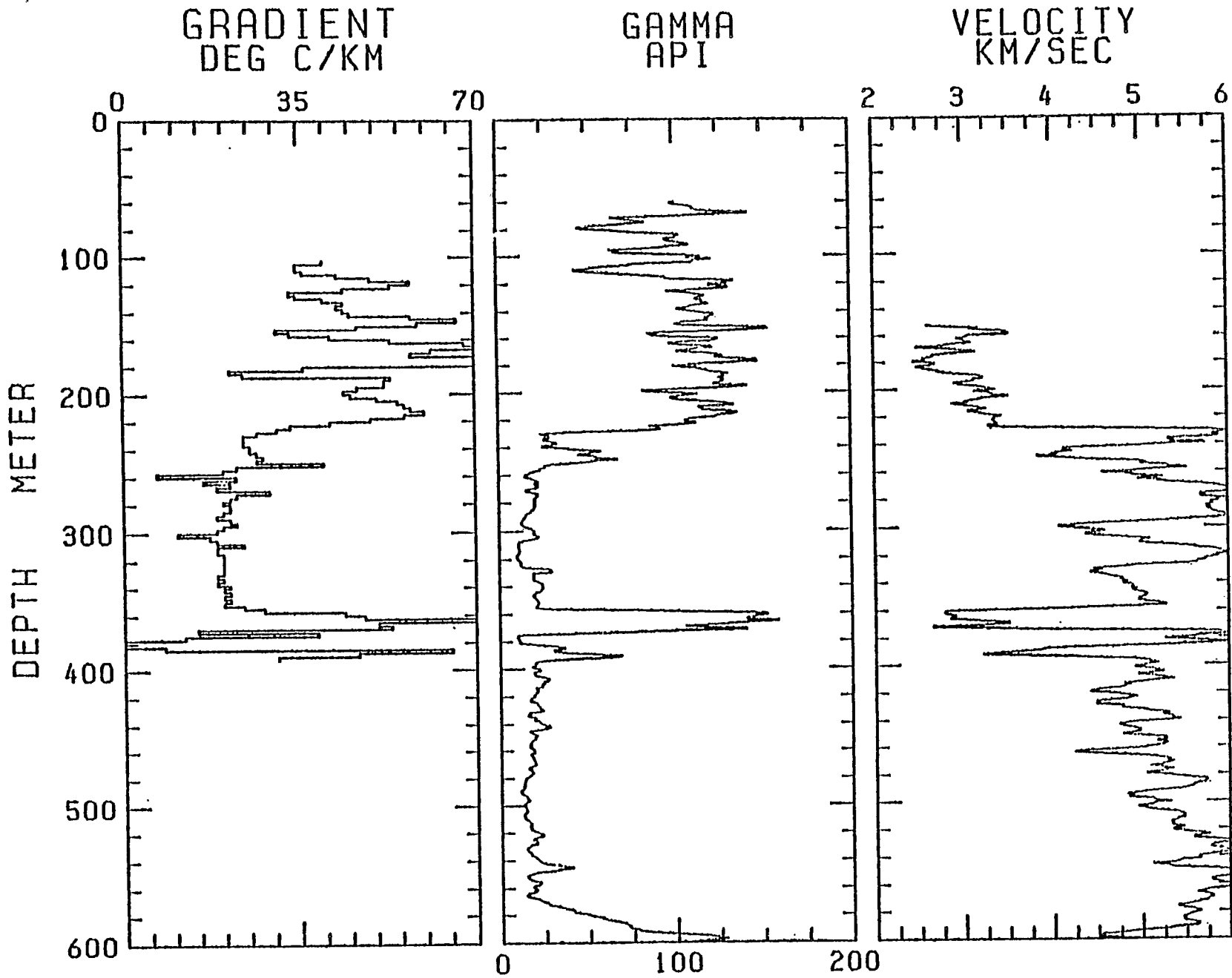


FIGURE 3-15

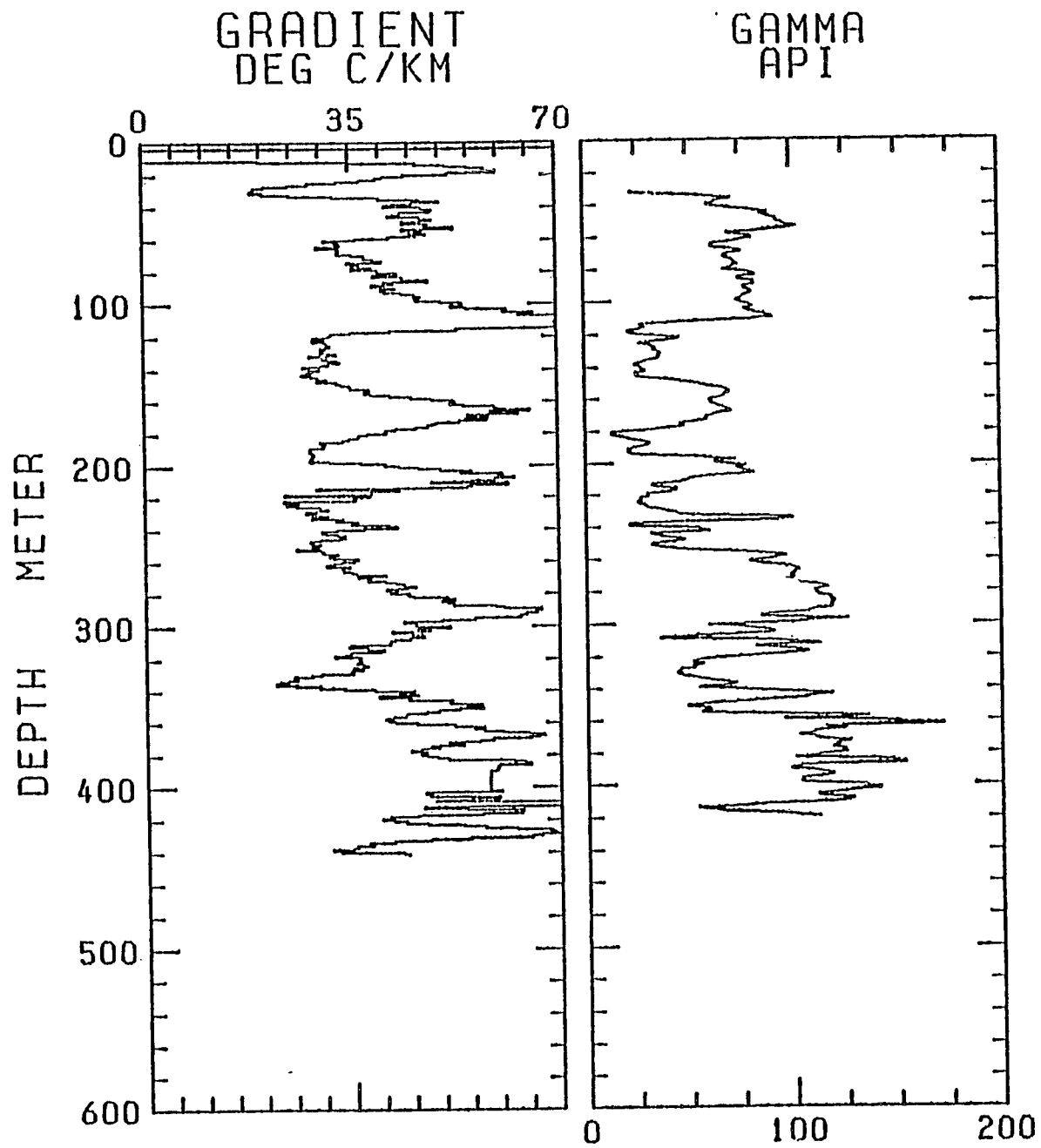


FIGURE 3-16

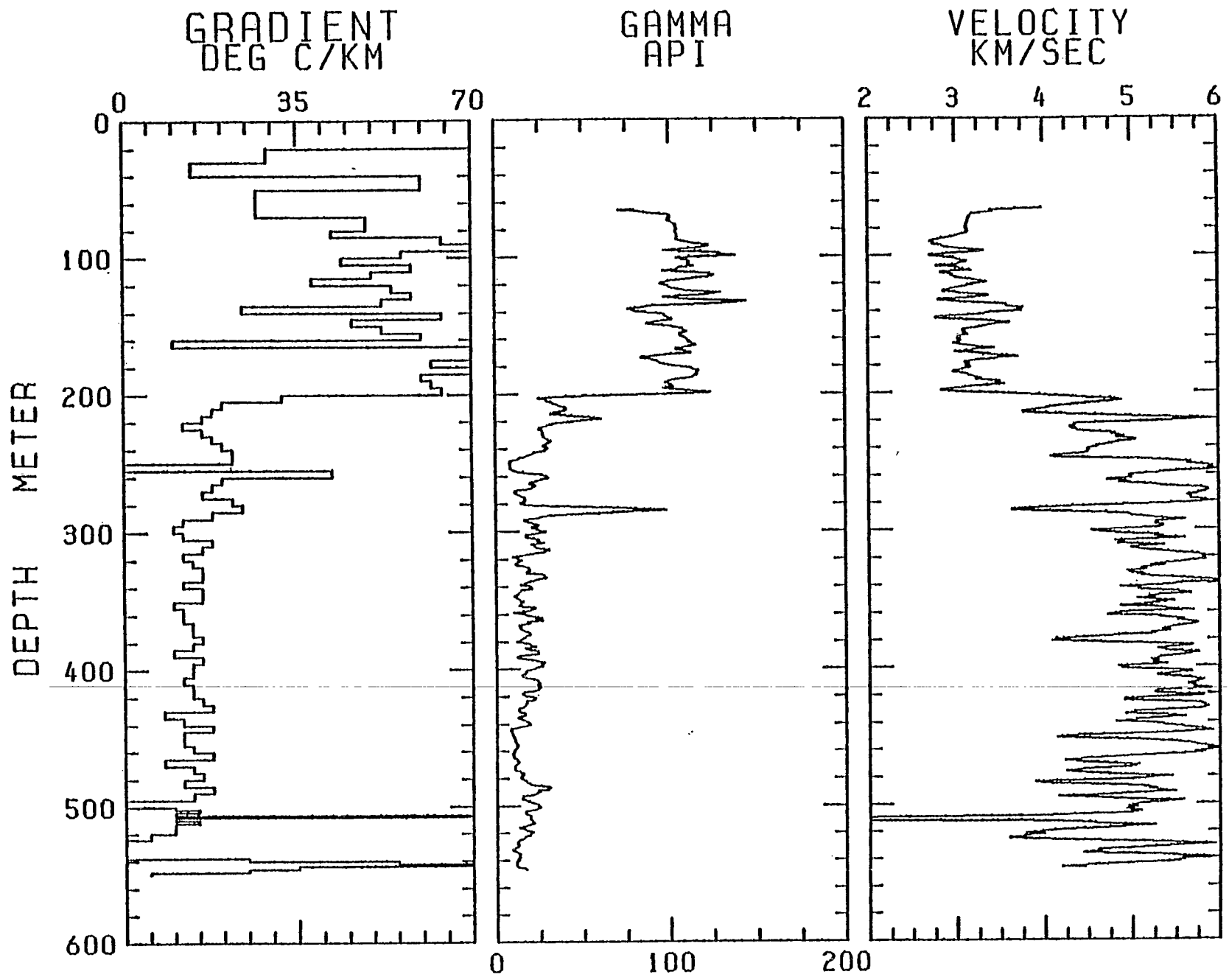


FIGURE 3-17

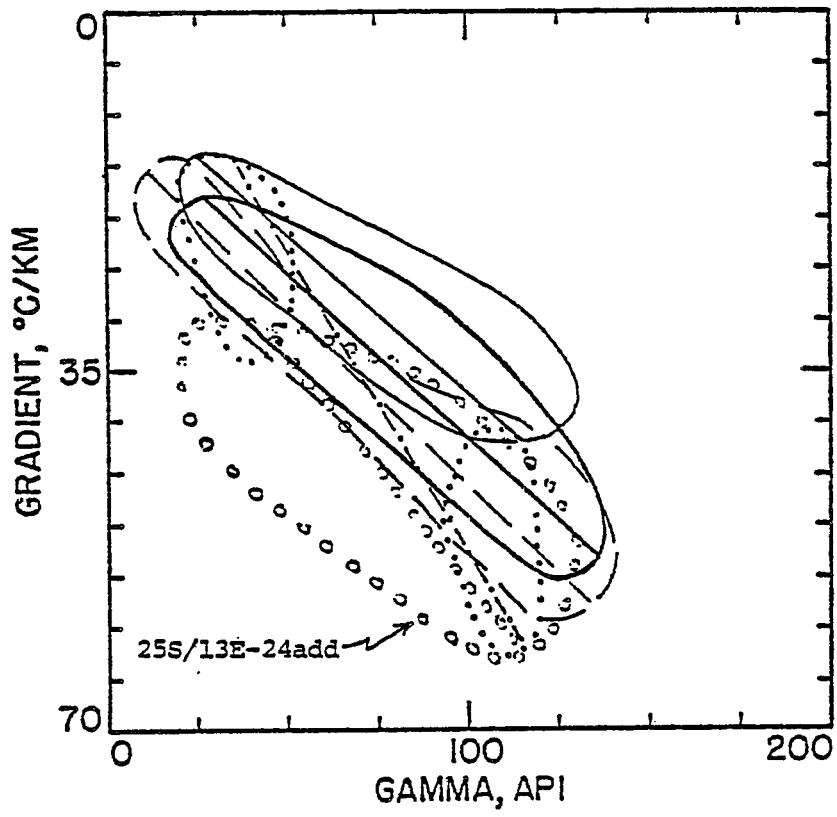
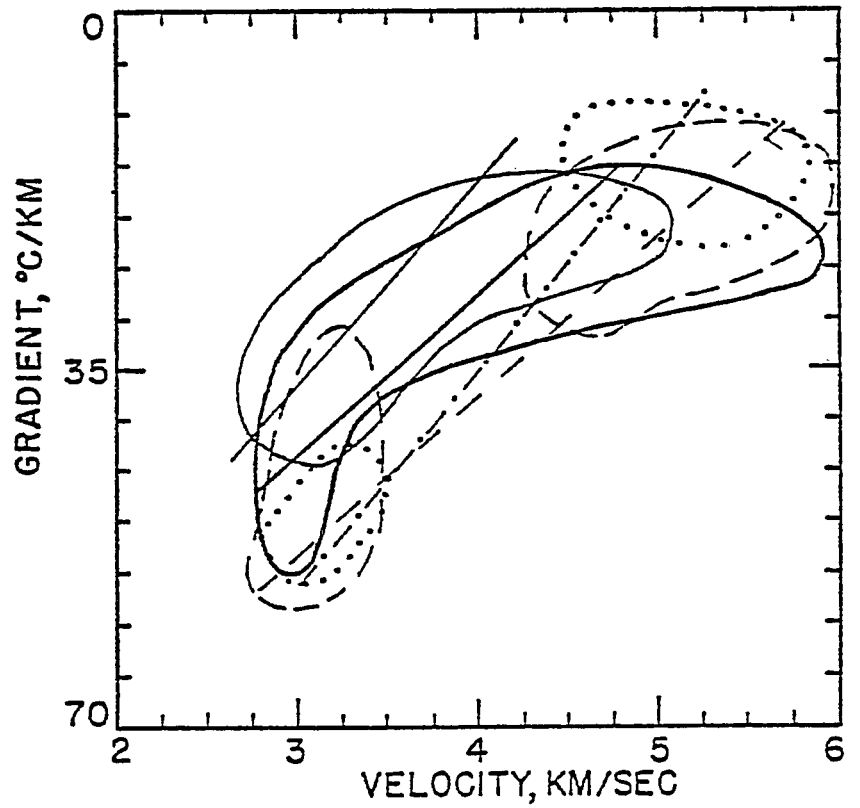


FIGURE 3-18

FIGURE 3-19



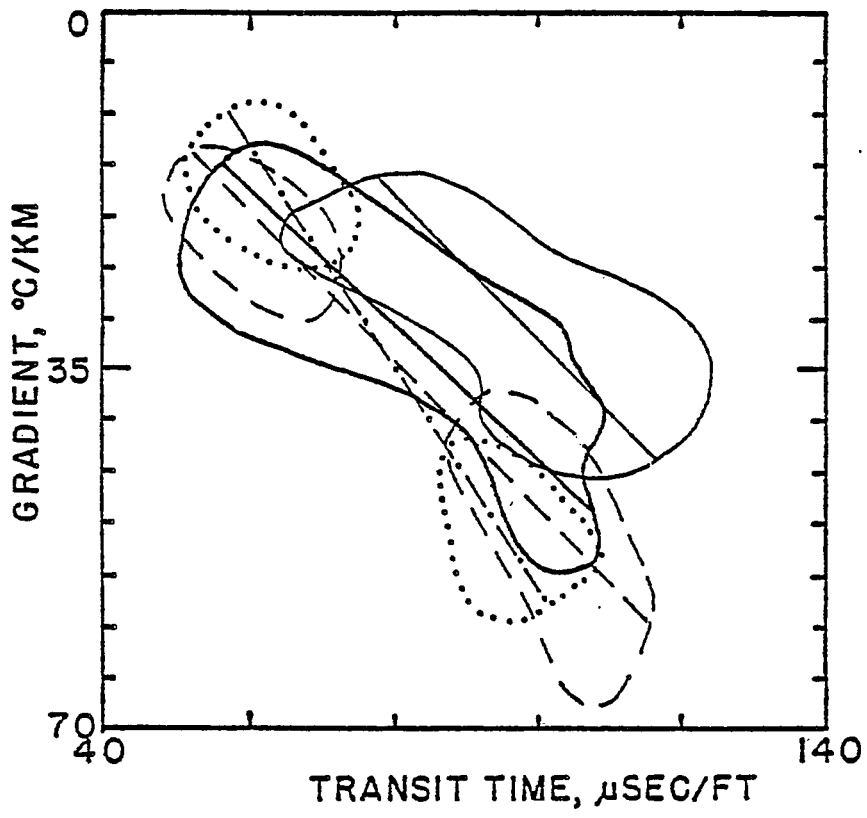


FIGURE 3-20

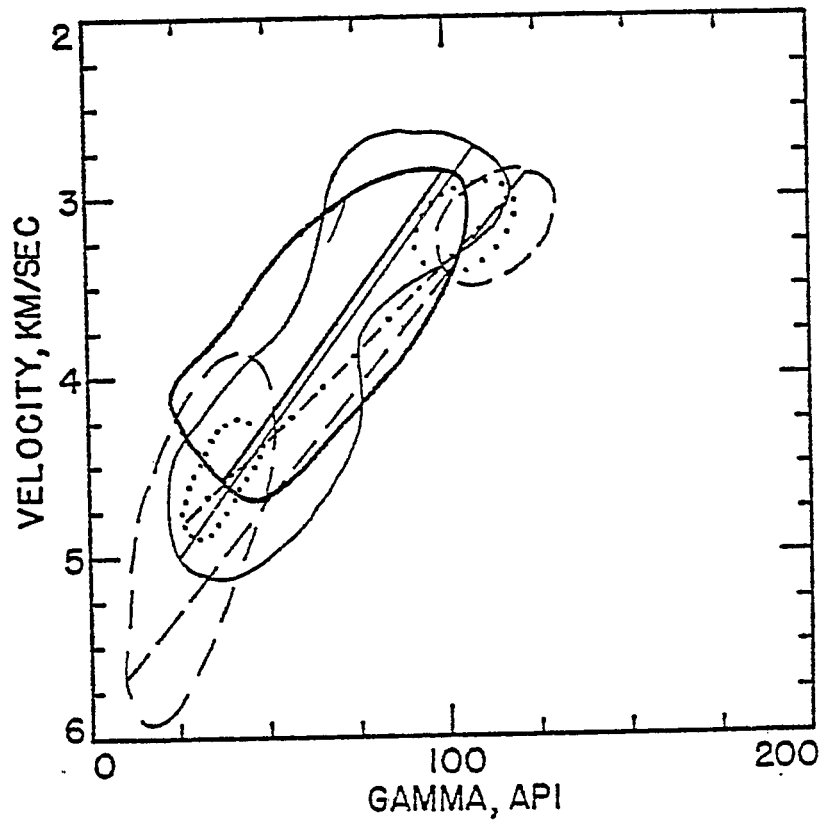


FIGURE 3-21

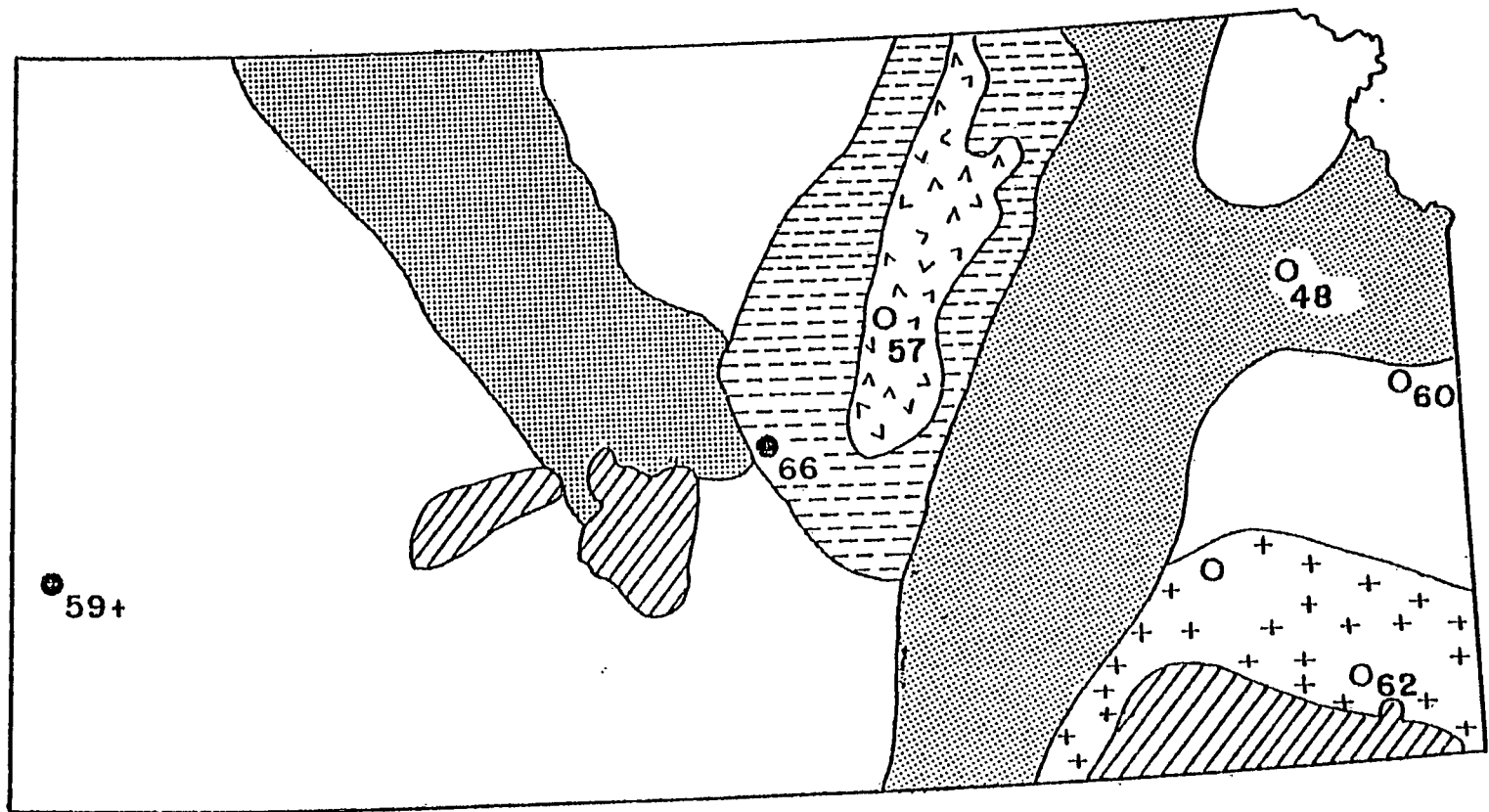


FIGURE 3-22

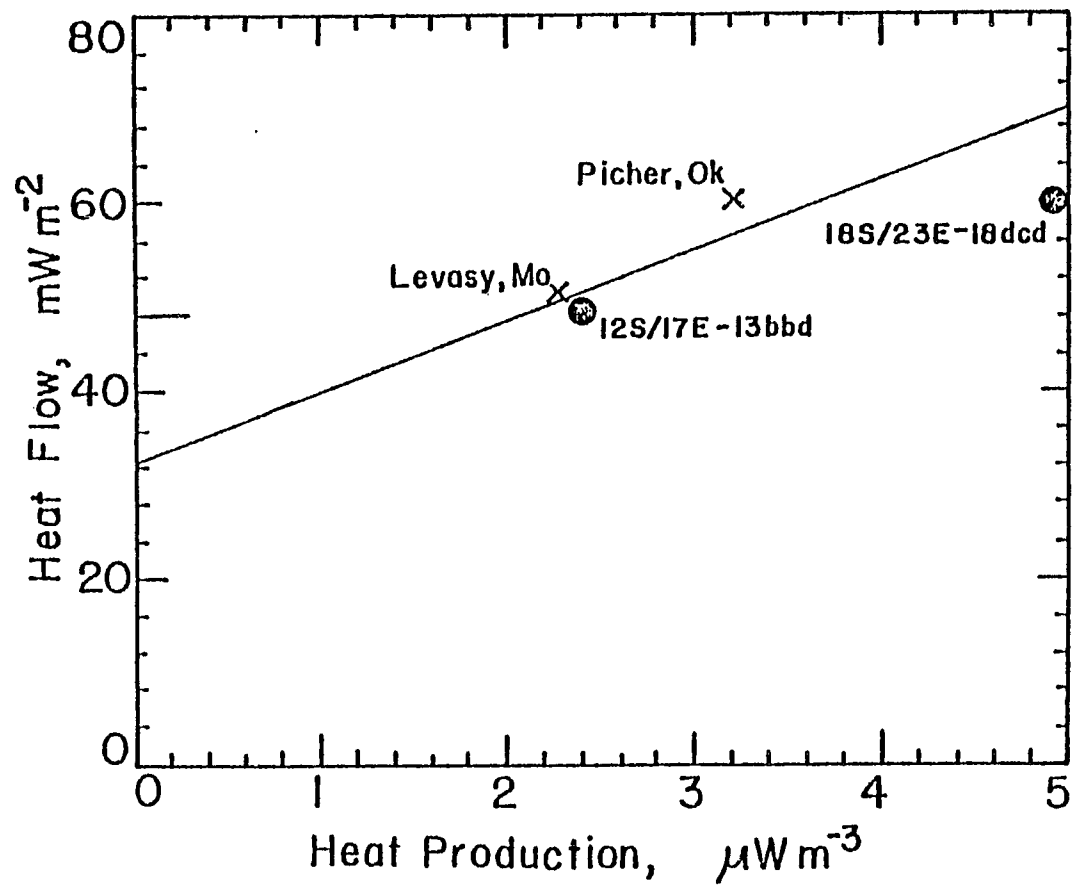


FIGURE 3-23

TABLE CAPTIONS

- TABLE 3-1: Location data for holes logged.
- TABLE 3-2: Temperatures measured at selected depths. Extrapolated temperatures are in parentheses.
- TABLE 3-3: Interval thermal conductivity, geothermal gradient and heat flow for hole 12S/17E-13BBB.
- TABLE 3-4: Interval thermal conductivity, geothermal gradient and heat flow for hole 13S/2W-32CCC.
- TABLE 3-5: Interval thermal conductivity, geothermal gradient and heat flow for hole 18S/23E-18DCD.
- TABLE 3-6: Interval thermal conductivity, geothermal gradient and heat flow value for hole 31S-20E-22CAC.
- TABLE 3-7A: Adopted values of heat flow.
- TABLE 3-7B: Heat flow derived from temperature and transit time logs using the procedure described in the text.
- TABLE 3-8: Inferred values of thermal conductivity and observed geothermal gradient and thickness of major shale units.

TABLE 3-1

<u>Township/Range -Section</u>	<u>North Latitude</u>	<u>West Longitude</u>	<u>Hole Name</u>	<u>Date Logged</u>	<u>Collar Elevation</u>	<u>Depth Logged</u>
9S/20W-27bdc	39°14.7'	99°32.6'	Rooks Co.	11/15/80	689 m	1045 m
12S/17E-13bbd	39°00.8'	95°28.7'	Big Spgs.	6/ 5/80	365 m	565 m
13S/ 2W-32ccc	38°52.3'	97°34.5'	Smokyhill	6/ 5/80	369 m	1044 m
18S/23E-18dcd	38°28.6'	94°54.3'	Watson-1	1/ 9/80	256 m	385 m
19S/ 8W-23 *	38°23.0'	98°10.0'	LK-1	11/17/70	525 m	229 m
19S/ 8W-26 *	38°22.0'	98°10.0'	LK-2	11/17/70	512 m	328 m
25S/ 4E-34dad	37°49.8'	99°58.3'	Butler Co.	11/19/80	405 m	737 m
25S/ 8E-36acc	37°50.0'	96°28.6'	Sallyard 9	11/19/80	402 m	384 m
25S/13E-24add	37°51.6'	95°55.4'	T.E. Bird	11/18/80	308 m	441 m
30S/24E- 2ddd	37°27.4'	94°44.5'	Frontenac	1/10/80	289 m	340 m
31S/20E-22cac	37°19.8'	95°12.4'	USGS-Bst	6/ 4/80	285 m	550 m

* Data from Sass et al. (1971).

TABLE 3-2

<u>Location</u>	Depth (meters)				
	<u>0</u>	<u>400</u>	<u>500</u>	<u>750</u>	<u>1000</u>
9S/20W-27bdc	(14.0)	26.2	28.4	34.2	41.8
12S/17E-13bbd	13.9	25.7	29.4		
13S/ 2W-32ccc	14.0	25.8	29.1	37.1	45.2
18S/23E-18dcd	(13.0)	27.3	(30.0)		
19S/ 8W-26	15.0	(25.5)			
25S/ 4E-34dad	(14.0)	28.4	32.2	40.7	
25S/ 8E-36acc	(13.0)	29.5			
25S/13E-24add	14.0	30.8	(34.0)		
30S/24E- 2ddd	(15.0)	25.0			
31S/20E-22cac	15.0	28.6	30.0		

TABLE 3-3

Depth Interval meters	Thermal Conductivity				Gradient mKm ⁻¹	Heat Flow mWm ⁻²	Generalized Lithology
	N	ϕ	Wm ⁻¹ K ⁻¹				
			(1)	(2)			
120 - 145	1	0.10	2.36	1.17	41.0 0.1	97	Lawrence Shale
145 - 165	1	0.10	2.91	1.85	26.0 0.1	76	Predominantly limestone
165 - 180	2	0.10	2.16	1.30	37.0 0.1	80	Predominantly shale
180 - 260	5	0.10	2.23 0.12	1.64	29.2 0.5	65	Predominantly limestone
260 - 315	8	0.10	2.56 0.10	1.88	25.5 0.3	65	Predominantly limestone
315 - 520	15	0.10	2.51 0.15	1.34	35.8 0.4	89.7	Cherokee Shale
520 - 565	9	0.06	2.79 0.15		17.1 0.1	48	Limestone and dolomite
BEST HEAT FLOW VALUE						48	
						5	

TABLE 3-4

Depth Interval meters	Thermal Conductivity $\text{Wm}^{-1}\text{K}^{-1}$				Gradient mKm^{-1}	Heat Flow mWm^{-2}	Generalized Lithology
	N	ϕ	(1)	(2)			
110 - 150	2	0.16	1.93		25.5 0.3	49	Shale and limestone
150 - 275	4	0.12	2.20 0.15		29.0 0.2	64	Limestone and shale
150 - 455					34.4 1.0		Shale and limestone
455 - 555					27.4 0.3		Shale and limestone
558 - 598	2	0.09	2.44	1.17	48.6 0.1	119	Lawrence Shale
598 - 634	1	0.09	2.25		26.9 0.1	61	Limestone
634 - 644	1	0.06	2.60		31.3 0.1	81	Conglomerate and shale
644 - 694	3	0.06	2.45		27.5 0.1	67	Limestone and shale
694 - 710					34.6 0.1		Shale and limestone
710 - 736	1	0.09	2.47		25.3 0.1	62	Sandstone
736 - 796	2	0.09	2.31	1.54	37.0 0.2	86	Cherokee Shale
796 - 862	3	0.10	2.92		20.4 0.3	60*	Mississippian Limestone
862 - 912	2	0.06	2.30	1.09	52.2 0.1	120	Chattanooga Shale
912 - 942	2	0.09	2.82		17.3 0.1	49*	Hunton Group
944 - 970	2	0.05	2.70	1.25	45.5 0.1	123	Sylvan Shale
970 - 1044	5	0.06	2.73 0.25		21.0	57*	Viola & Arbuckle Group
BEST HEAT FLOW VALUE						57 '6	

TABLE 3-5

Depth Interval <u>meters</u>	Thermal Conductivity				Gradient <u>mKm⁻¹</u>	Heat Flow <u>mWm⁻²</u>	Generalized <u>Lithology</u>
	<u>N</u>	<u>φ</u>	Wm ⁻¹ K ⁻¹				
			<u>(1)</u>	<u>(2)</u>			
100 - 115					36.9 0.1		Shale and limestone
115 - 220	7	0.12	2.25 0.15	1.15	52.4 1.1	115	Cherokee Shale
220 - 297.5	6	0.08	2.56 0.25		23.2 0.4	60*	Mississippian Limestone
297.5 - 360	4	0.12	3.00 0.30		20.1 0.2	60*	Dolomite
360 - 375	2	0.06	2.24	1.14	52.5 0.1	118	Chattanooga Shale
375 - 395	9	0.05	3.96		14.5 0.1	57*	Dolomite
BEST HEAT FLOW VALUE						60 3	

TABLE 3-6

Depth Interval <u>meters</u>	Thermal Conductivity			Gradient <u>mKm⁻¹</u>	Heat Flow <u>mWm⁻²</u>	Generalized <u>Lithology</u>
	<u>N</u>	<u>φ</u>	<u>Wm⁻¹K⁻¹</u>			
70 - 205			(1.16)	53.4 1.5		Cherokee Shale
205 - 220				18.0 0.1		Mississippian Limestone
220 - 240				16.6 0.1		Mississippian Limestone
240 - 290				20.5 0.1		Limestone and some shale
290 - 550	17	0.08	4.46 0.50	14.0	62	Arbuckle Dolomite
BEST HEAT FLOW VALUE					62 6	

TABLE 3-7A

LOCATION	BEST HEAT FLOW VALUES mWm ⁻² (μ cal/cm ² sec)	ESTIMATED ERROR mWm ⁻²
12S/17E-13bbd	48 (1.15)	±5
13S/2W-32ccc	57 (1.36)	±6
18S/23E-18dcd	60 (1.43)	±3
31S/20E-22cac	62 (1.48)	±5

TABLE 3-7B

LOCATION	DEPTH INTERVAL meters	HEAT FLOW mWm ⁻²
12S/17E-13bbd	120-550	40
13S/2W-32ccc	270-780	50
	780-1000	54
	270-1000	50
18S/23E-18dcd	110-380	61
31S/20E-22cac	70-290	66

TABLE 3-8

Location	Lawrence			Cherokee			Chattanooga			Sylvan		
	K	G	t	K	G	t	K	G	t	K	G	t
12S/17E-13bbd	1.17	41	25	1.34	36	200						
13S/2W-32ccc	1.17	49	40	(1.54)	37	60	1.09	52	50	1.25	46	26
18S/23E-18dcd				1.15	52	105	1.14	53	15			
31S/20E-22ccc				1.10	53	135						

DEVELOPMENT OF A LOW COST THERMAL CONDUCTIVITY PROBE

by

Marios Sophocleous and Mitchell Hall
Kansas Geological Survey
Lawrence, Kansas

One phase of the assessment program of geothermal resources of Kansas includes the construction and calibration of practical, low cost thermal conductivity probes, and the demonstration of their reliability and accuracy as sensors of the thermal conductivity of Kansas rocks. This brief report addresses those aspects of the geothermal assessment project.

The thermal conductivity of rocks together with the geothermal gradient are the two quantities required for heat flow determinations. Two procedures are generally popular for thermal conductivity measurements: the divided bar apparatus and the needle or cylindrical probe. The latter has the advantage of being capable of measuring thermal conductivities of rocks both in situ and in the laboratory; also, of being a more economical instrument. For these reasons and our previous experience on cylindrical probes (Sophocleous, 1979), we decided to build and calibrate a number of such probes at the Kansas Geological Survey.

The theory of the thermal conductivity probe is well known (De Vries and Peck, 1958; Wechsler et al, 1965) and will not be elaborated here. The procedures outlined in Sophocleous (1979) were followed in constructing three conductivity probes. In short, teflon-coated constantan wire tightly wound (using a lathe) in a bifilar manner around a plastic tube filled with casting resin, in the wall of which a bead thermistor was potted with epoxy,

formed the heating element (constantan) and the temperature sensing component (bead thermistor) of the probe. This entire setup was then epoxied into a stainless steel tube, at one end of which a stainless steel plug (tip) was water-tightly attached, thus making the probe a mechanically strong and durable one. The purpose of these probes is to be used for measuring the thermal conductivity of cores collected from the Arbuckle Group and possibly other rocks. Some physical characteristics of the three constructed probes are shown in Table 4-1.

Table 4-1

Physical Characteristics of the Constructed Probes

Probe No.	Length of Stainless Steel Tube (cm)	Tip Length (cm)	Stainless Steel Tube OD (cm)	Length of Heating Element, constantan (cm)
I	40.40	2.30	0.76	35.80
II	39.45	1.35	0.76	33.50
III	39.55	1.45	0.76	35.72

The calibration procedure consisted of inserting the probe into a PVC cylinder (12.3 cm ID, 44.5 cm height) filled with fine Ottawa sand (ASTM C-109) compacted to a bulk density of 1.68 gm/cc for which thermal conductivity values are available (Slusarchuk and Foulger, 1973) and comparing the probe measurements to those available from the literature. A constant voltage of

32 V was applied to the constantan leads using a Systron Donner model TLB-3 power supply, and a digital multimeter HP 3466A was used to monitor the change of the thermistor resistance with time. A sample of typical runs with air-dry and with water-saturated fine-grained Ottawa sand are shown in Figures 4-1 and 4-2, respectively.

Thermal conductivity values were calculated using the formula:

$$\lambda = 18.34Q/S \text{ (Wm}^{-1}\text{C}^{-1}\text{)}$$

where $Q = I^2R'$ is the heat produced per unit time and unit length of the probe heating element; I is the current and R' is the resistance per centimeter of the heating element; $S = \Delta T/(\log(t_2/t_1))$ is the slope of the temperature versus the logarithm of time curve and ΔT is the temperature rise (or drop) during the time interval (t_2-t_1) . Comparison of the mean values of thermal conductivity for the fine-grained Ottawa sand, obtained from our three probes and the standard value obtained by Slusarchuk and Foulger (1973) using the guarded hot plate apparatus is considered satisfactory for our purpose (Table 4-2).

TABLE 4-2

Measured Thermal Conductivity, λ , of Air-Dry Fine Ottawa Sand

Probe No.	No. of Trials	Mean Thermal Conductivity (Wm ⁻¹ C ⁻¹)	Standard Deviation	Ratio of Measured λ to the Standard Value, λ_s Obtained Using the GHP
I	8	.245	8.08×10^{-5}	0.806
II	10	.254	2.50×10^{-4}	0.837

TABLE 4-2 (continued)

III	8	.283	8.71×10^{-5}	0.931
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*GHP-Guarded Hot Plate: $\lambda_{\text{GHP}} = 0.304 \text{ Wm}^{-1} \text{ C}^{-1}$ (Slusarchuk and Foulger, 1973)

Once the probes were checked and calibrated, they were ready for thermal conductivity determinations of rocks. Ideally, the cylindrical probes are suited for soft rock thermal conductivity determinations, where the probes can simply be inserted into the sediments and measurements taken. However, in our case, we had a number of hard rock cores which required thermal conductivity determinations. 8.9 cm cores are available from the Arbuckle Group, but in order to carry out such analyses we need a core length of at least 40 cm, which is not easy to obtain. One procedure that can be followed to overcome such problems would be crushing the core into fine rock chips and then compacting them to the core bulk density in a cylinder where probe would be inserted. However, such procedure was not followed since we noticed that many of the available core lengths matched almost perfectly and that the core lengths were such that only two core pieces would more than compensate for the necessary core length. Therefore, we decided to combine two well-fitting core lengths and with a masonry bit drilled a hole through the center of the core of exactly the same diameter as the stainless steel probe tube. Such cores were very slowly saturated with water by inserting them into a cylinder and slowly introducing water from its bottom.

A sample result of such measurements is shown in Figure 4-3 for an air-

dry dolomite core from the Arbuckle Group (33S/19W-CD, Comanche County; depth interval 1970.2-1983.9 m) and for the same core under saturated conditions in Figure 4-4. The results are very satisfactory, well within the range of values reported by Blackwell and Steele (Chapter 3, this report) on similar Kansas rocks.

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FIGURE CAPTIONS

- FIGURE 4-1: Sample calibration run for thermal conductivity measurement of air-dry fine-grained Ottawa sand.
- FIGURE 4-2: Sample calibration run for thermal conductivity measurement of water-saturated fine-grained Ottawa sand.
- FIGURE 4-3: Sample thermal conductivity measurement of air-dry dolomite core.
- FIGURE 4-4: Sample thermal conductivity measurement of water-saturated dolomite core.

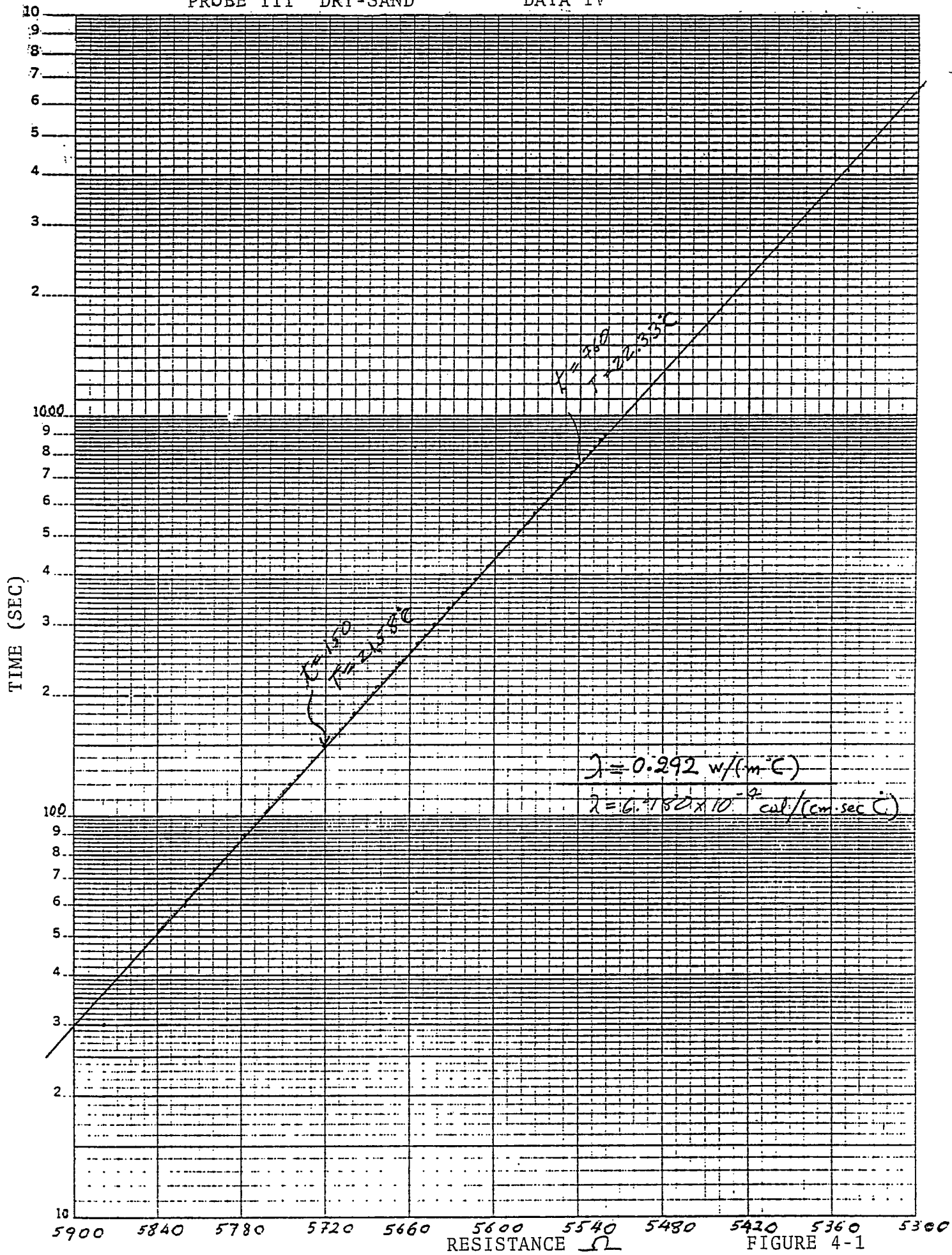


FIGURE 4-1

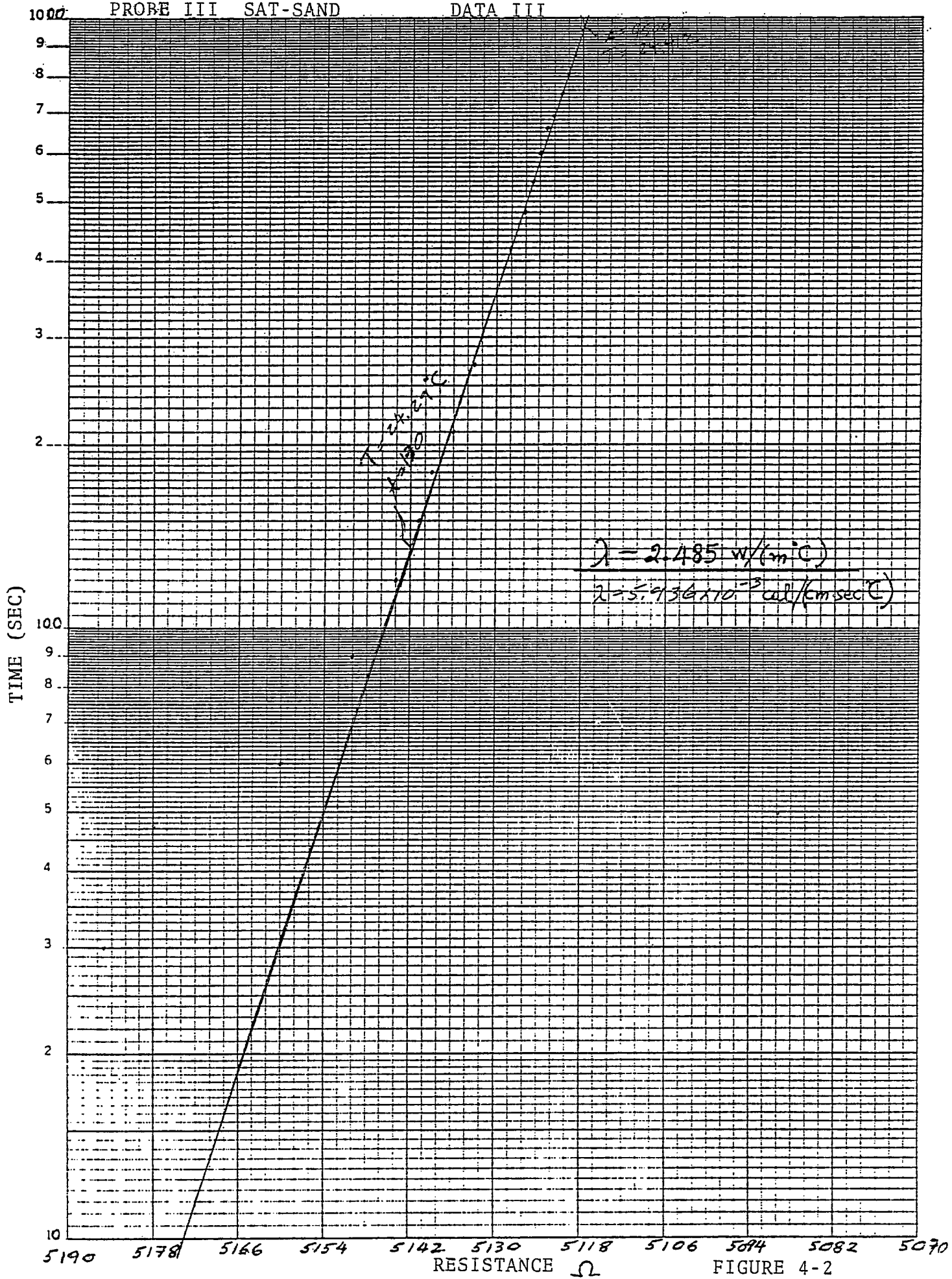


FIGURE 4-2

PROBE III DRY-CORE @32V

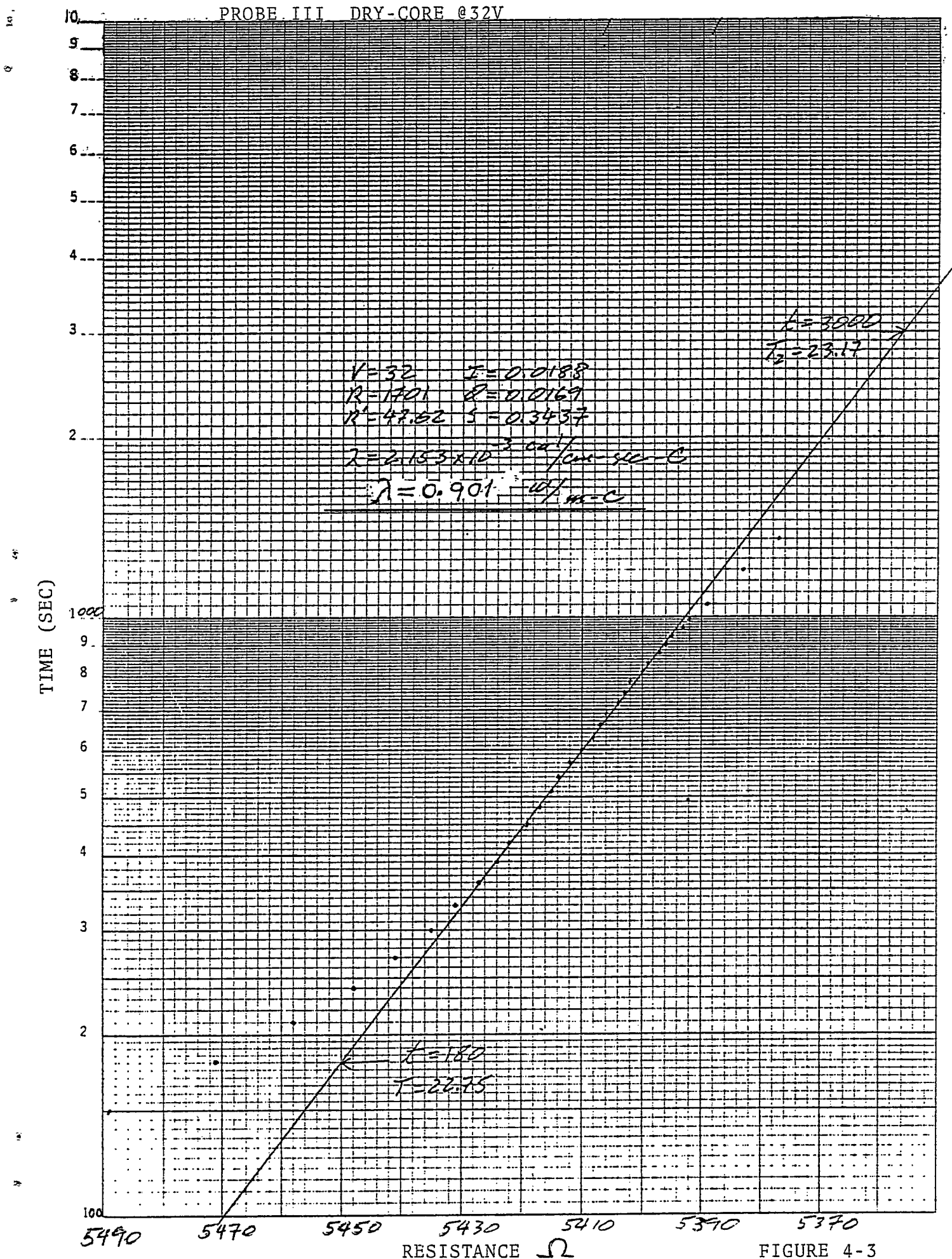


FIGURE 4-3

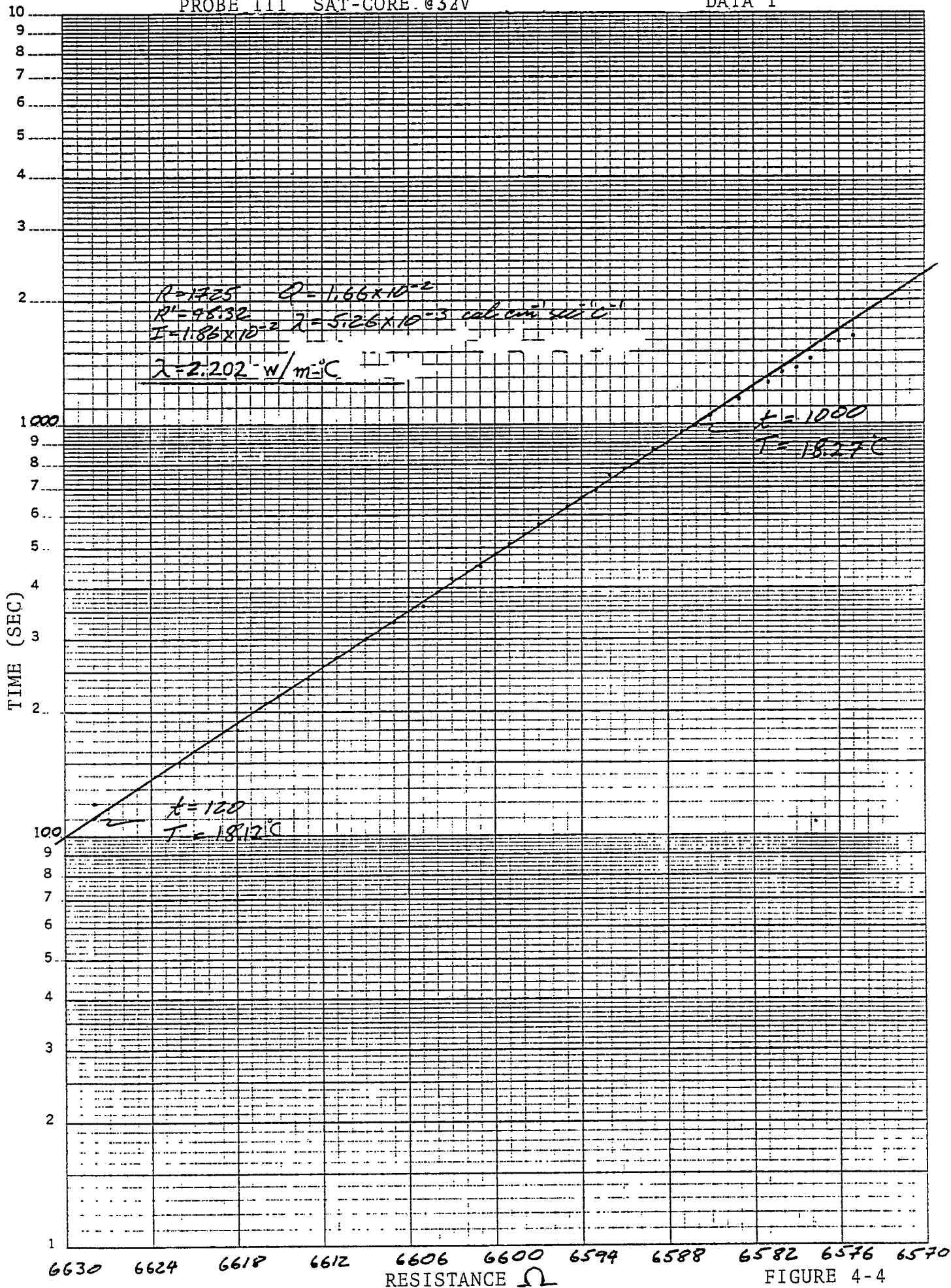


FIGURE 4-4

KGS
OF
82-22

REGIONAL INTERPRETATION OF KANSAS AEROMAGNETIC DATA

by

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INTRODUCTION

The Kansas Geological Survey (KGS) has recently completed a regional aeromagnetic survey of the state. This report documents the aeromagnetic mapping techniques used and presents a qualitative regional interpretation of the magnetic basement. The total intensity magnetic field contour map and some spectrally filtered magnetic maps are used in the interpretation. This study is a compilation and extension of earlier preliminary reports (Yarger, 1979, 1980 and 1981; Yarger et al, 1976, 1977 and 1978; Robertson et al, 1978). It is expected that more detailed studies of some of the larger anomalies, which make use of quantitative modeling and other interpretation schemes, will appear in future reports.

In addition to information presented in this report on basement composition and paleotectonics, the magnetic data should eventually prove useful for a variety of purposes such as petroleum, mineral and geothermal exploration, earthquake hazard evaluation, and other scientific studies. Sedimentary rocks that contain petroleum are essentially nonmagnetic. However, sedimentary rocks are usually underlain by magnetic basement rocks that

produce magnetic anomalies. Magnetic data are sometimes useful for determining relief on the basement surface that may be directly related to structure favorable for accumulation of gas and oil in overlying sedimentary rocks. Regional aeromagnetic data can be used to estimate the depth to the bottom of the magnetic portion of the crust and thus to map the Curie isotherm surface. Regions of thin magnetic crust are promising areas for geothermal exploration. Recent research has indicated that some continental earthquakes in the U.S. occur near boundaries of large mafic igneous intrusions within the basement (McKeown, 1978). Aeromagnetic data provide an effective tool for locating and defining the boundaries of these mafic bodies.

BACKGROUND

The earth's main magnetic field is approximated fairly well by postulating a strong permanent bar magnet at the center of the earth inclined 11.5° from the geographic north-south axis. However, this explanation is highly unlikely since the temperature at the center is much too hot for any known material to be permanently magnetized. Therefore, different mechanisms that produce a field equivalent to that produced by a bar magnet, a dipole field, have been postulated. The theory best accepted, but not proven, is that of a self exciting hydrodynamic dynamo within the metallic liquid core of the earth which generates a large electric current much like dynamos in commercial power plants do (see for example, Stevenson, 1981).

Near surface crustal rocks, which are cool enough to be permanently magnetized, slightly distort the earth's main field. Measurement of the distortion of the main field yields information on the magnetic source rocks within the crust. The main field strength in the northern mid-latitudes is

typically 50,000 gammas (0.5 Oersted). Magnetic field strengths from crustal sources are typically hundreds of gammas and rarely exceed several thousand gammas so that the distortion of the main field by the magnetic crust is usually less than one or two per cent.

Magnetic methods have had a long and successful history of mapping the earth's crust for both basic and applied scientific objectives. Recent development in the past decade of more sensitive magnetometers capable of absolute measurements and digital recording have opened new vistas for magnetic exploration of the earth. Approximately fifty per cent of the U.S. is covered by available magnetic surveys conducted by federal agencies, states and academic institutions. Additional areas covered by private industry surveys are generally not available in the public domain. Probably less than ten per cent of the existing U.S. coverage is of high enough quality to glean maximum potential information from the data (Hinze, 1976). The specifications used in the Kansas aeromagnetic survey fall in this elite category.

DATA AQUISITION

Measurements of the total intensity of the earth's magnetic field were made with a Geometrics model G-806 proton precession magnetometer modified for airborne use. This instrument has a ± 1 gamma sensitivity and a two second sampling rate (since completion of the regional survey this instrument has been modified to ± 0.25 gamma sensitivity and one second sampling rate). The magnetic sensor, housed in an aerodynamically stabilized "bird", is trailed 30 meters behind the Twin Beech model D-18 aircraft used in flight operation. Other major components of the magnetometer system are a Geometrics model G-704 Data Aquisition System, a Cipher model 70 digital magnetic tape

recorder, a Sperry model RA-227 radar altimeter, an Automax model G-2 35mm camera with a 30 meter film magazine, and a solid state intervalometer designed by KGS personnel. This system digitally records on magnetic tape, at two second intervals, the magnitude of the total magnetic field, time, ground clearance, camera fiducial number and other bookkeeping information. The 35mm camera is triggered by the magnetometer at a rate appropriate for continuous or near-continuous coverage of the flight path. The fiducial number and time are recorded simultaneously on film and magnetic tape for subsequent correlation of flight path coordinates with magnetic field measurements.

Eastern Kansas was flown during the summer of 1975 and summer and fall of 1976. Western Kansas was flown during the summers of 1977, 1978 and 1979. In both eastern and western Kansas the flight lines were approximately 340 kilometers in length and were flown east or west with tie lines, approximately 345 kilometers in length, were flown north or south. The flight lines were spaced 3.2 kilometers (2.0 miles) apart. The tie lines were spaced 32 kilometers apart. In eastern Kansas the airplane was flown at a fixed barometric elevation of 762 meters (2500 feet) above sea level. In western Kansas the flight elevations were 915 meters (3000 feet) above sea level in the eastern portion and 1372 meters (4500 feet) above sea level in the westernmost quarter of the state. U.S. highway 283, which runs north-south through western Kansas was used as a visual landmark signal to the pilot to change elevations while flying the east-west flight line. The ground clearance, which averaged 366 meters (1200 feet), was measured by the radar altimeter and recorded on magnetic tape along with magnetic

measurements. Navigation was accomplished by visual siting along section roads. The northernmost flight line is located 1.6 kilometers (one mile) north of the Kansas-Nebraska border and the southernmost flight line is located 1.6 kilometers south of the Kansas-Oklahoma border. Normally a crew of three, the pilot, navigator and equipment operator, flew in the plane. As a back-up to the flight path camera, the navigator recorded the time the plane passed over predesignated checkpoints spaced along the flight line every 15 to 30 kilometers. During flight a 24 BCD (binary coded decimal) character record was digitally recorded on magnetic tape with a 7 track, 556 bits/inch tape drive.

To avoid excessive magnetic fluctuation due to solar wind disturbance, the magnetic activity k index (Lincoln, 1967) reported from the World Data Center A (NOAA) in Boulder, Colorado was required to be ≤ 3 before flight takeoff. For $k = 4$ or 5 the magnetic field was monitored on the ground for at least one half hour before takeoff. If the noise did not exceed ± 1 gamma the flight went as scheduled. For $k \geq 6$, flight was cancelled.

DATA REDUCTION

After each flight all records on the magnetic tape were edited for obvious noise and illegal characters. The original unedited data were saved on a permanent summary tape. The flight path film was used to identify landmarks spaced 10 to 15 miles apart on 1:125,000 scale county road maps. The longitude and latitude coordinates of landmarks (fiducial points) were digitized on a ± 0.001 inch x, y digitizing table and saved on digital tape. The fiducial coordinates tape was then merged with the magnetic field tape for final assignment of longitude and latitude to all magnetic measurements.

The resulting flight path map is presented in Figure 5-1.

The International Geomagnetic Reference Field (IGRF) 1975 was calculated at each measurement location at the appropriate epoch and subtracted from the total intensity.

The diurnal drift was removed by analysis of the tie line-flight line intersection mismatches of magnetic field values. This procedure, which does not require a recording base station, assumes diurnal drift during flight is a smoothly varying low order polynomial in time. The polynomial coefficients were determined by minimizing magnetic field residuals at flight line-tie line intersections (for further detail see Yarger, et al, 1978). Before least squares adjustment, the intersection residuals were "corrected" by searching for the minimum intersection residual within a 150 meter radius, the estimated uncertainty in the flight path recovery procedure, from the originally calculated intersection location. After 5th order adjustment to tie lines and flight lines the residuals were normally distributed about zero with an RMS of approximately 2.0 gammas. This residual distribution is adequately narrow to permit contouring at contour intervals of 5 gammas and greater.

A master grid for the state was prepared with 0.16 km (0.1 mile) east-west spacing and 3.2 km (2 mile) north-south spacing which is nearly equivalent to the original measurement spacing. The grid was determined by shifting magnetic field values from quasi-straight flight lines to nearby grid lines. The overall grid location was determined by minimizing (in the least squares sense) the difference between grid lines and the flight line coordinates. this procedure, which takes advantage of a regular grid flight line pattern

avoids smoothing that normally occurs when done by the available computer algorithms written primarily for arbitrary spaced data. The master grid, which represents the residual total intensity magnetic field, is useful for machine contouring over a wide range of scales and contouring intervals. It is also useful for most quantitative analyses since the gridding procedure preserved the original integrity of the data. Figure 5-2 presents the aeromagnetic map contoured by a CALCOMP contouring program at an original scale of 1:500,000 and 50 gamma contour interval.

SPECTRAL FILTERING

BACKGROUND

Several spectrally filtered versions of the original contour map (Figure 5-2) are used in this regional interpretation. The purpose of filtering a map is to remove certain unwanted characteristics and to enhance desirable characteristics depending on the interpretation objective. Because of the simple mathematical form most potential field filters have in the spectral domain, it is advisable to transform the original unfiltered map to the spectral domain, apply the filters, then transform the filtered map back to the spatial domain for use in interpretation (Gunn, 1976).

A suite of spectrally filtered magnetic maps has proven useful in this study of Kansas basement composition, paleotectonics, and age terranes. Certain composite filters reveal basement influence on the magnetic field, not readily apparent in the original contour map.

An ordinary contour map, where the contoured variable is a function of spatial coordinates, is said to be in the spatial domain. In Figure 5-2 the magnetic field, $M(x,y)$, is a function of the spatial coordinates x,y . The

units of x,y are in kilometers (or miles). The map, M(x,y), in the spatial domain was transformed into a map, M(u,v), in the spectral domain using the Fast Fourier Transform (FFT) algorithm (Singleton, 1969) where u,v are the orthogonal spectral domain coordinates. The units of u,v are in cycles/kilometer (or cycles/mile). After applying various filter combinations to the map, M(u,v), in the spectral domain, the resulting filtered maps were transformed back to the spatial domain.

Cycles/kilometer refers to magnetic highs and lows per kilometer. The characteristic frequency, $[u^2 + v^2]^{-1/2}$, of a positive (or negative) anomaly in $[2 \times \text{anomaly width}]^{-1}$. For example, an anomaly of width one-half kilometer has a characteristic frequency of one cycle/kilometer. For further discussion of spectral filtering see Nettleton (1976).

FILTER APPLICATION

The State was divided into two equal 216x216 grids for input into the FFT program. The grid cell size was approximately 1.6 kilometer on a side. The filtered maps were compiled using a variable black and white density scale instead of the more traditional contour lines. This format was chosen for several reasons. Density maps are considerably more cost efficient and time efficient to produce. Some of the filtered maps have a large dynamic range (i.e., the data range from very large numbers to very small numbers) or have sharp gradients which are difficult to contour. And finally, density maps make it much easier for the reader to see relative magnitudes.

A suite of seven filtered maps, which appear to be useful in enhancing basement features, are presented in Figures 5-3 through 5-9. These represent a subset of a much larger suite of filtered maps originally examined. The

filtered maps were derived from a combination of two or more filters presented in Table 5-1.

Figure 5-3 presents a map reduced to the pole and downward continued to 760 meters above sea level. Reduction to the pole removes the distortion caused by the earth's inclined magnetic field direction (which is approximately 65° from the horizontal in Kansas). This results in a slight migration to the north of anomaly locations and increases, in some cases, anomaly amplitudes. The western half of the map was downward continued to 760 meters above sea level which makes it comparable to the eastern half which was flown at 760 meters above sea level. This operation relates all anomaly magnitudes and gradients to the same base level of 760 meters above sea level. This is not the case for the original contour map in Figure 2 where anomaly magnitudes and gradients are somewhat attenuated in western Kansas relative to eastern Kansas because of the different flight elevations. In the remainder of the text all maps that have been downward continued to the eastern flight elevation of 760 meters above sea level are referred to as "leveled" maps. To summarize, Figure 5-3 is the same as Figure 5-2 except that it has been corrected for the earth's inclined field and for differences in flight elevation.

Figure 5-4 presents an aeromagnetic map reduced to the pole and upward continued to 9 kilometers above sea level. This map emphasizes deep seated long wavelength magnetic sources within the crust.

Figure 5-5 presents an aeromagnetic map reduced to the pole, and downward continued to 850 meters below sea level which corresponds roughly to the average elevation of the Precambrian surface. This map emphasizes magnetic

sources at or near the Precambrian surface.

Figure 5-6 presents an aeromagnetic map reduced to the pole, leveled and high frequency pass filtered. This filter passed all frequencies above 0.8 cycles/kilometer and attenuated lower frequencies. The attenuation function used, which is linear in radial-frequency, was $1.25[u^2 + v^2]^{1/2}$. This map emphasizes anomalies due to magnetic sources at or near the Precambrian surface to a greater extent than does the downward continued map (Figure 5-5). Note that negative amplitudes are not displayed in Figure 5-6. All amplitudes below +5 gammas appear as white. This choice was made to enhance several statewide magnetic trends evident in the original maps displaying the full spectrum of negative and positive amplitudes. There were no significant trends with negative amplitudes that are not also apparent in the positive amplitudes. Negative amplitudes in Figures 5-7 through 5-9 were also suppressed for the same reason.

Figure 5-7 presents an aeromagnetic map reduced to the pole, leveled, high pass filtered and trend pass filtered. This map is the same as Figure 6 except that an additional filter has been applied which passes anomalies trending northeast $\pm 45^\circ$. This map emphasizes anomalies due to magnetic sources at or near the Precambrian surface and also trending northeast $\pm 45^\circ$.

Figure 5-8 is the complement of Figure 5-7 and emphasizes anomalies due to sources at or near the Precambrian surface and also trending northwest $\pm 45^\circ$. Note that the simple addition of Figure 5-8 to Figure 5-7 would yield the original high pass filtered map in Figure 5-6.

Figure 5-9 presents the aeromagnetic map reduced to pole, leveled and the second vertical derivative calculated. This map emphasizes near-vertical

contacts between contrasting magnetization at or near the Precambrian surface.

REGIONAL INTERPRETATION OF AEROMAGNETIC DATA

BACKGROUND

Major variations in total magnetic field strength at or near the land surface are normally due to lateral changes in magnetic susceptibility of basement rock. Overlying sedimentary rocks have relatively low magnetic susceptibilities. Susceptibility is proportional to the amount of magnetite in the rock (Clark, 1966). The amount of magnetite in rock, to a rough approximation, is inversely proportional to silica content. For a given source rock volume and depth of burial, mafic rocks such as gabbro and basalt will produce larger magnetic anomalies than silicic rocks such as granite and rhyolite.

The relative total intensity magnetic map (Figures 5-2 and 5-3) depicts a rather complex crustal magnetization pattern in eastern Kansas. The dynamic range of the total magnetic field is almost 2000 gammas. The contour levels vary from 450 to 2350 gammas with an average value of approximately 1200 gammas. The base level of the map was established by arbitrarily adding 1500 gammas after subtraction of the IGRF from the absolute total intensity. Relative to the IGRF, the magnetic field in Kansas is anomalously low by some 300 gammas. If the IGRF accurately describes the large scale magnetic field intensity in the Midcontinent, then the net magnetization of the crust in Kansas is slightly below average.

DEPTH TO MAGNETIC BASEMENT

Comparison of the magnetic patterns (Figures 5-2 and 5-3) with the Pre-

cambrian relief map (Figure 5-10) reveals little obvious correlation. The Humboldt Fault, which has in some places over 600 meters of vertical displacement, is only weakly discernable. The correlation can be seen in the alignment of magnetic contours along the fault. This is evident in southern Nemaha, northern Pottawattomie and Waubaunsee Counties. The influence of the vertical displacement can also be seen in southern Morris County where the fault trace splits the north-northwest trending anomaly. The horizontal gradient of the anomaly on the high side (west side) of the fault is steeper than the gradient on the low side. It follows that the source rock for the anomaly was probably emplaced before vertical displacement along the fault took place. The presence of this anomaly across the fault also suggests that there has been no major (less than 500 meters) strike-slip movement along the fault. The difference of 50 gammas in magnitude of this anomaly on either side of the fault suggests that most Precambrian relief features in eastern Kansas will have less than a 50 gamma influence on the total magnetic field. This is normally the case in areas where the crystalline basement has a fairly thick sediment cover (see for example, Steenland, 1965). Most of the observed field is due to intrabasement rock lying below the Precambrian surface and above the depth corresponding to the Curie Point isotherm, which is normally 30 to 40 km below sea level. Suprabasement features such as relief and thin lenses of crystalline rock at the surface contribute only a small part to the observed field. Suprabasement anomalies are characterized by small magnitudes with sharp horizontal gradients and short wavelengths superimposed on large intrabasement anomalies with gentle horizontal gradients and longer wavelengths. Although not considered in this report, suprabasement anomalies are often useful

for estimating depth to basement (Chapter 15, Nettleton, 1976).

BASEMENT TERRANES

The total intensity aeromagnetic maps (Figures 5-2 and 5-3) exhibit a northwest trending grain consistent with the Precambrian surface terrane (Figure 5-10), which is interrupted in northeastern Kansas by a northeast trending linear positive anomaly flanked by adjacent linear negative anomalies. (The positive anomaly, caused by CNARS rocks of gabbroic composition, will be discussed in a later section.) The CNARS anomaly appears to terminate in central Kansas against a roughly linear trend of negative anomalies. This negative trend is defined by a near-continuous band across the state defined by total intensity amplitude <1200 gammas. The most prominent low is centered over Wichita with negative anomalies of lesser magnitude continuing west beyond the Colorado border. This trend can also be traced into Missouri (Missouri Geological Survey, 1943). The southern boundary of this band is clearly visible in the high frequency passed filtered map (Figure 5-6). This boundary corresponds to a fairly sharp magnetization contact suggesting contrasting rock types. This apparent contrast may correspond to a distinct boundary between the older mesozonal granitic terrane to the north and the younger epizonal granitic terrane to the south. This "spectral" boundary is caused by an abrupt attenuation of high frequency signal, from south to north, and presumably corresponds to the onset of the southern edge of the mesozonal granitic terrane or to some kind of transition zone between the two basement terranes. The northern boundary of the transition zone is not so sharply defined. Outside the CNARS the width of the transition zone varies from 25 to 50 km. The zone may correspond to

foundered granitic rock overlain by a Precambrian sedimentary or metasedimentary wedge. Alternatively, it could be a band of nonmagnetic granitic basement. The high frequency signal north of the transition zone and outside of CNARS appears similar to that of the southern terrane. The second vertical derivative map (Figure 5-9) emphasizes near vertical contacts between contrasting magnetizations. The boundary, which is clearly outlined in the high frequency pass filtered map (Figure 5-6), is not as prominent in the second vertical derivative map. Certain portions, however, are enhanced such as the southern edge of the Wichita low and areas in western Kansas. The boundary is also discernable in the upward continued map (Figure 5-4), which emphasizes the deep seated magnetic character of the crust.

INTRUSIVES

The extreme northeastern portion of the aeromagnetic map (Figures 5-2 and 5-3) shows a series of strong positive, roughly circular anomalies with diameters of approximately 15 km. Basement cores from two of these anomalies, located in Douglas and Miami Counties^{*}, yielded U/Pb zircon ages of about 1350 m.y. (Steeple and Bickford, 1981). Although these rocks are more coarse grained than rocks in the southern terrane, they are clearly epizonal granite and related to them (Bickford et al, 1981). The Miami County core^{*} contains about 2 per cent magnetite by weight (Steeple and Bickford,

* Referred to by township-range location in Blackwell and Steele, Chapter 5; by Department of Transportation County Code in Stavnes, Chapter 2; and by town near where hole is located in Kodama, Chapter 6.

1981), which may account for the positive magnetic anomalies. The close similarity of the circular magnetic anomalies makes it probable that most, if not all, of them are caused by intrusive bodies similar to those drilled in Douglas and Miami Counties. This suggests that the 1625 m.y. terrane in northeastern Kansas and northwestern Missouri is peppered with isolated shallow granite plutons, possibly related to the 1400 m.y. granitic terrane to the south, but younger by some 50 m.y. This series of circular magnetic highs along with similar highs in Missouri (Missouri Geological Survey, 1943) roughly track the boundary of the southern half of the Forest City Basin. These mid-Proterozoic granitic plutons may have been intruded along a zone of weakness that later influenced the formation of the late-Proterozoic Forest City Basin.

There are also at least six major near circular anomalies in western Kansas, five of which are closely associated with the granitic terrane boundary discussed previously. Over the entire state there are at least five circular intrusive bodies just to the north of the terrane boundary (Figure 5-6). These could possibly be the remnants of volcanic centers associated with Precambrian plate convergence along this boundary.

THE CENTRAL NORTH AMERICAN RIFT SYSTEM

The pervasive influence the Central North American Rift System had on the Kansas crust is perhaps best seen in Figure 5-7. This map, which emphasizes high frequency anomalies trending northeast, indicates that the rift system extends south across the entire state.

A magnetic quiet zone, the predominantly white area in Figure 5-7, surrounds the magnetic high along the mafic belt and corresponds to a basin

filled with clastic rocks, presumably of Keweenawan age. The magnetic quiet zone is due to the extreme depth to magnetic basement, presumably granite, which foundered during the extensional phase of the CNARS. Both the eastern and western boundaries of this Keweenawan basin are fairly sharply defined, suggesting that they may be fault bounded.

The magnetic lineations to the southwest of the magnetic quiet zone, which are the most prominent in Figure 5-9, probably correspond to block faulting and possibly mafic dike intrusion that occurred during the initial stage of rifting.

Apparently the rift in southern Kansas did not progress beyond the stage of block faulting and dike intrusion, whereas the rift in northern Kansas developed to a more mature stage of volcanic flows followed by foundered crust and clastic deposits. The fracture system in southern Kansas is probably representative of the crust throughout the CNARS during the early stages of rifting, before upwelling of Keweenawan volcanics occurred. This southwest-trending system indicates that the CNARS extends into Oklahoma.

The Humboldt Fault Zone (Figures 1-3, 1-4 and 5-10), which borders the eastern side of the Nemaha Ridge, closely parallels the CNARS across the state, suggesting that this apparent post-Mississippian fault may be a reactivated CNARS fault. This Proterozoic forerunner of the Humboldt Fault may have developed within the easternmost part of the CNARS crust that was not involved in subsequent foundering. Alternatively, the Humboldt Fault Zone may be a zone of Pre-Keweenawan crustal weakness that has been reactivated, or it may not have formed until Paleozoic time.

POSSIBLE BASEMENT FAULTS

The trend pass filtered maps (Figures 5-7 and 5-8) reveal significant magnetic lineations in both the northeast and northwest directions. The most prominent northeast linear trends correspond to the rift system through central Kansas, but there are also a number of northwest trends outside the rift, particularly in northwestern Kansas. Figure 5-8 exhibits northwest magnetic linears extending over large parts of the state, substantially interrupted however within the rift zone. This, of course, implies that the northwest grain is older than the rift.

Figure 5-11 presents the magnetic linears appearing in Figures 5-7, 5-8, and 5-9 superimposed on the Precambrian relief map. Determining what constitutes a magnetic linear trend is very subjective. The linears shown in Figure 5-11 represent what I consider "middleground". Another researcher, depending on his criteria and biases could easily identify more or fewer linears from the same maps. The linears I have chosen are at least 50 km long or belong to a trend of shorter segments at least 50 km long.

In addition to suites of northeast and northwest trending linears across the state (seen in Figure 5-11), there is a third suite of linears located primarily in southern Kansas that trend east-northeast.

Figure 5-11 reveals that the number of magnetic linears far outnumbers the heretofore mapped faults in the Precambrian. There are, however, a number of one-to-one correlations.

The northern half of the Humboldt Fault Zone, which borders the eastern side of the Nemaha Ridge, shows up clearly as a continuous magnetic linear. The northwest trending magnetic linear in Rush County matches the southwest

bounding fault of the Rush Rib. This fault (Merriam, 1963) lies along the postulated Precambrian age boundary (Figure 5-6) discussed earlier. There is also good correlation with the northeast trending fault segments in western Reno and Pratt Counties. The fault through Ellsworth County, which trends northwest along the southwest side of the Ellsworth Anticline, apparently serves as the northern boundary for several of the southwest trending magnetic linears within the rift zone.

The northwest trending fault in Pawnee County coincides with a magnetic trend that continues to the northwest up into Rush County. Part of the southwest trending fault bounding the northwest side of the Voshell Anticline coincides with a short magnetic linear at the intersection of McPherson, Reno and Harvey Counties.

Although the northwest trending magnetic grain in eastern Kansas parallels the Precambrian surface grain, there is little one-to-one correlation with mapped faults. One exception to this is the fault through Bourbon and Linn Counties which coincides with a magnetic trend that continues northwest into Anderson and Osage Counties.

Whether all magnetic linears correspond to basement faults is an open question. The fact that some of them correspond to known faults strongly implies that at least some of the remaining linears must also correspond to unmapped faults. The northeast trending magnetic linears within the rift zone surely must correspond to faulting in Keweenawan time. The post-Mississippian movement along the Humboldt Fault is most likely a reactivation of a Keweenawan rift fault.

Microearthquake results for the last four years (Steeple, 1980) indi-

cate that the Humboldt Fault Zone is still active. The northeastern magnetic trend through Washington, Republic and Cloud Counties, which corresponds to the postulated boundary between the rift sediments (Rice Formation) and the older granitic terrane, is seismically active (Figure 5-12). There is slight evidence (two events) that the eastern boundary between the rift sediments and granitic terrane is also seismically active. The only other significant recent seismic activity recorded within the state is located in Barber County and may be related to the southwest magnetic trend through Harper and Barber Counties.

SUMMARY AND DISCUSSION

The recently compiled aeromagnetic map of Kansas is proving to be very useful in studying the composition and paleotectonics of the Precambrian crust. Examination of the magnitudes and gradient of the total intensity magnetic field map and a suite of spectrally filtered maps coupled with existing geologic information, has yielded the following regional interpretation of the Precambrian crust in Kansas.

The postulated Precambrian terranes are summarized in Figure 5-13. There appears to be a rather distinct boundary between the northern 1625 m.y. old mesozonal granitic terrane and the southern 1400 m.y. old epizonal granitic and rhyolitic terrane, whose magnetic signature is a series of nearly contiguous lows trending west cross the state. The southern boundary of this band of lows is sharply defined by steep horizontal gradients and short wavelengths. The magnetic source of this band is not clear. Gravity measurements in this region, which are being taken by the KGS, along with potential field modeling should help to clarify this.

Drilling results from two of the 14 circular magnetic highs in northeastern Kansas suggest that the older 1625 m.y. old crust in northeastern Kansas is pockmarked with younger, 1350 m.y. old granitic plutons similar in composition to the southern, 1400 m.y. old terrane of epizonal granite and rhyolite. The one to two per cent magnetite, by weight, found in the two basement cores may account for the positive magnetic anomalies whose magnitudes range from 500 to more than 1000 gammas.

The CNARS extends through Kansas and probably into Oklahoma. Although it is clear that large volumes of mafic volcanics did not reach the Proterozoic surface in southern Kansas, there is strong magnetic evidence for block faulting and possible dike intrusion normally associated with initial stages of continental rifting. The extreme southern portion of the 1100 m.y. old rift that extends into the 1400 m.y. old crust in Kansas did not evolve into the more mature stages of deep rift valley formation accompanied by voluminous volcanics and clastics as did the main part of the rift to the north.

There are three main suites of magnetic linears of basement origin. Predominantly northwest trending linears are found in southeastern and northwestern Kansas, whereas central Kansas is dominated by north-northeast trending linears associated with the CNARS. Both of these trends are present in south central Kansas resulting in a system of roughly orthogonal intersecting linears. A third suite of east-northeast trending linears are present in southern Kansas.

Several of the magnetic linears correspond to previously mapped basement faults suggesting that at least a small fraction of the remaining linears

correspond to heretofore unknown faults. These remaining linears must be examined by other geophysical methods to establish which ones are faults.

The Humboldt Fault Zone, bounding the eastern side of the Nemaha Uplift, parallels the CNARS system suggesting that it may have developed in Keweenawan time and was reactivated in late Paleozoic time. Recent microearthquake results in Kansas indicate that the Humboldt Fault is still active. There is also some activity along two other magnetic linears within the CNARS.

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FIGURE CAPTIONS

- FIGURE 5-1: Flight paths for aeromagnetic map of Kansas.
- FIGURE 5-2: Aeromagnetic contour map of Kansas. Contour interval is 50 gammas.
- FIGURE 5-3: Aeromagnetic map reduced to pole and downward continued to 760 meters above sea level.
- FIGURE 5-4: Aeromagnetic map reduced to pole and downward continued to 9 kilometers above sea level. (The continuous line delineates a possible deep seated paleoplate boundary within the crust. The dashed lines outline the possible deep seated boundaries of the CNARS.)
- FIGURE 5-5: Aeromagnetic map reduced to pole and downward continued to 850 meters below sea level.
- FIGURE 5-6: Aeromagnetic map reduced to pole, leveled and high pass filtered. (The continuous line delineates a sharp high frequency boundary within the crust. Also delineated are shallow intrusive plutons.)
- FIGURE 5-7: Aeromagnetic map reduced to pole, leveled, high pass filtered and trend pass filtered northeast $+45^{\circ}$. (The continuous lines outline the suggested near Precambrian surface boundaries of the main part of the CNARS and the southern extent of the Rice Formation.)
- FIGURE 5-8: Aeromagnetic map reduced to pole, leveled, high pass filtered and trend pass filtered northwest $+45^{\circ}$.
- FIGURE 5-9: Aeromagnetic map reduced to pole, leveled and second vertical derivative calculated. (The continuous lines outline the suggested boundaries of the Keweenawan gabbros and the location of the Humboldt Fault Zone.)
- FIGURE 5-10: Configuration of the top of Precambrian rocks in Kansas. After Cole (1976).
- FIGURE 5-11: Magnetic lineations. (The lineations, which are superimposed on Figure 5-10, were derived from Figures 5-2 and 5-5 through 5-9.)
- FIGURE 5-12: Microearthquakes in central Kansas. After Steeples (1980). (Microearthquakes are superimposed on central part of Figure 5-9.)
- FIGURE 5-13: Precambrian terranes in Kansas. (Inferred from magnetic data and age data of Bickford et al, (1981).)

FLIGHT PATHS FOR AEROMAGNETIC MAP OF KANSAS

H. Yarger, R. Robertson, J. Martin, K. Ng, R. Sooby, and A. Wrenland

OPEN FILE SEPT. 1, 1993

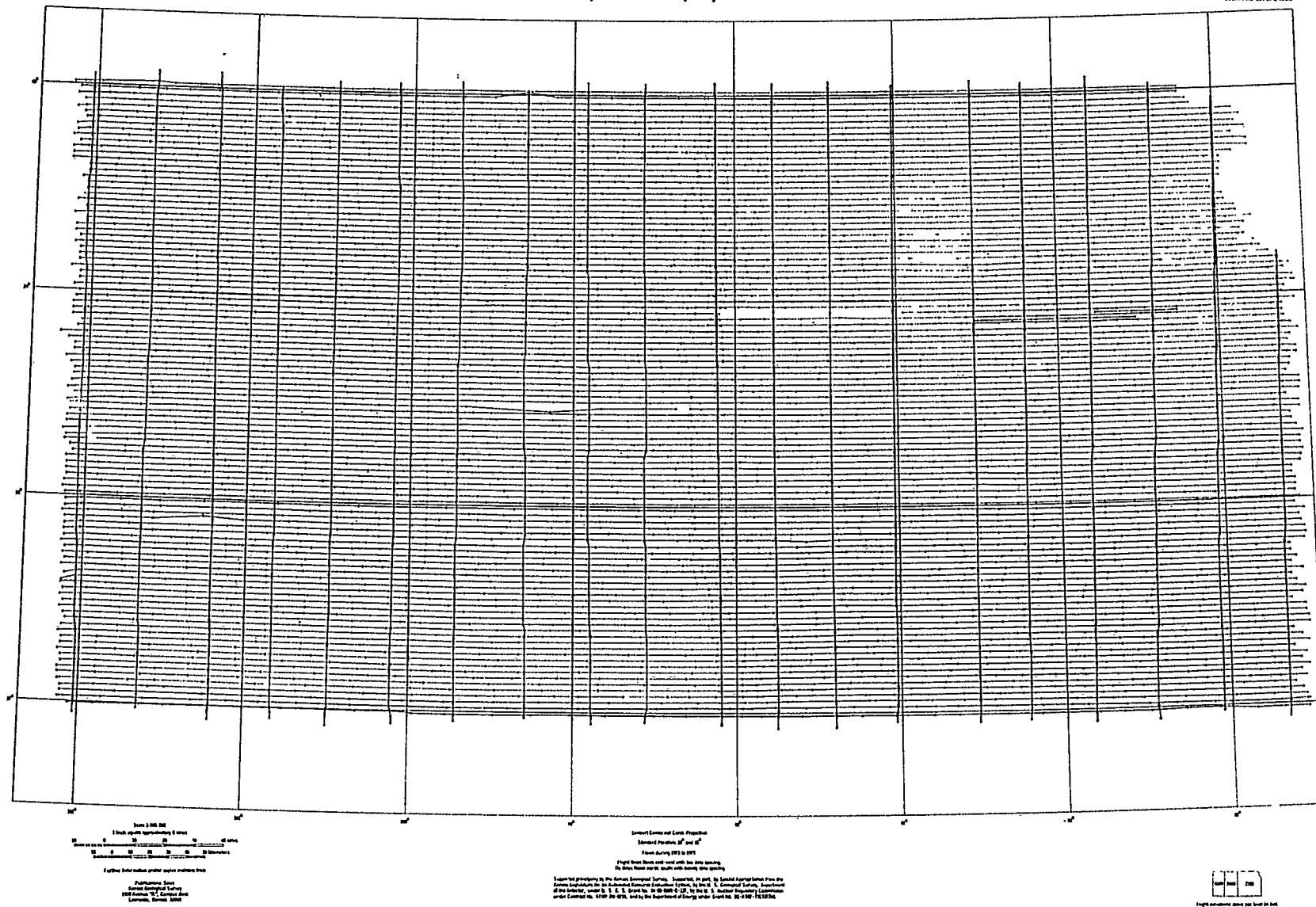


FIGURE 5-1

AEROMAGNETIC MAP OF KANSAS

H. Yarger, R. Robertson, J. Martin, K. Ng, R. Sooby and R. Wentland

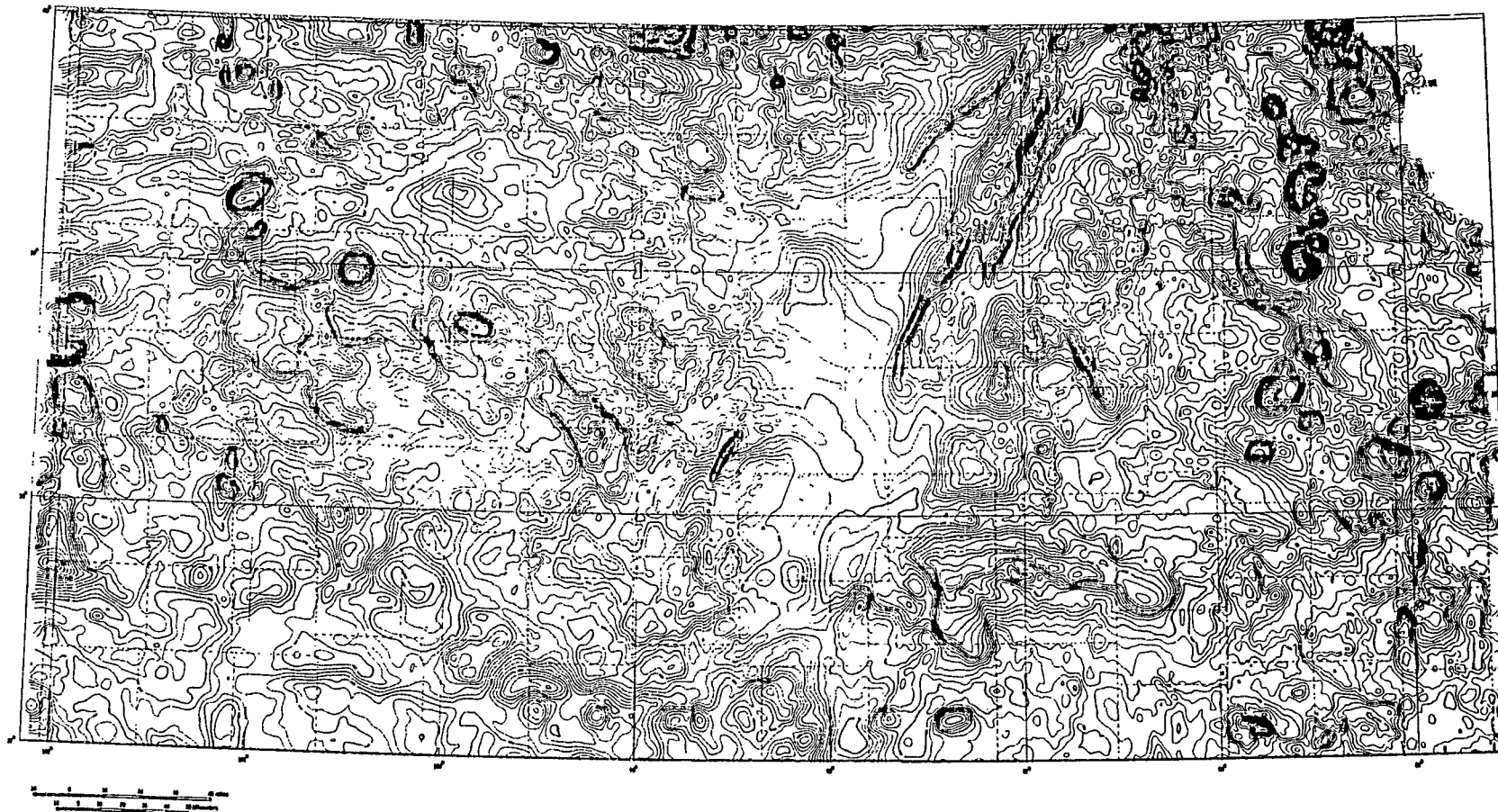


FIGURE 5-2

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND DOWNWARD CONTINUED TO 760 METERS ABOVE SEA LEVEL

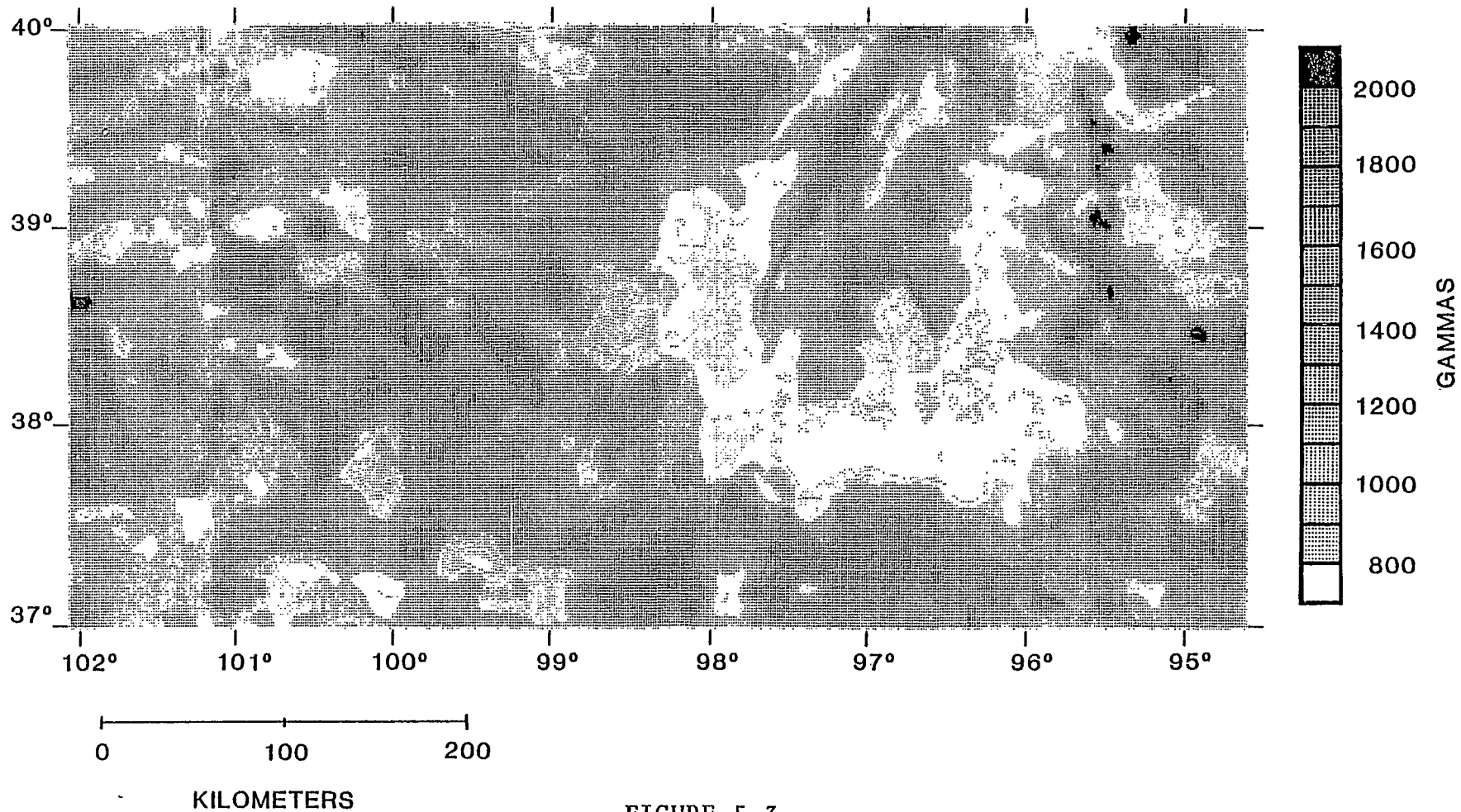


FIGURE 5-3

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND UPWARD CONTINUED TO 9 KILOMETERS ABOVE SEA LEVEL

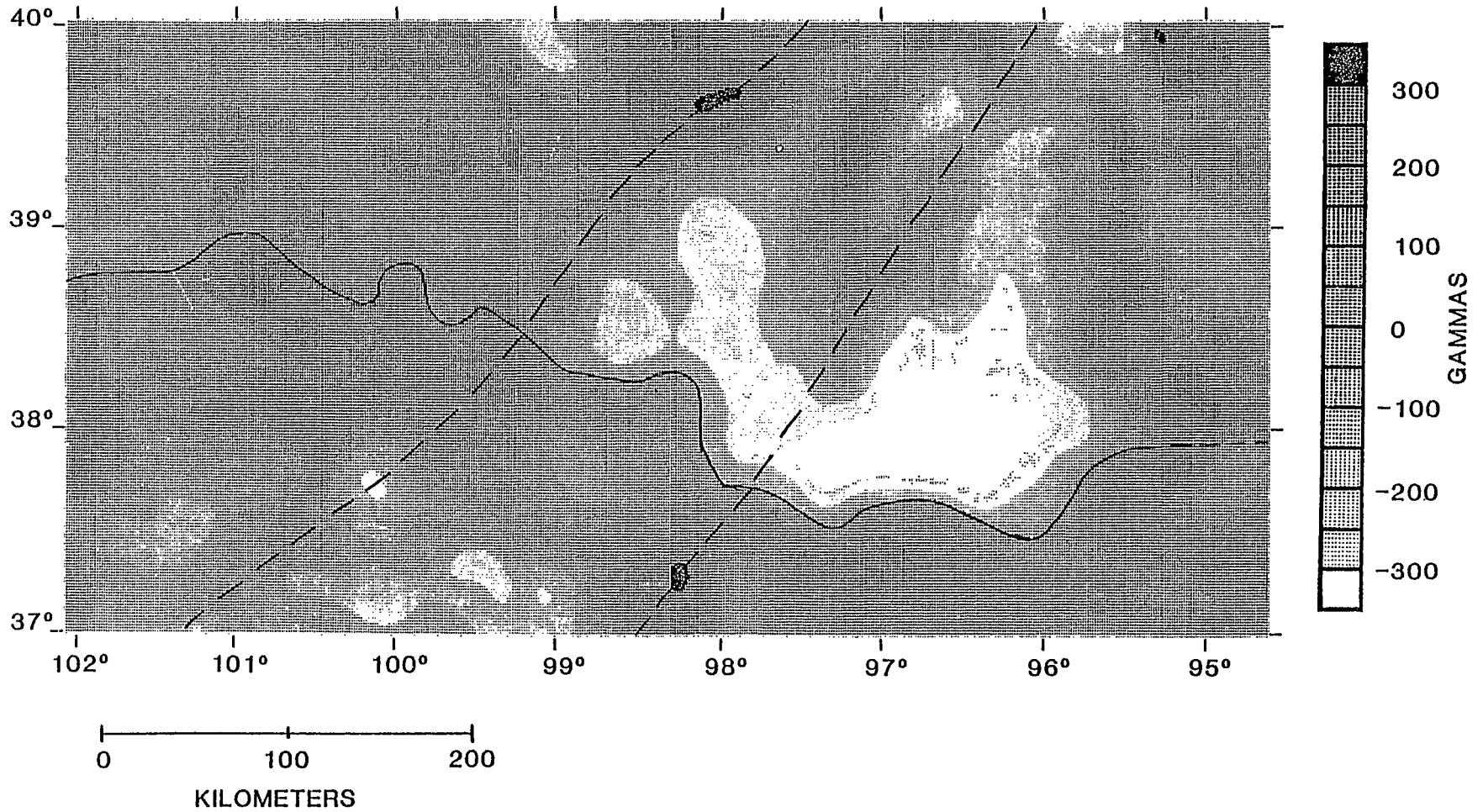


FIGURE 5-4

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND DOWNWARD CONTINUED TO 850 METERS BELOW SEA LEVEL

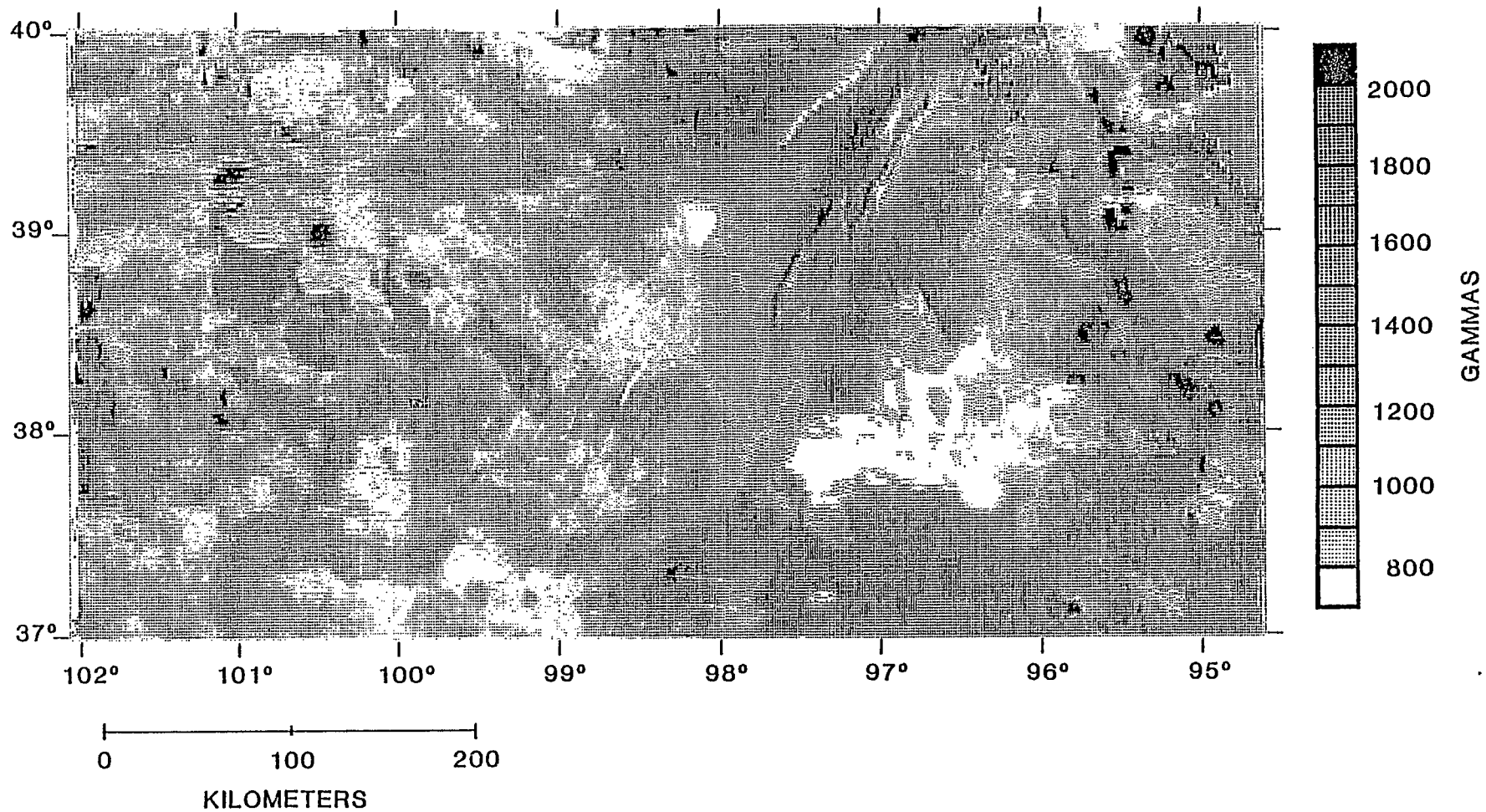


FIGURE 5-5

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND HIGH FREQUENCY PASS FILTERED

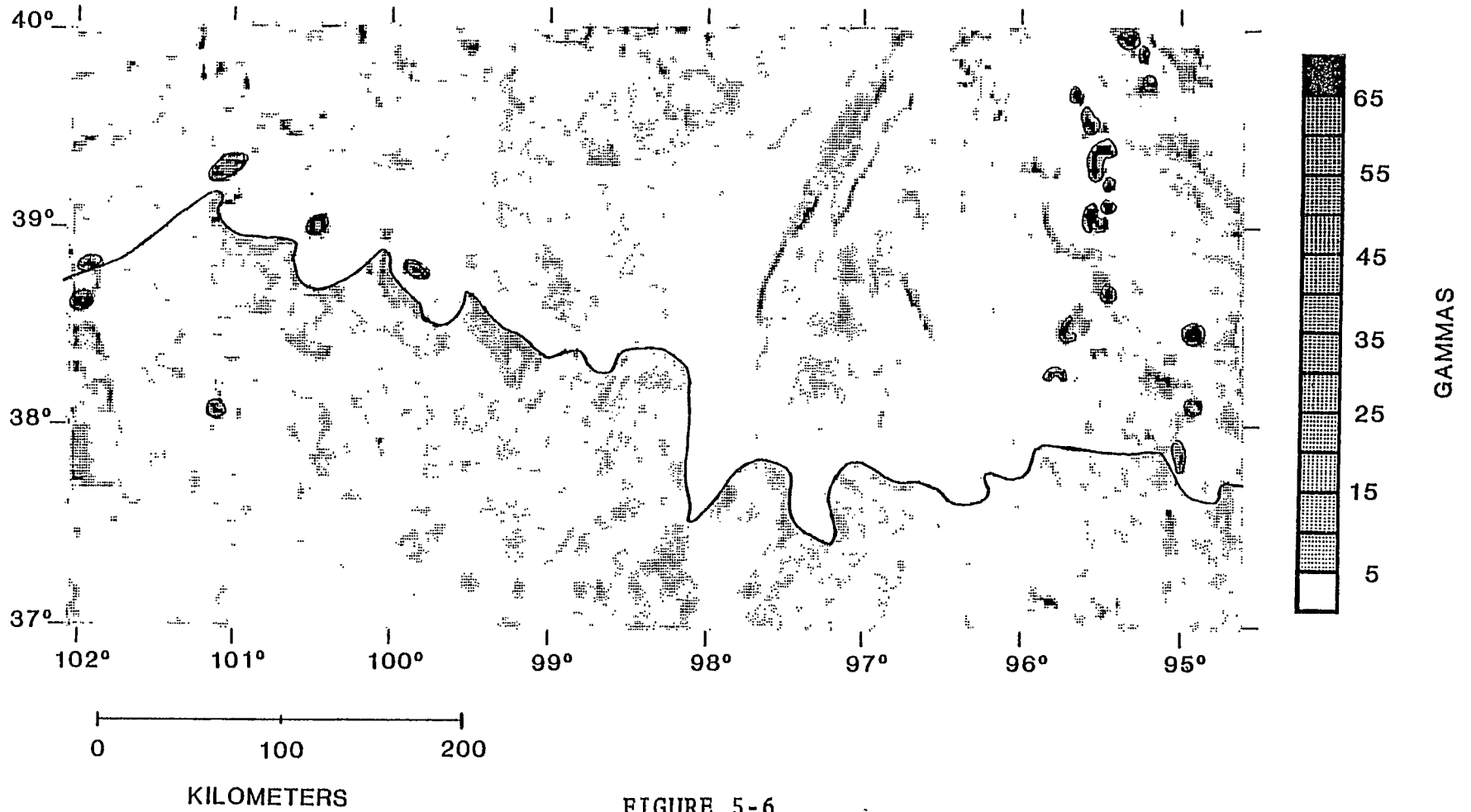


FIGURE 5-6

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND TREND PASS FILTERED NORTHEAST $\pm 45^\circ$

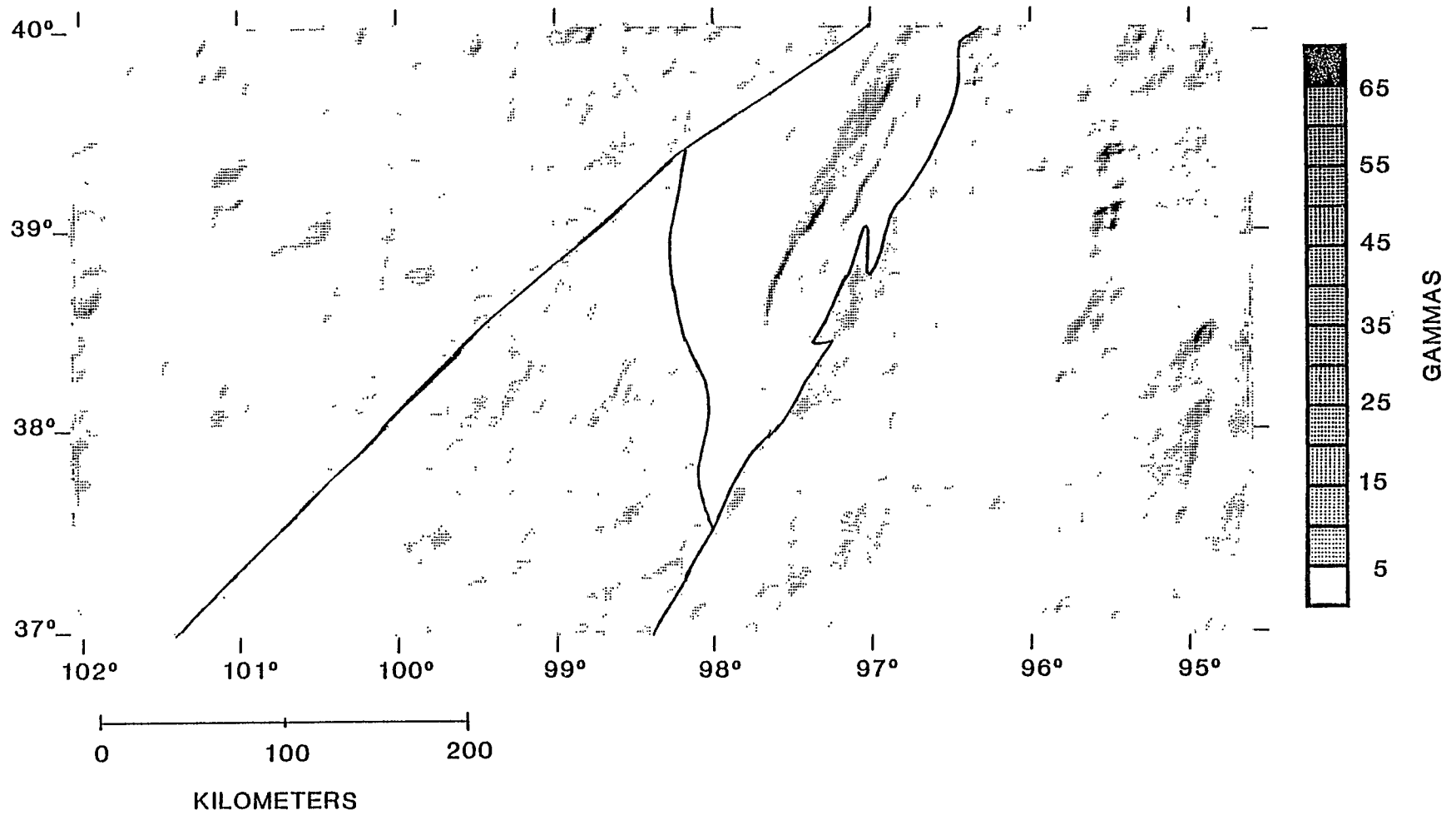


FIGURE 5-7

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND TREND PASS FILTERED NORTHWEST $\pm 45^\circ$

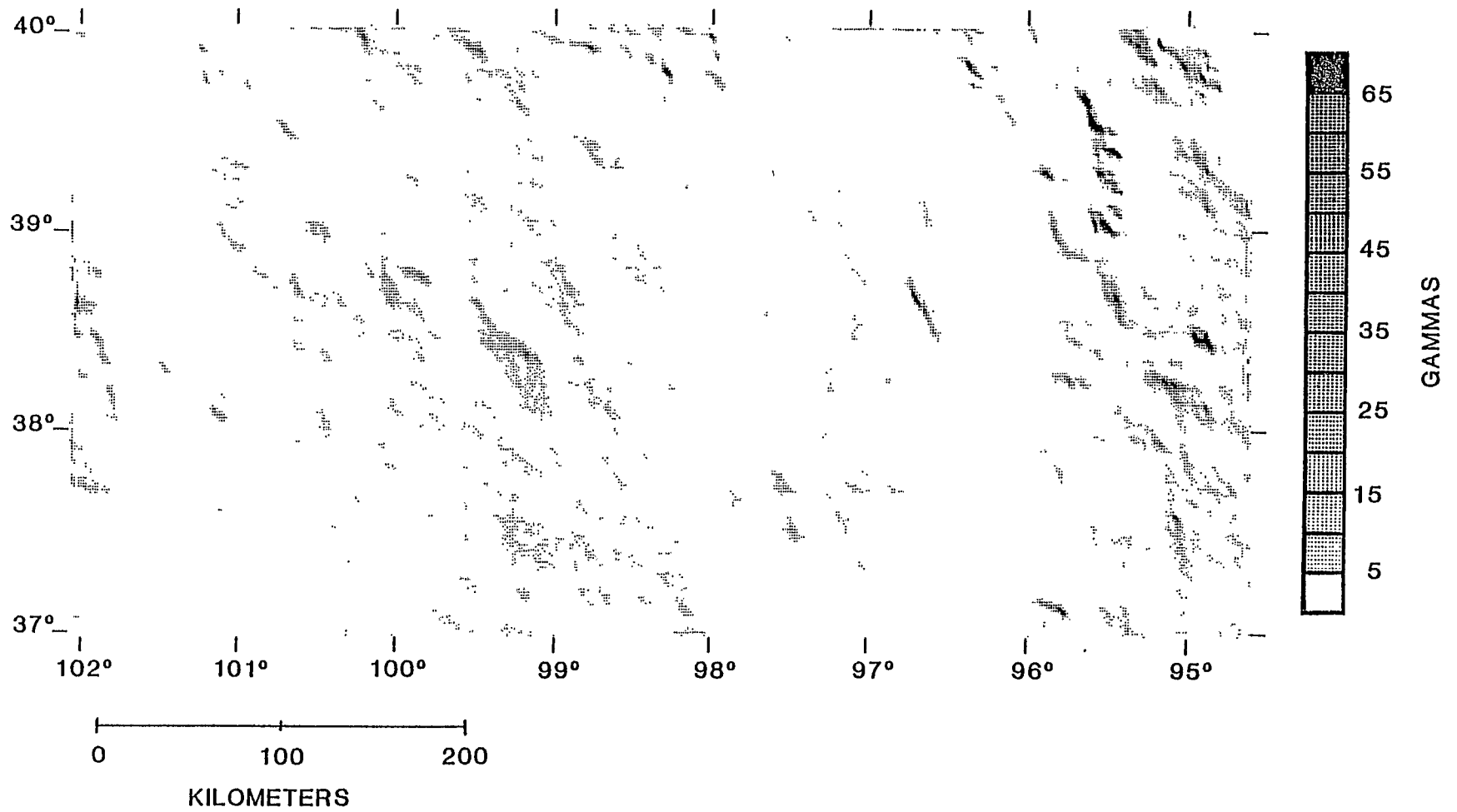


FIGURE 5-8

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND SECOND VERTICAL DERIVATIVE TAKEN

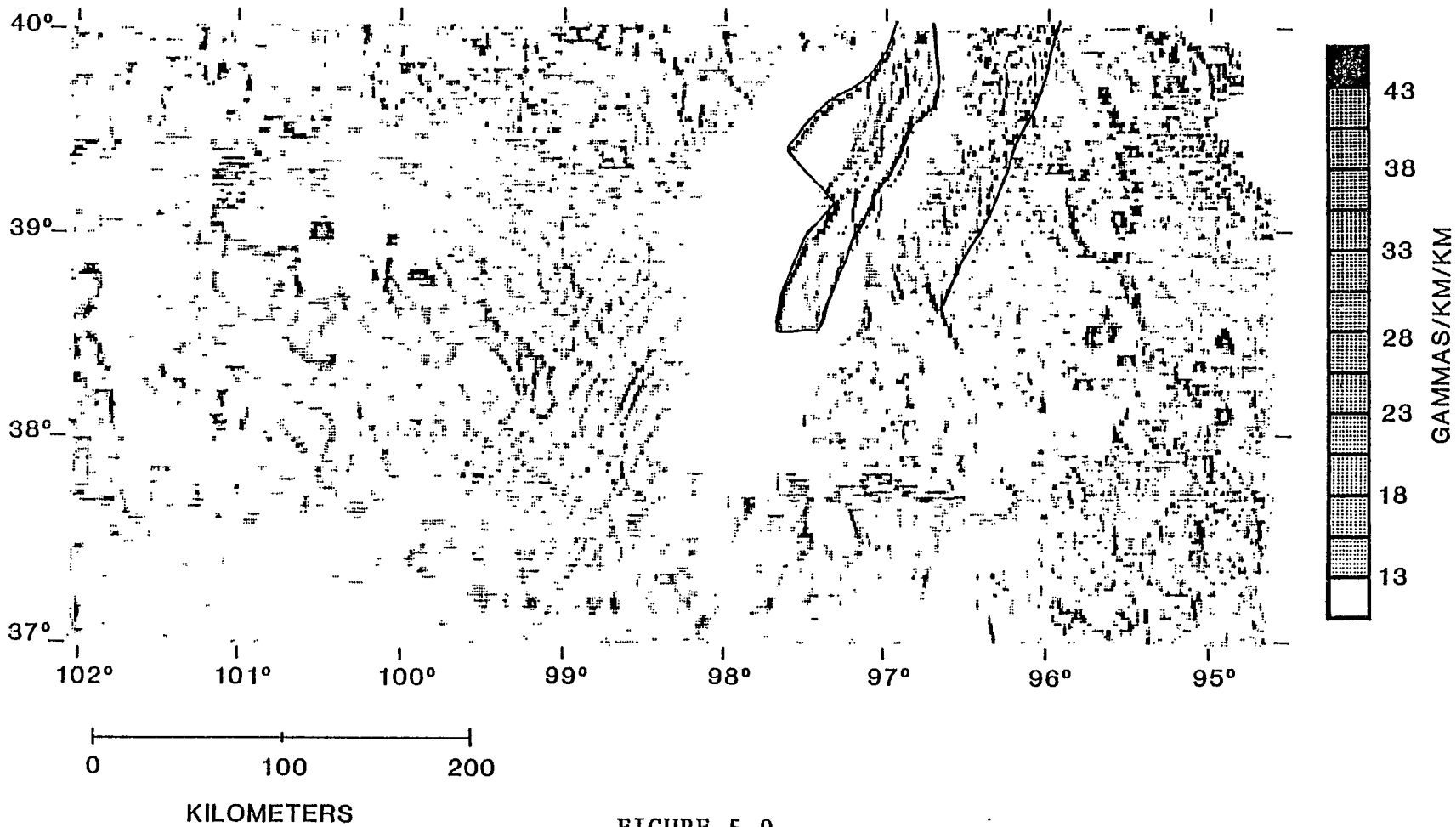


FIGURE 5-9

CONFIGURATION OF THE TOP OF PRECAMBRIAN ROCKS IN KANSAS

Wright B. Cole
1978

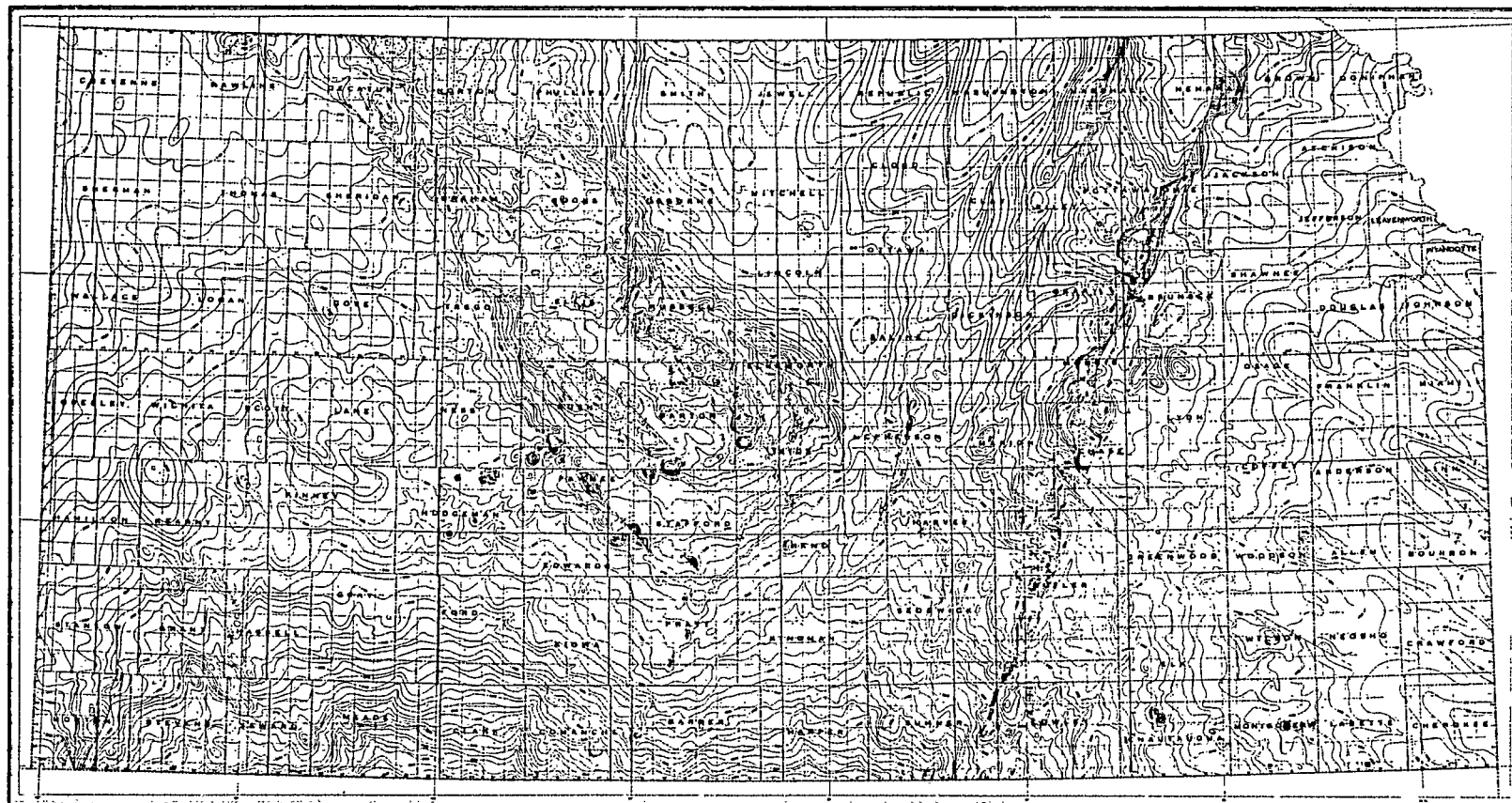
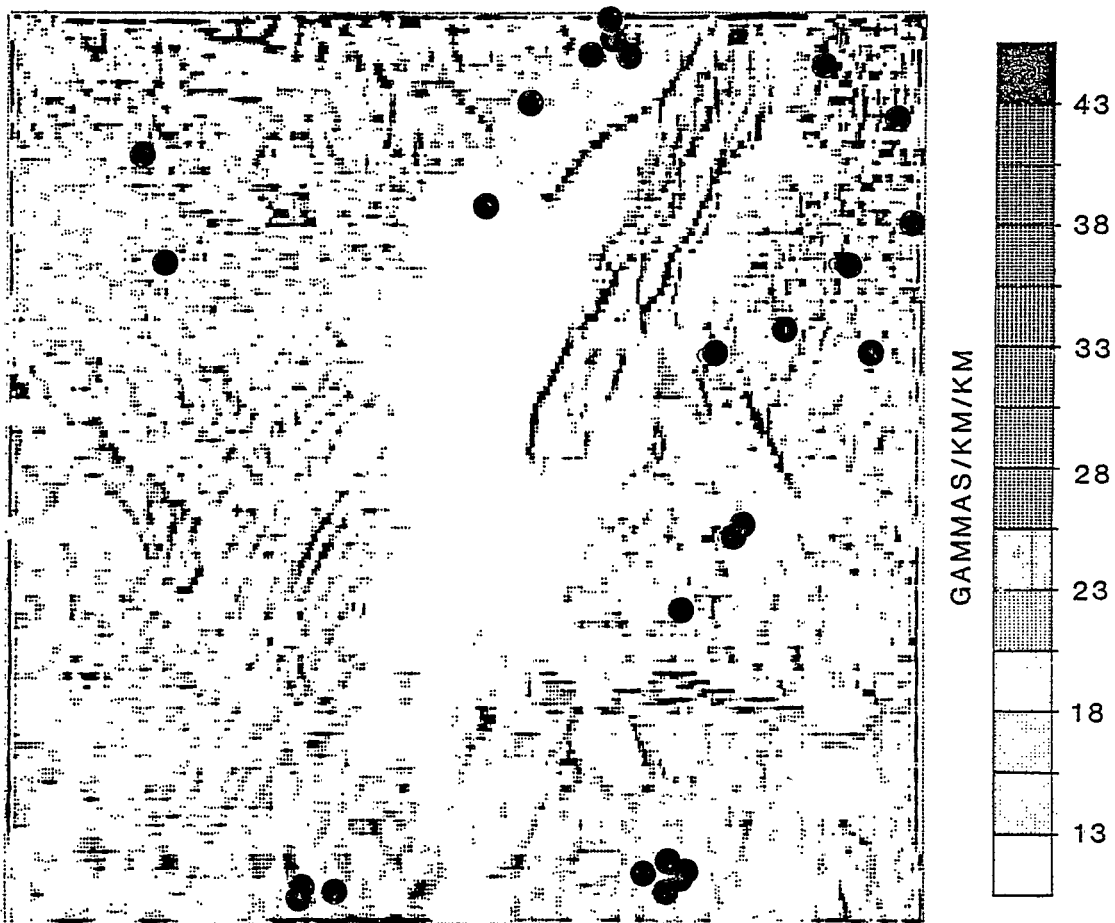


FIGURE 5-10

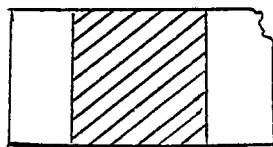
AEROMAGNETIC MAP OF CENTRAL KANSAS

Reduced to pole and second vertical derivative taken







● Microearthquakes


8/18/77 to 6/30/80



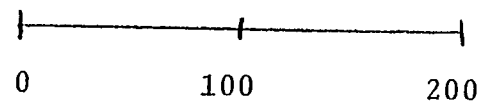
Index Map

FIGURE 5-12

-  Mesozonal granite (1625 my)
-  Epizonal granite (1400 my)
-  Gabbro (1100 my)
-  Arkosic sandstone (1100 my)

 Epizonal granitic intrusives
(1350 my - based on two
drill holes in eastern Kansas)

----- Boundary of rift system



KILOMETERS

PRECAMBRIAN TERRANES

FIGURE 5-13

TABLE CAPTIONS

TABLE 5-1: Spectral filters applied to Kansas Aeromagnetic Data.

TABLE 5-1

<u>Spectral Filter Name</u>	<u>Function</u>	<u>Result</u>
Reduction to the Pole	Removes the effect of the earth's inclined magnetic field.	Improves the resolution and location of anomalies, particularly along north-south direction.
Downward Continuation	Recalculates the magnetic field at elevations below flight elevation.	Enhances anomalies due to near-surface sources.
Upward Continuation	Recalculates the magnetic field at elevations above flight elevation.	Enhances anomalies due to deep-seated sources.
High Frequency Pass	Attenuates low frequency (long wavelength) signals and passes high frequency (short wave length) signals.	Enhances anomalies due to near-surface sources.
Trend Pass	Removes spectral surface trends outside selected directions, passes trends within selected directions.	Enhances anomalies trending in selected directions.
Second Vertical Derivative	Calculates second vertical derivative of the magnetic field.	Delineates near-vertical magnetic contacts.

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

by

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INTRODUCTION

In December 1979 the Kansas Geological Survey drilled into the Precambrian age basement rocks at an aeromagnetic high located near Osawatomie, Kansas. In March 1980 the Precambrian basement rocks were drilled at another aeromagnetic high near Big Springs, Kansas. Nine independently oriented samples from the Osawatomie core* and four independently oriented samples from the Big Springs core* were provided to this laboratory for magnetic studies. The primary motivation for the magnetic studies was to determine if the Precambrian age basement rocks were magnetic enough to produce the observed total field anomalies. Natural remanent magnetization (NRM) intensities measured for these rocks average 2.79×10^{-3} emu/cm³ ($\sigma = 1.41 \times 10^{-3}$ emu/cm³) for the Osawatomie core and 5.53×10^{-4} emu/cm³ ($\sigma = 2.92$

* Referred to by township-range location in Blackwell and Steele, Chapter 3; by Department of Transportation County Code in Stavnes, Chapter 2; by County in Yarger, Chapter 5.

$\times 10^{-4}$ emu/cm³) for Big Springs core. These rocks, based on their NRM intensities, are comparable in magnetic strength to a basalt (Nagata, 1961). The NRM directions from the Osawatomie core were somewhat unusual because they were nearly vertically downward (Appendix I.). Since these directions were parallel to the core axis, the possibility of a remanence acquired during drilling had to be considered. The NRM directions from the Big Springs core were not consistently vertically downward (Appendix I.).

Susceptibilities of the specimens from the Osawatomie core average 2736×10^{-6} cgs units ($\sigma = 522 \times 10^{-6}$) (Appendix I.) giving an average Konigsberger ratio of 2.0 ($\sigma = 0.79$) for these rocks. The Big Springs specimens yield an average susceptibility of 2703×10^{-6} cgs units ($\sigma = 1337 \times 10^{-6}$) (Appendix I.), but since their average NRM intensity is smaller than for the Osawatomie core the average Konigsberger ratio for the Big Springs core is 0.41.

A detailed paleomagnetic study of the samples was carried out so that their final demagnetized paleomagnetic directions could be compared to the local field directions predicted for this site by Irving and McGlynn's (1976) apparent polar wander path for the North American Precambrian. Radiometric age dating suggests that these rocks are 1355 m.y. (Steeple and Bickford, 1981). Based on Irving and McGlynn's (1976) apparent polar wander path for North America, Kansas would have been near the equator at this time and very shallow inclinations would be expected for these rocks (Figure 6-1).

In order to determine the stable remanent directions for these

rocks they must be magnetically cleaned by thermal and alternating field demagnetization techniques (Collinson and others, 1967, p.207-311; McElhinny, 1973). These methods remove spurious secondary magnetizations from the rocks by either randomizing the magnetizations of magnetic grains with low blocking temperatures or randomizing the magnetizations of magnetic grains with low magnetic coercivities.

The assumption made when using these techniques is that the magnetic grains with magnetizations which are stable at high temperatures or high coercivities have been stable for geologically long times ($\sim 10^9$ yrs.).

One aspect of the NRM's from the Osawatomie core which can be studied by demagnetization techniques is the steepness of the magnetic directions. If the Osawatomie samples acquired an isothermal remanent magnetization (IRM) from being exposed to highly magnetic drilling equipment, this type of magnetization would be easily removed by alternating field demagnetization (Gough, 1967; McElhinny, 1973). Alternatively, if the vertical magnetization were acquired by being exposed to a vertical field for a geologically long period of time (10^5 years or more) (in this case it would be called a viscous remanent magnetization (VRM)), it would be more easily removed by thermal demagnetization than by alternating field demagnetization (Dunlop, 1973). Although the acquisition of a vertical VRM is unlikely it should be considered as a possibility.

Ideally, when determining the paleomagnetic vector in a sample, the azimuthal and vertical orientation of the sample should be

known. In a core it is usually impossible to recover its absolute azimuthal orientation; however, a relative azimuthal orientation between pieces of the core is desirable and possible. This relative azimuthal orientation is available for the pieces of the Osawatomie core.

This laboratory has been supplied with three groups of three independently oriented samples from the top, bottom and middle of the core. Four pieces from the Big Springs core were also supplied; however, there had been no retention of the relative azimuthal orientations of these pieces. In the Osawatomie core it is possible to study variations in paleomagnetic directions along the core. This is not possible for the Big Springs core. In either core the absolute paleomagnetic declination is unrecoverable and only the paleomagnetic inclination can be used to tie into Irving and McGLynn's (1976) apparent polar wander path. This leads to some ambiguity (Figure 6-1) since an inclination of 50° , as an example, could indicate ages of 1150 m.y., 1225 m.y., 1475 m.y., 1725 m.y. or 1850 m.y. b.p. The paleomagnetic data will only indicate whether the inclination is consistent with the radiometric age and will not give an independent age for the core.

DEMAGNETIZATION DATA

Two specimens were drilled from each Osawatomie core sample, one was thermally demagnetized and one alternating field demagnetized.

Four specimens were drilled from each paleomagnetic sample from

the Big Springs core. Two of these specimens were thermally demagnetized and two were subjected to alternating field demagnetization.

THERMAL DEMAGNETIZATION

The thermal demagnetization experiments involved heating the specimens to a given temperature, cooling them in field-free space, measuring them, then repeating this procedure at progressively higher temperatures. The specimens were demagnetized in twelve steps up to 640°C (100°C, 200°C, 300°C, 400°C, 450°C, 500°C, 525°C, 550°C, 575°C, 600°C, 620°C, 640°C).

The thermally demagnetized specimens from the bottom (samples 1a, 1b, 1c) and middle (2a, 2b, 2c) of the Osawatomie core (Figure 6-2) maintain their steep inclinations up to 575°C, then they become scattered in direction. Samples from the top of the Osawatomie core (3a, 3b, 3c) (Figure 6-2) start at less steeply inclined directions and move toward shallow inclinations upon demagnetization.

The thermal demagnetization behaviour of the Big Springs specimens are different from that of the Osawatomie core specimens. In samples 1, 2, and 4 (bottom, second from the bottom, and top) the inclinations change from steep to intermediate (50° from the horizontal) with demagnetization up to 575°C. The NRM inclinations for sample 3 started at approximately 50° and remained at that inclination; however, similar to the Osawatomie core the directions are well grouped up to 575°C and then scatter above this temperature. Sample 2 is interesting since it has reversed (upward) inclinations. This could indicate a geomagnetic field reversal, but it is more likely the result of an

upside-down piece of core.

The scattering of directions above 575°C for the specimens from both the Osawatomie and Big Springs cores is very suggestive of magnetite being the main, or only, magnetic mineral in these rocks (Curie Point 580°C) (Nagata, 1961; McElhinny, 1973). This is supported by the large decrease in magnetic intensity with thermal demagnetization (Figure 6-3) above 575°C.

ALTERNATING FIELD DEMAGNETIZATION

In alternating field demagnetization experiments a specimen is exposed to an alternating magnetic field which is decreased from some peak value to zero. The sample is then measured and this procedure is repeated with the sample being exposed to progressively higher peak fields. At least one specimen from each group of three samples from the Osawatomie core and one specimen from three Big Springs samples were progressively demagnetized in 5 mT to 10 mT steps up to a peak field of 100 mT (100 mT = 1000 gauss). This treatment indicated that only one component of magnetization was present in these rocks and that it resides in grains with coercivities that range from 50 mT to 70 mT. For the remainder of the specimens progressive demagnetization was carried out only until the stable final demagnetization direction was reached at about 60 mT.

The alternating field demagnetization results for the Osawatomie core were surprisingly quite different than the thermal demagnetization data (Figure 6-4). The final AF (alternating field) demagnetization directions derived from Zijderfeld diagrams (Zijderfeld, 1967) of specimens

from Osawatomie samples 1a, 1b, 1c (bottom of the core) and samples 3a, 3b, 3c (top of the core) all clustered around an arbitrary declination of 208.4° and an inclination of -20.5° ($\alpha_{95} = 6.6^{\circ}$). The vertically downward NRM directions were completely removed above peak alternating fields of 35 mT; however, greater than 95 per cent of the original NRM intensity was also removed at these peak demagnetization fields. The final AF demagnetization directions of specimens from samples 2a, 2b, 2c were quite different from samples 1 and 3 and cluster about an arbitrary declination of 135.9° and an inclination of -19.8° with a good deal more scatter ($\alpha_{95} = 19.1^{\circ}$). This anomalous demagnetized direction and the increased scatter of specimen directions could possibly be due to a quickly changing geomagnetic field during cooling through the Curie Point suggesting a geomagnetic field excursion; however, this seems highly improbable since it is more likely that the samples 2a, 2b, 2c were not properly aligned during reconstruction of the core after it was recovered from the drill hole. Based on very simplified calculation of the cooling rate for a body of this size (Lovering, 1935) it probably took several hundred to 1000 years for a core this length (7.6 cm) to cool through the Curie Point. Since a geomagnetic excursion itself is possibly as long as several hundred to one thousand years (Liddicoat and Coe, 1979), the core may not be long enough to have a geomagnetic excursion recorded in one part of it. More core material is being supplied to check the validity of the anomalous directions from samples 2a, 2b, and 2c. Paleomagnetic directions will be measured at 0.67 m intervals down the core and shifts in declination compared to the positions where the core was

broken during drilling.

The results from the alternating field demagnetization of the Big Springs core were similar to the results from thermal demagnetization (Figure 6-5). Since we have no relative azimuthal reference down the core only inclinations can be compared. Specimens from samples 1, 3 and 4 all demagnetized to an average inclination of 50.8° at peak fields of 50 mT. Specimens from sample 2 started with NRM directions which were pointing nearly vertically upward and demagnetized to an average inclination of -48.3° . Since even very short geomagnetic reversals may be 10^5 years in length and the Big Springs core is even shorter than the Osawatomie core (2.9 m), it is unlikely that there would be enough of a time interval between the cooling of sample 1 and sample 3 (2.1 m of separation along the core) to record a geomagnetic reversal. It is more likely that sample 2 was inadvertently turned upside down during core reconstruction. However, the possibility of a short reversal being recorded in the Big Springs core is being checked by measuring samples taken from a single piece of core from between samples 2 and 3.

The decrease in intensity of the magnetization with AF demagnetization for the Big Springs core is similar to that seen for the Osawatomie core with less than 5 per cent of the NRM intensity remaining at peak fields of 50 mT.

INTERPRETATION

By plotting the progressive demagnetization data for each specimen on a Zijderveld diagram (Zijderveld, 1967) (Figure 6-6) it is possible to determine a characteristic direction for that specimen. Characteristic

directions from the Osawatomie and Big Springs specimens (Figures 6-5 and 6-7) can be used to tie into Irving and McGlynn's (1976) apparent polar wander path for the North American Precambrian (Figure 6-1).

The Osawatomie core's mean inclination, based on specimens from sites 1 and 3, is -20.5° with an alpha 95 of 6.6° . If errors in Irving and McGlynn's data are $\pm 10^{\circ}$ the Kansas site could have been far enough south of the equator to produce the Osawatomie core inclinations in a normal polarity geomagnetic field at only two times during the Precambrian, 100 m.y. b.p. and 1300 m.y. b.p. If we consider the possibility that the field was of reversed polarity during the cooling of the Osawatomie core then the core's inclinations would be consistent with ages of 1050 m.y., 1275 m.y., 1425 m.y. and 1800 m.y. on Irving and McGlynn's apparent polar wander path. Since Bickford has obtained a good radiometric date of 1355 m.y. b.p. for the Osawatomie core (Steeple and Bickford, 1981), it is more likely that the core has a normal polarity direction with ages of 1275 m.y. or 1425 m.y. The Osawatomie core's paleomagnetic directions are consistent with its radiometric age.

Assuming that sample 2 from the Big Springs core has been turned upside-down, the mean inclination for this core is 51.5° . This inclination is close to the axial geocentric dipole inclination for this latitude ($I = 57.8^{\circ}$) and could be the result of present day magnetic overprinting. However, the stability of the magnetization to both thermal and AF demagnetization probably suggests that it is the primary magnetization of the rock. If this is true an inclination of 51.5° could correspond to ages of 1150 m.y., 1225 m.y., 1475 m.y., 1725 m.y. or 1850 m.y. b.p. on Irving

and McGlynn's (1976) apparent polar wander path. The most likely interpretation of the Big Springs magnetization is that it cooled through its Curie Point at either 1225 m.y. b.p. or 1475 m.y. b.p., as close to its radiometric age of 1355 m.y. b.p. (Steeple and Bickford, 1981) as possible. The paleomagnetic data does suggest that even though the Osawatomie and Big Springs cores give the same radiometric age the paleomagnetic data indicates that their cooling times probably differ by 50 - 80 m.y.

The Osawatomie specimens have a mean NRM magnetization intensity which is five times stronger than the mean NRM magnetization of the Big Springs specimens. Alternating field and thermal demagnetization experiments suggest that the Osawatomie specimens have suffered from an IRM, possibly during drilling. Some Big Springs specimens also may have acquired an IRM, but this seems to be less of a problem in this core. If samples with steep NRM inclinations in the Big Springs core did acquire an IRM, their NRM intensities should be higher than specimens whose demagnetized directions and NRM directions are nearly the same. Apparently this may be the case (Figure 6-8). NRM's of Big Springs specimens which appear to be unaffected by the hypothesized IRM are approximately two times weaker than those which may have an IRM. Since it appears that most or all of the Osawatomie samples have been affected by an IRM their measured NRM intensities could be somewhat stronger than the NRM intensity of the rock in situ. If it can be assumed that the magnetic mineralogy of the Osawatomie and Big Springs cores are similar, then the in situ NRM intensity of the Osawatomie rocks may be one-half of

its measured value.

CONCLUSIONS

Alternating field and thermal demagnetizations studies suggest that most of the Osawatomie core samples and some of the Big Springs core samples are affected by an IRM which may have been acquired during drilling. The in situ magnetic intensity of the Osawatomie core may be somewhat less than the measured NRM intensity, although the in situ magnetization is probably strong enough to account for the observed aeromagnetic anomaly at the drill site. The Osawatomie demagnetized paleomagnetic inclinations are consistent with the radiometric age of 1355 m.y. b.p. obtained for this rock. The demagnetized directions determined for the Big Springs core suggests that is older or younger than the Osawatomie core, and that there is probably a 50 - 80 m.y. age difference between the cooling of the two cores.

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FIGURE CAPTIONS

- FIGURE 6-1: Variation of normal polarity inclination as a function of age for eastern Kansas (lat = 38.4°N ; long = 95°W); based on Irving and McGlynn's (1976) apparent polar wander path for the Precambrian.
- FIGURE 6-2: Progressive thermal demagnetization of three representative specimens from the Osawatomie core. Solid circles are lower hemisphere. Data is plotted on a stereo net.
- FIGURE 6-3: Magnetization intensity normalized by NRM intensity (J/J_0) as a function of thermal demagnetization. Note the large decrease above 575°C .
- FIGURE 6-4: Progressive AF demagnetization of three representative specimens from the Osawatomie core. Open circles upper hemisphere; solid circles lower hemisphere. Data is plotted on a stereo net.
- FIGURE 6-5: Final demagnetization directions for the Big Springs core. These directions have been devised from Zijderveld (1967) plots.
- FIGURE 6-6: Zijderveld (1967) plots for an AF demagnetized specimen from the Osawatomie core and for a thermally demagnetized sample from the Big Springs core. Note that above 40 mT the Osawatomie sample tends to trend toward the origin. This indicates a final demagnetization (characteristic) direction. This is better seen in the thermal demagnetization data from 500°C to 575°C for Big Springs specimens 1b. Note that above 575°C the data does not trend toward the origin.
- FIGURE 6-7: Final demagnetization directions (based on Zijderveld plots) for the Osawatomie core.
- FIGURE 6-8: Plot of magnetization intensity versus inclination for the Big Springs core. The data may suggest that the steep NRM inclinations are a result of an IRM acquired perhaps, during drilling.

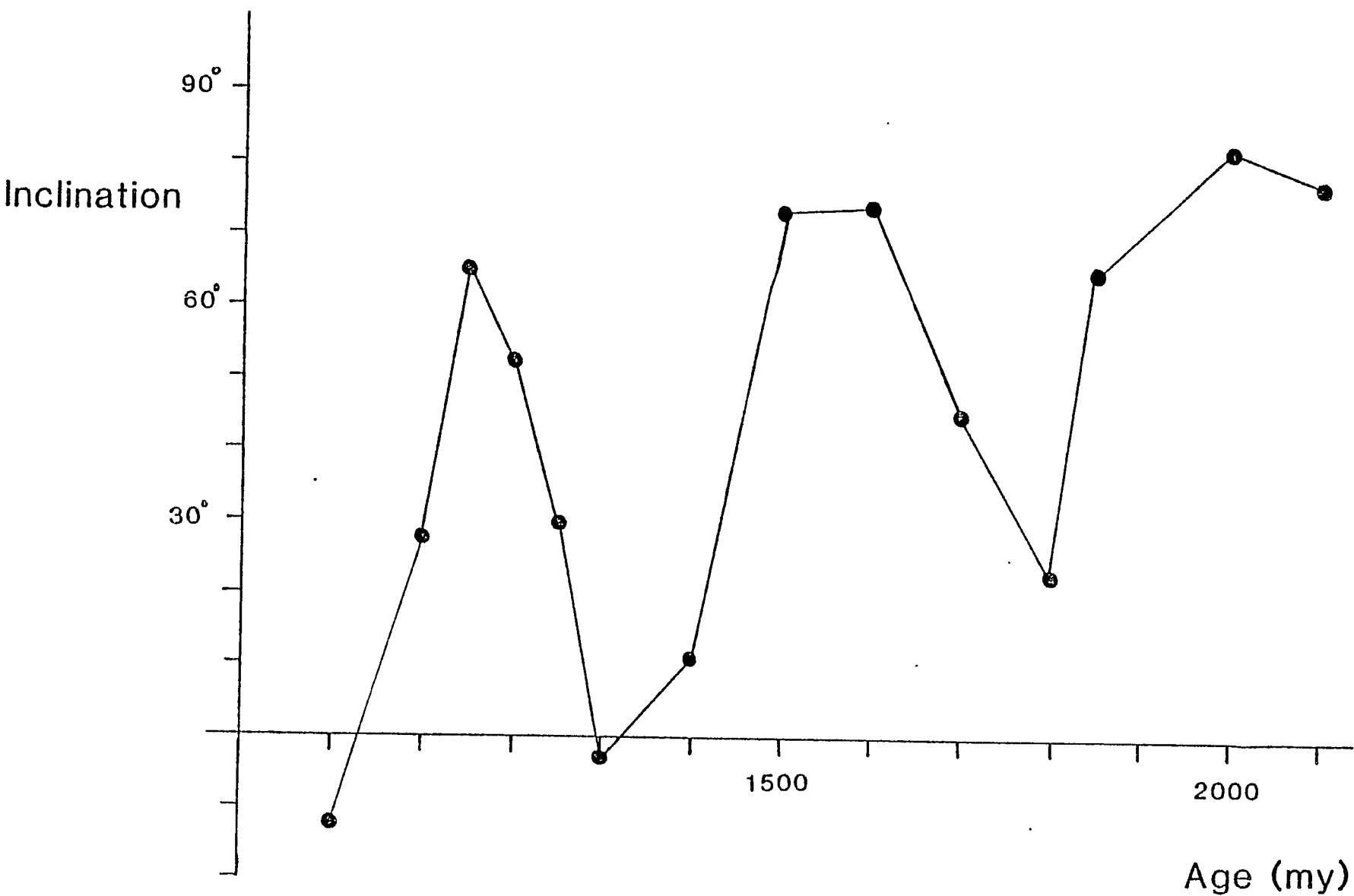
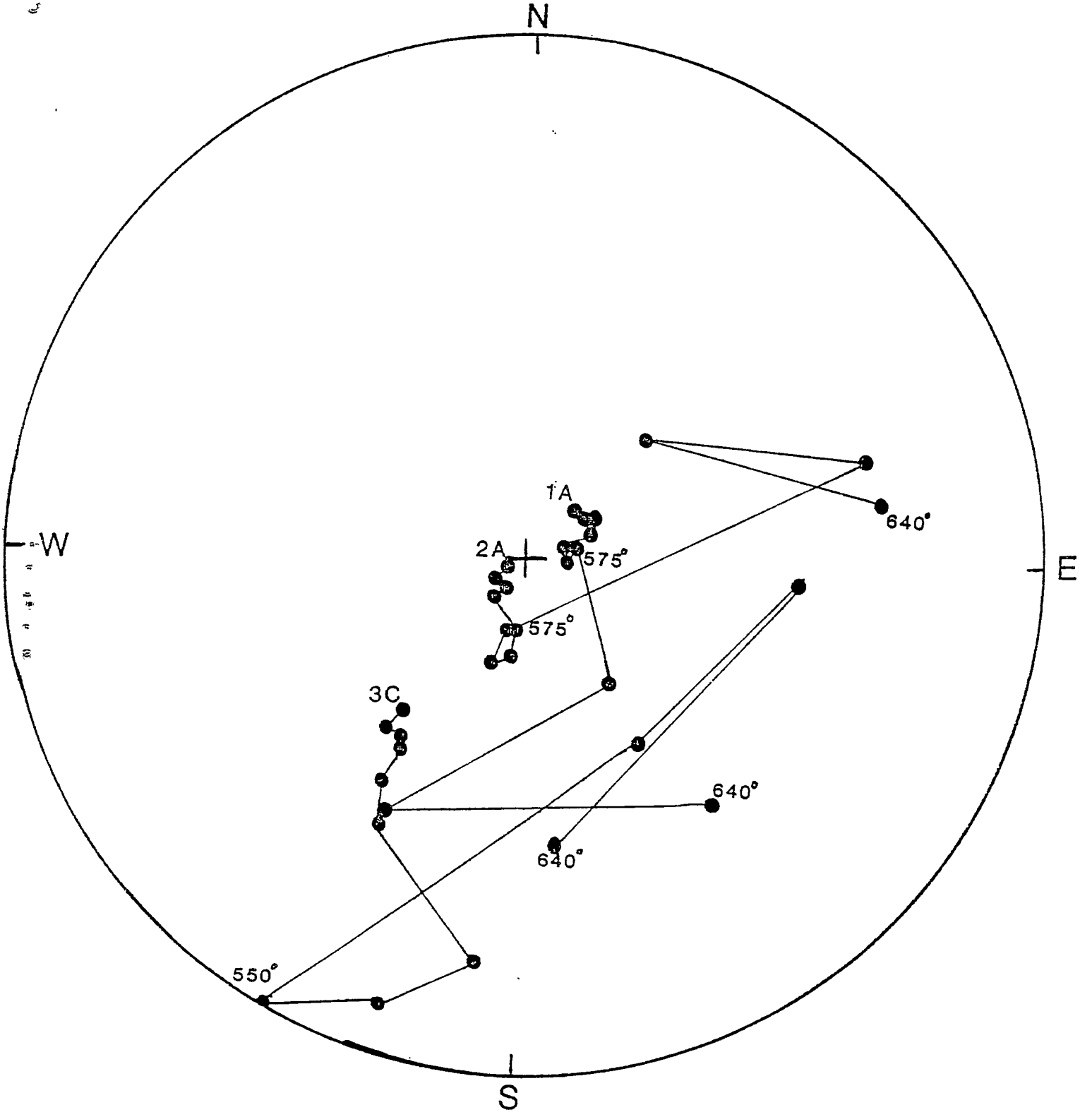


FIGURE 6-1



Thermal Demagnetization

Osawattamie Core

FIGURE 6-2

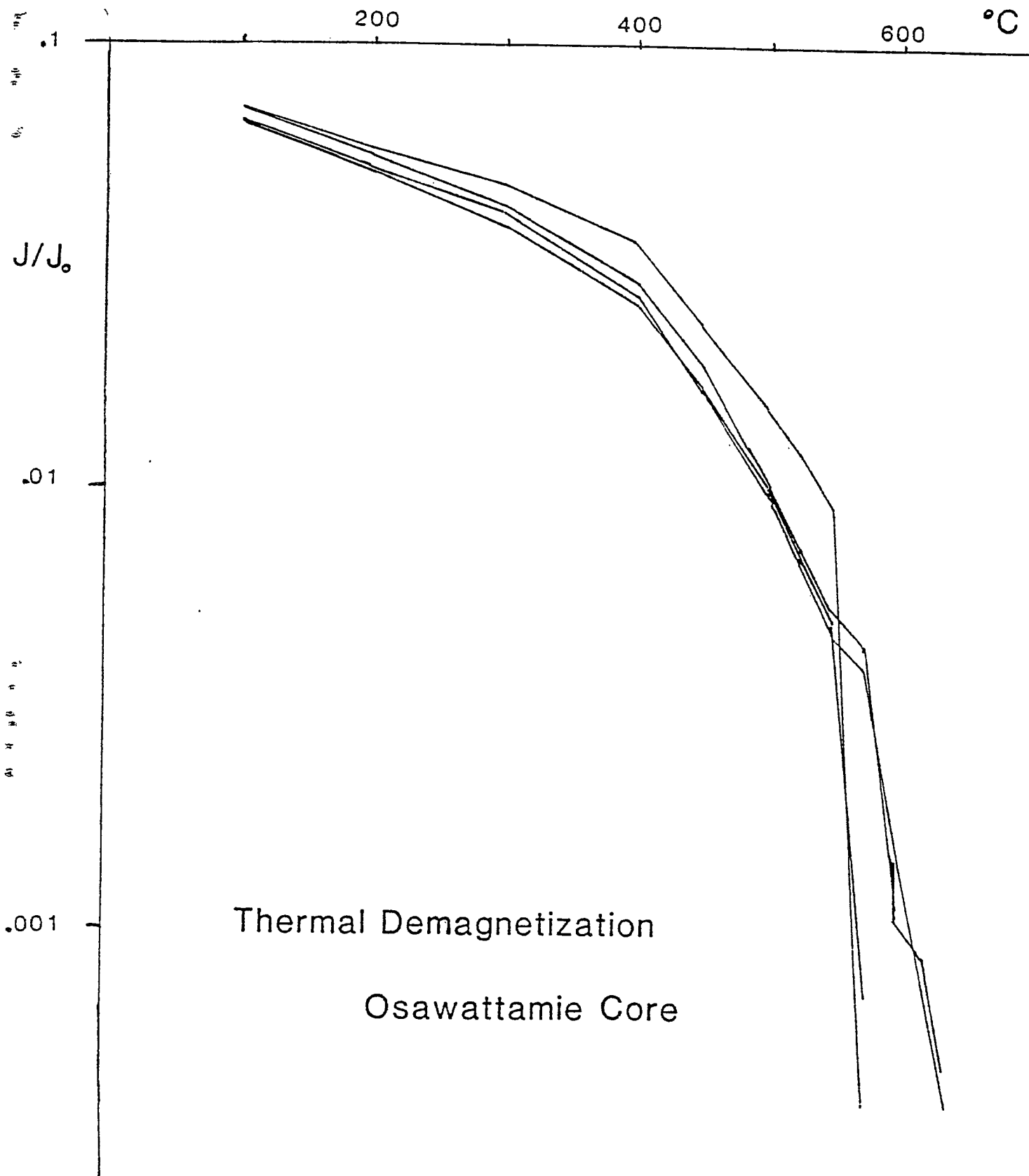
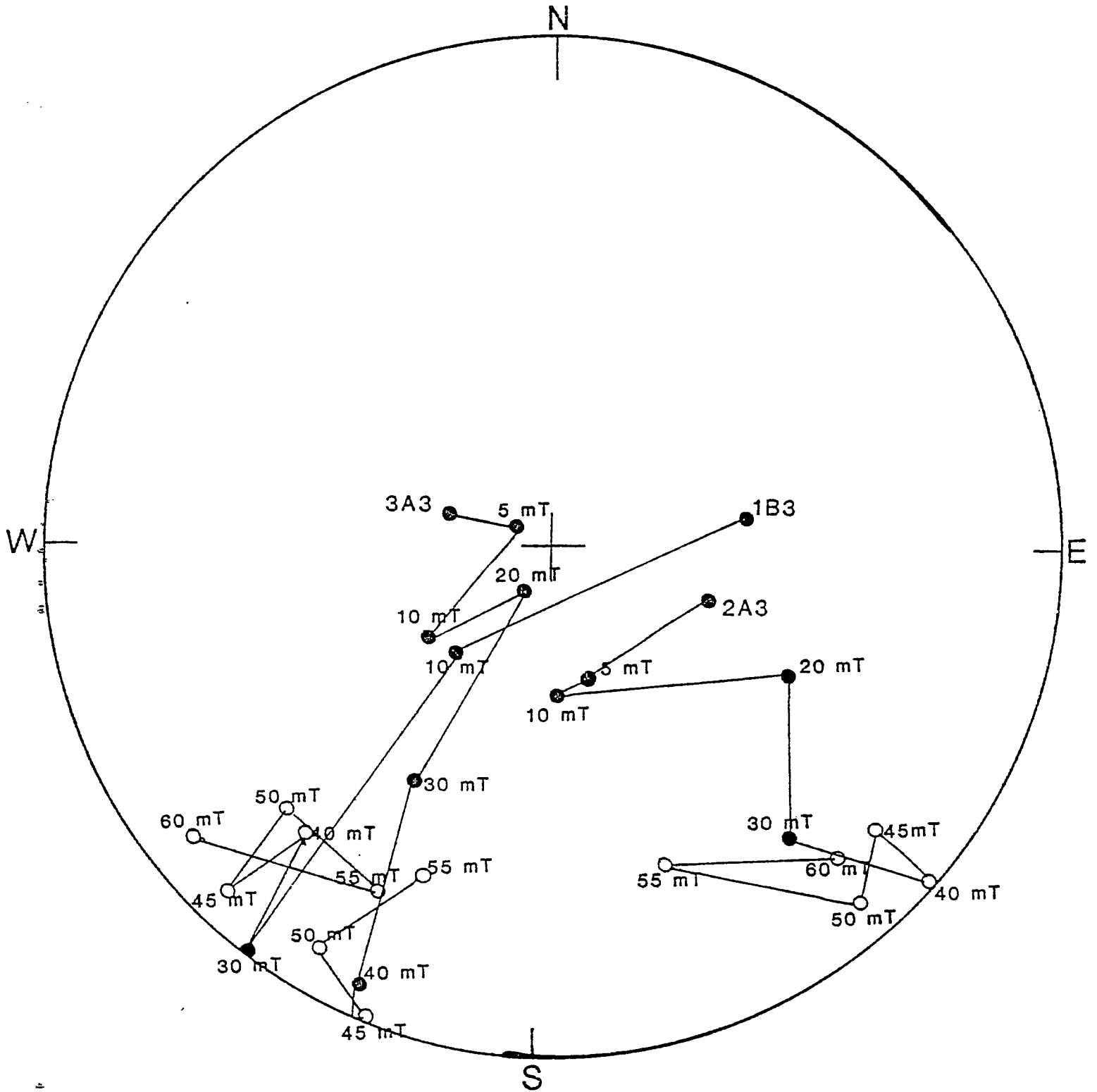


FIGURE 6-3



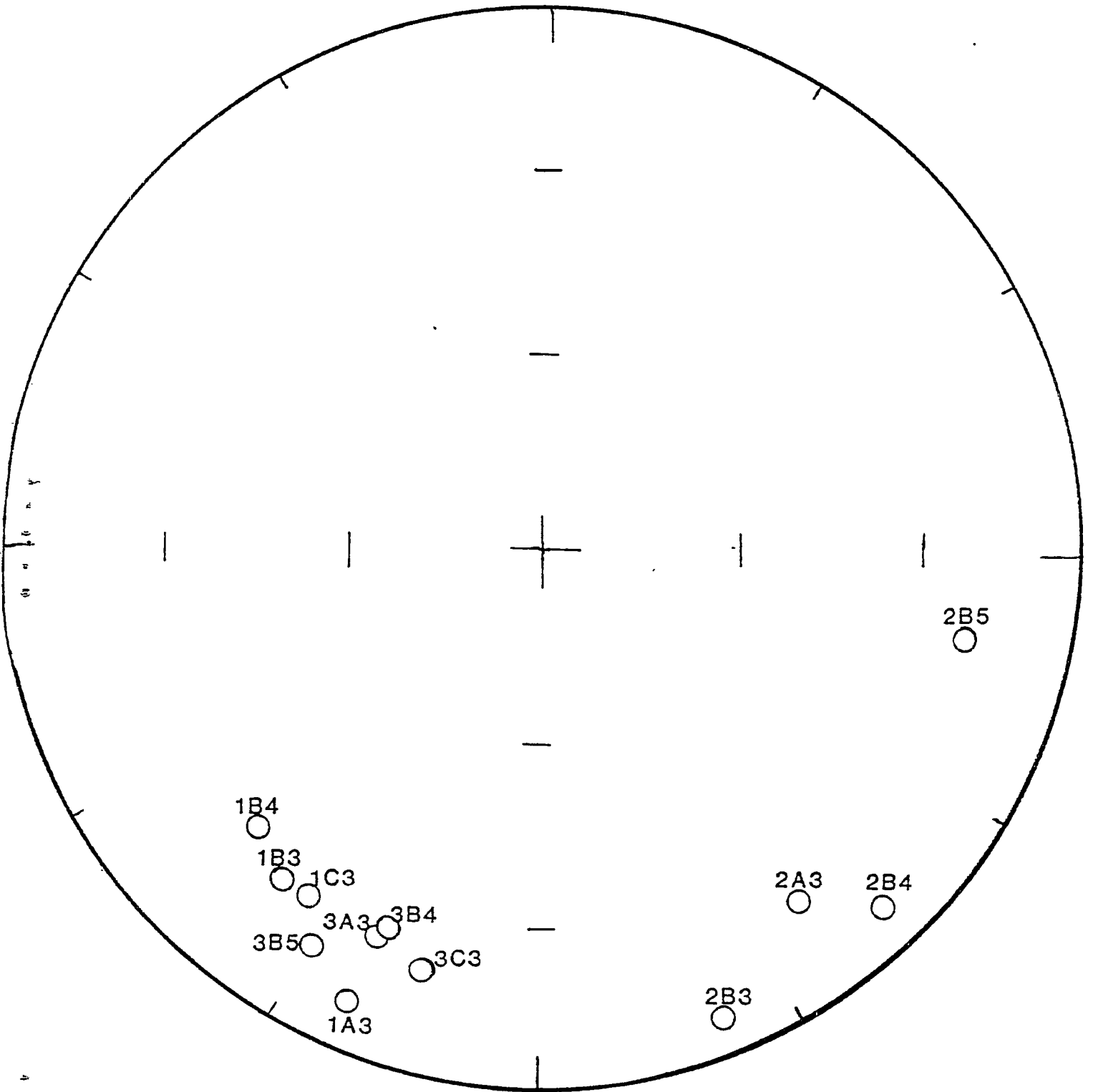
AF Demagnetization

Osawattamie Core

FIGURE 6-4

Osawattamie

Final Demagnetization Directions



all directions of demagnetization

FIGURE 6-5

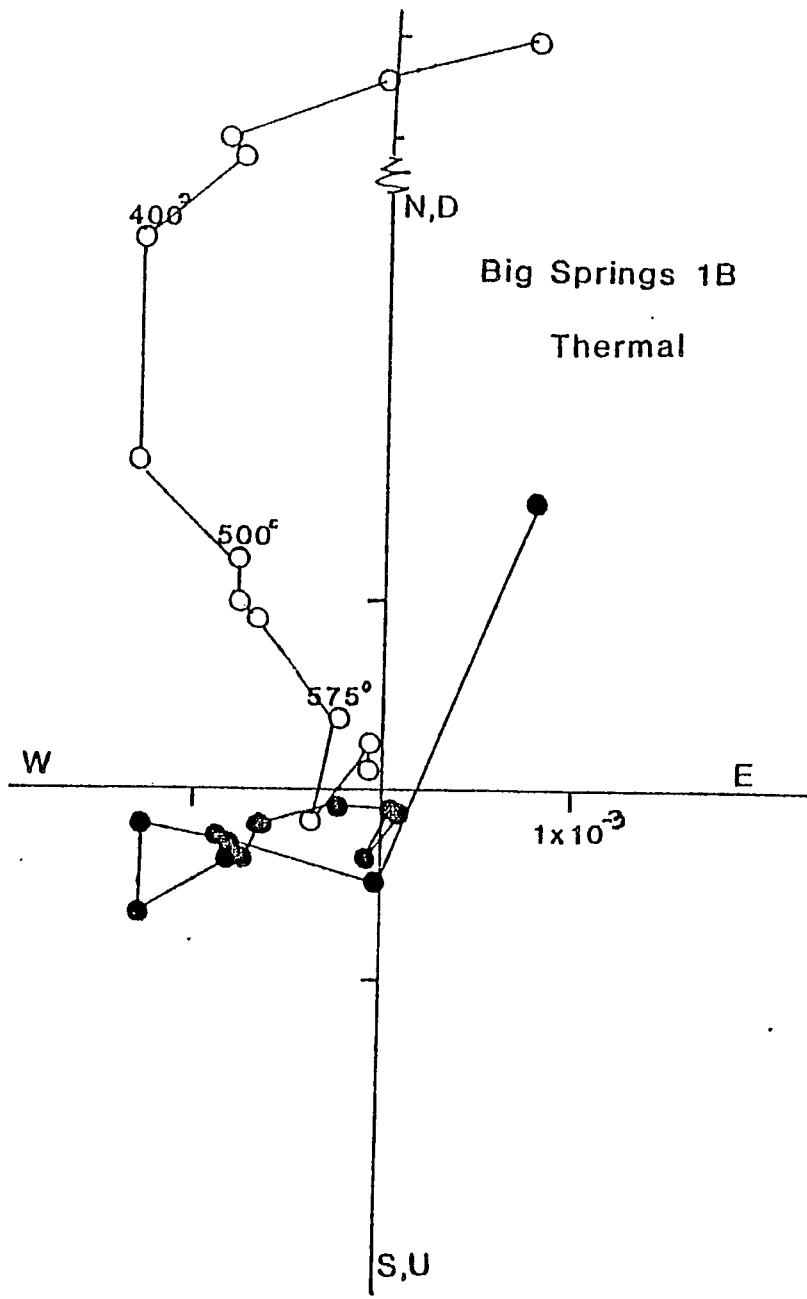
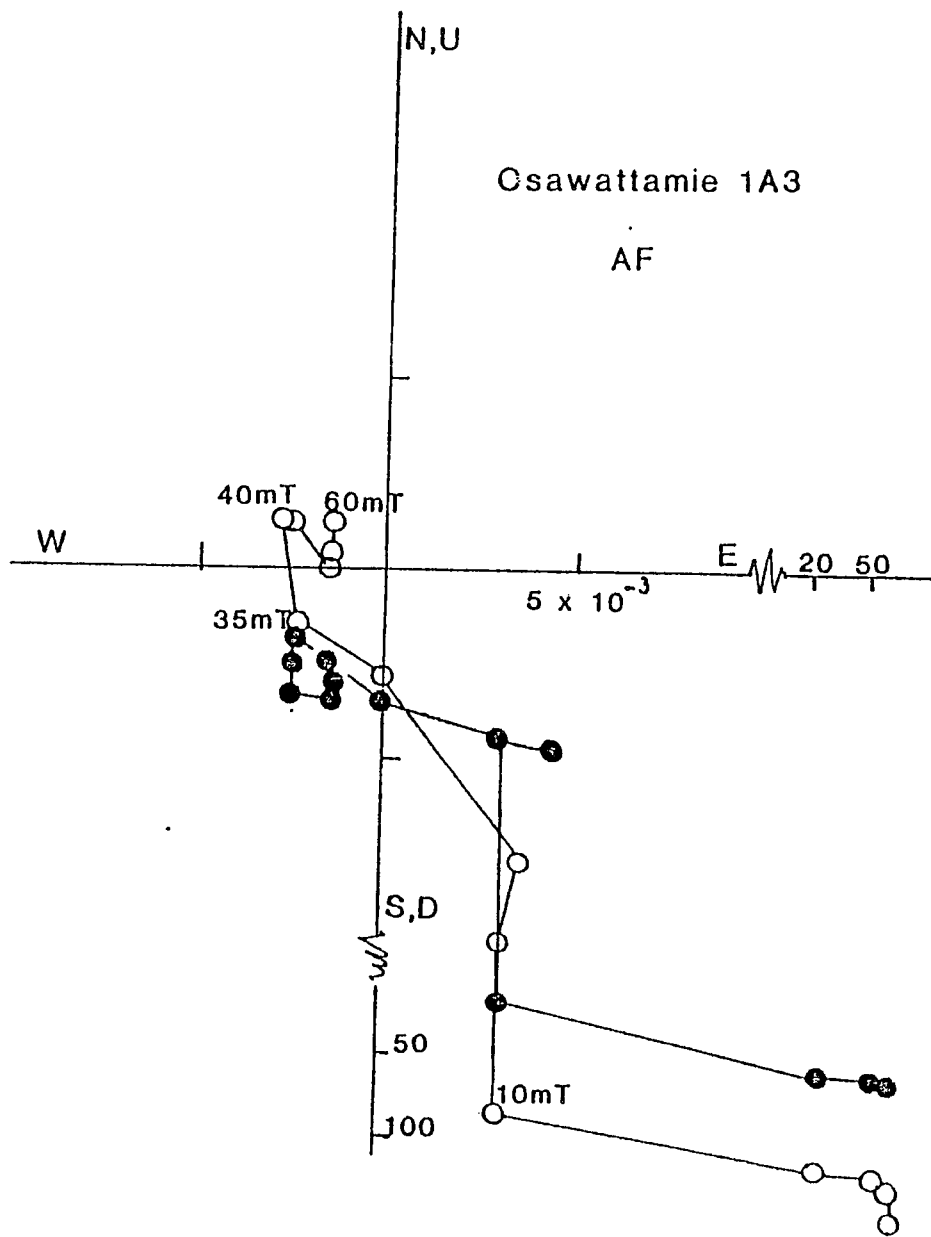


FIGURE 6-6

Big Springs

Final Demagnetization Directions

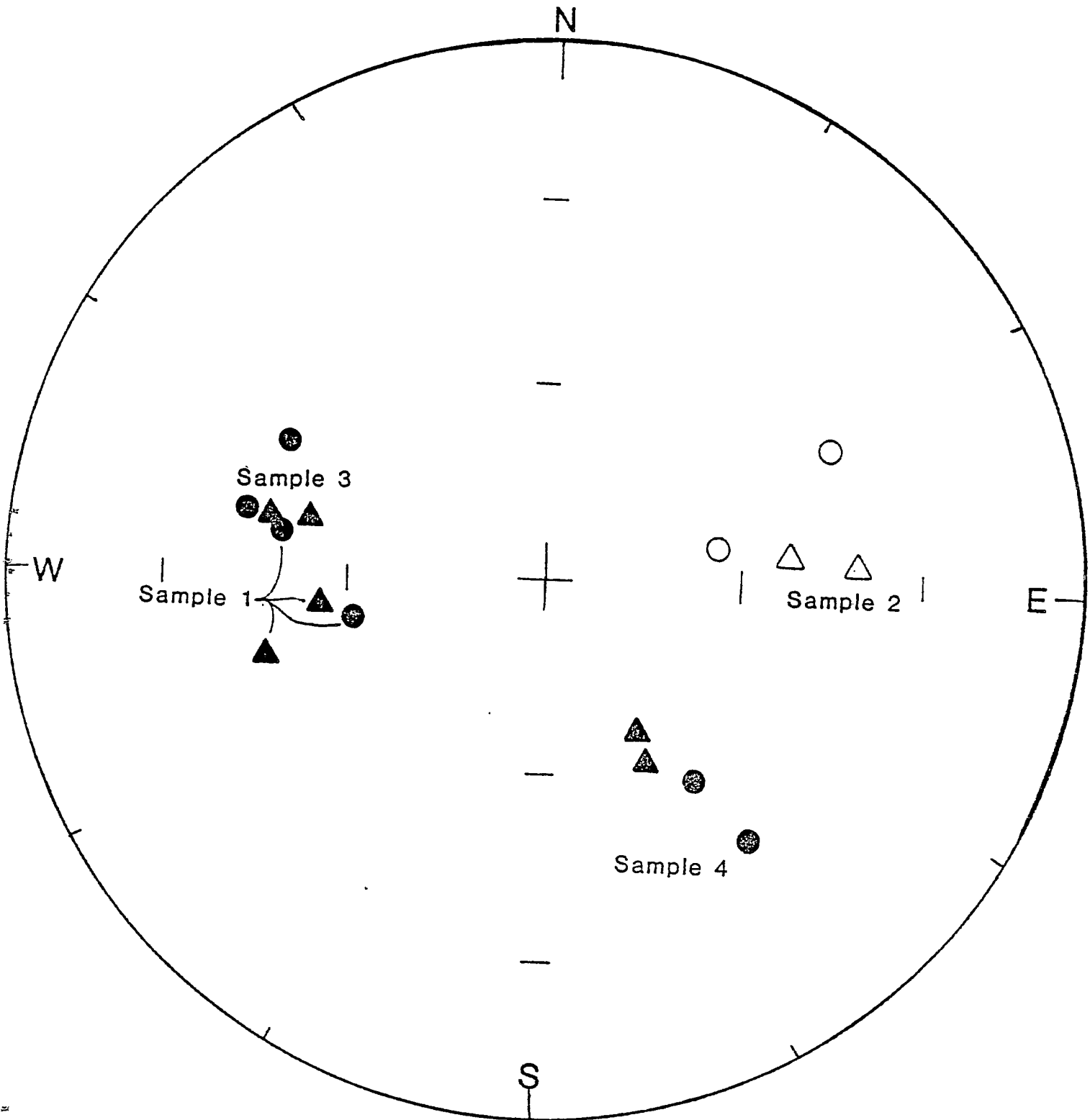
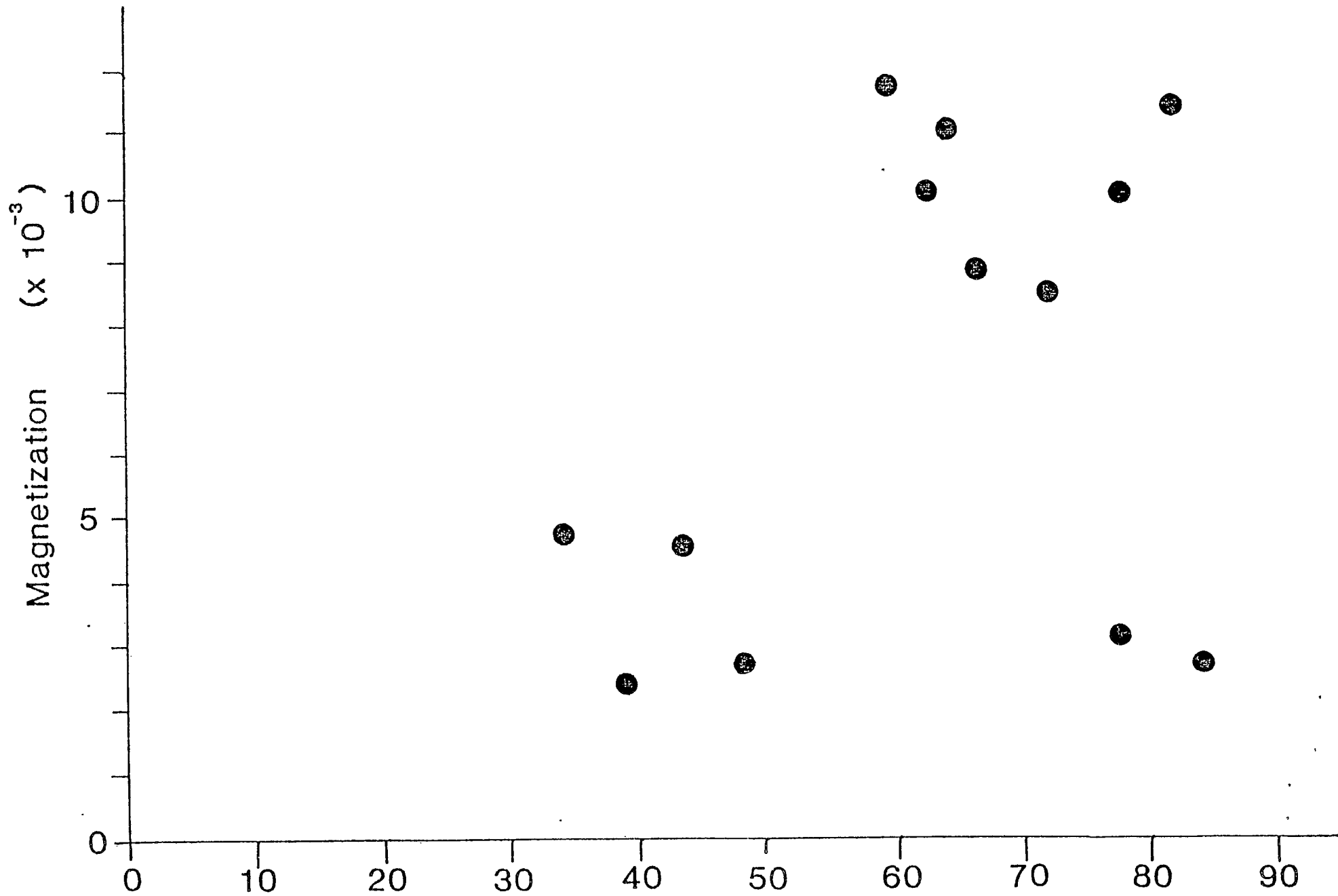


FIGURE 6-7

○ ● AF Demagnetization
△ ▲ Thermal Demagnetization



10 5 0

10 5 0

10 5 0

GRAVITY MEASUREMENTS IN KANSAS

by

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INTRODUCTION

Woollard (1958) compiled a statewide gravity map with a 5 milligal contour interval at approximately a 1:2,000,000 scale (Figure 7-1). His data, which were mostly from proprietary files and unavailable now, were typically spaced five miles apart. The Kansas Geological Survey (KGS) has been improving state gravity coverage over the past several years (Figure 7-2).

Area A (Figure 7-3) has been open-filed at a scale of 1:500,000 and contour interval of one milligal (Yarger et al, 1980). The somewhat variable coverage patterns for this map are east-west traverses with one to two mile spacing between stations and one to six miles between traverses. The sources for these data were several master's theses and earlier unpublished field work done by KGS staff. Gravity data in area B were acquired under this contract during the summer of 1980. Approximately 3300 points were measured in a regular pattern of east-west traverses with one mile spacing between stations along the traverse and four mile spacing between traverses.

Area B (Figure 7-4) has been open-filed at a scale of 1:500,000 and contour interval of one milligal (Yarger et al, 1981). Approximately 3300 points were acquired in area C under this contract during summer 1981. The

coverage pattern was the same as for area B. Also during summer 1981 under this contract, approximately 6600 points were acquired in area D. In this area the desirable coverage patterns of one mile spacing along the east-west traverses and two mile spacing between traverses was used. Due to a backlog of work on our digitizing table, compilation of contour maps for areas C and D will not be completed until fall 1982. The KGS plans to complete coverage of area E, with the same coverage used in area D, during summers 1982 and 1983. Long term plans are to go back into areas A, B and C to upgrade coverage to one mile east-west by two mile north-south station density.

DATA ACQUISITION AND REDUCTION PROCEDURES

The following paragraphs describe the procedures used for gravity data acquisition and reduction in areas B, C and D that were funded under this contract.

Three Lacoste-Romberg model G gravity meters were used. The measurement stations were usually located at section road intersections spaced one mile apart along east-west section lines. USGS 7.5 minute topographic quadrangle maps, with 10 foot contour intervals were used to record station location and to determine station elevations to an estimated ± 1 foot accuracy.

The station identification scheme used was an x, y coordinate system based on the regular system of section lines within the state. The x coordinate represents the number of sections (or approximate miles) from the Kansas- Missouri border.

The surveyed area was divided into blocks of 25 miles east-west by 16 miles north-south. One base station was centrally located within each block. All stations at the eastern and western edges were designated as "overlap" stations and were reoccupied during coverage of the adjacent block. Base

station readings were normally taken four times: the beginning of the day; before lunch; after lunch; and end of day. After correction for the earth's tidal variation (Longman, 1959), meter drifts were usually less than 0.05 milligals/hour with a range of 0.01 to 0.1 milligal/hour.

Absolute gravity values were determined by tying all the local base stations (one for each 25 mile by 16 mile block) to Department of Defense (DOD) base stations within the state. Two loops between the local base and DOD base were used which allowed two independent determinations of absolute gravity at the local base station. The root mean square of the difference (RMS) between the two values was usually less than 0.01 milligals. To monitor the daily meter operation, the base station readings were plotted on a graph along with the continuous theoretical tidal variation. The RMS between the measured and theoretical tidal variation was usually less than 0.05 milligals with a range of 0.005 to 0.15 milligals. After subtracting tidal drift, a linear meter drift rate was determined for each pair of base station readings. All regular measurement stations were then corrected for tidal drift and meter drift. Meter drift rates were usually less than 0.01 milligals/hour.

Overlap stations were used to check consistency of base levels between adjacent blocks. The independent measurements of the overlap stations typically agreed within 0.1 milligals with the worst case being approximately 0.3 milligals. In some cases the overlap discrepancies were used to make slight level adjustments to local bases to bring the data blocks into better overall internal consistency. Final latitude and longitude coordinates for each measurement station were determined by digitizing the station locations on the 7.5 minute quadrangles. After assignment of latitude and longitude the following five variables were plotted against longitude for each east-

west profile: elevation, absolute gravity, free air gravity, Bouger gravity and horizontal gravity gradient. These profiles were screened for unphysical gradients. Most of the problem points found in this screening process could be traced back to an earlier error such as incorrect meter reading punched from field sheets.

The final corrected data file was used as input to the Surface II contour program (Sampson, 1978). The data were gridded into one mile by one mile nodes. The RMS between the original data points and interpolated grid values was 0.46 milligals. The grid was contoured at a scale of 1:500,000 and a one milligal contour interval (Figure 7-4). The reduction procedures outlined above are also being applied to data taken in south-central Kansas and northwestern Kansas.

PRELIMINARY INTERPRETATION

Figures 7-3 and 7-4 show considerable improvement in the resolution of gravity anomalies compared to Woollard's earlier map (Figure 7-1). These new gravity maps in eastern Kansas bring out the prevailing northwest trending grain evident in the Precambrian relief map (Figure 5-10) and the aeromagnetic map (Figure 5-2).

The most prominent gravity anomaly is the northeast trending 60 milligal high in northern Kansas. The source for this is a trough of Keweenaw mafic igneous rocks, approximately 1.1 billion years old, that extend from central Kansas through the North American continent to the Lake Superior region. The flanking gravity lows are correlated with Precambrian clastic sediments. These mafic and associated clastic sedimentary rocks are interpreted to be the result of a Late Precambrian crustal rifting event (Halls, 1978). The gravity and magnetic anomalies associated with this rift are often referred

to as the Midcontinent Geophysical Anomaly (MGA). Recent interpretation of the aeromagnetic map of Kansas (Chapter 5, this report) indicates that the rift extends through central Kansas to the Kansas-Oklahoma border. Forthcoming gravity data from south-central and west-central Kansas should be very useful in further study of this major crustal rift.

A prominent circular gravity high, of ~10 milligal magnitude, is evident in Jewell County just west of the MGA. This suggests the existence of mafic intrusions within the crust underlying the Salina Basin. The relatively gentle horizontal gradients may be located well below the Precambrian subcrop surface.

A circular anomaly of similar size and magnitude also occurs in northeastern Kansas suggesting that the Forest City Basin may also be underlain by mafic intrusives at depth.

A large area in southeastern Kansas is characterized by a 30 to 40 milligal positive gravity anomaly and correlates well with a 1400 m.y. old rhyolite terrane (Bickford, 1979). This suggests that a sizeable volume of intermediate to mafic rock underlies the relatively low density rhyolite.

Another positive anomaly of large areal extent (Figures 7-3 and 7-4), with magnitudes ranging between 5 to 10 milligals, trends northwest from Miami and Johnson counties to Shawnee and Jackson counties. This gravity feature does not correlate with known basement rock type or with the magnetic map (Figure 5-2). It most probably represents a mass of deep seated rock that intruded, during Precambrian time, a northwest trending zone of weakness.

Although the main northwest trending gravity anomaly is not reflected in the magnetic map, certain local features within this trend do have correspond-

ing magnetic counterparts. The positive 5 to 6 milligal circular gravity anomaly located in northern Douglas County is coincident with a sharply defined 1000 gamma circular positive magnetic anomaly. This anomaly, which is located near the town of Big Springs, is part of a series of north-south trending circular magnetic anomalies. A similar circular magnetic anomaly in Miami County is approximately correlated with a south trending positive gravity nose, a local feature within the northwest trending gravity high.

A study of basement cores derived from drilling the Big Springs and Miami county anomalies (Steeple and Bickford, 1981) reveals that these rocks are epizonal granites emplaced approximately 1350 m.y. ago. Gravity and magnetic modeling of these bodies (Yarger, 1982) indicate that they are approximately 15 kilometers in diameter and extend from the Precambrian surface to a depth of 10 kilometers.

Apparent in Greenwood, Butler and Sedgwick counties (Figure 5-2) is a prominent negative magnetic anomaly elongate in the east-west direction. The source for this feature, which is often referred to as the Wichita magnetic low, is poorly understood. Gravity data in Greenwood County (Figure 7-4), which is located within the eastern end of the Wichita low, reveal two circular anomalies of opposite polarity. Completion of the gravity map of south-central Kansas should enhance our understanding of this geophysically complex region.

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FIGURE CAPTIONS

- FIGURE 7-1: Bouger gravity anomaly map of Kansas; 5 milligal contour interval (After Woollard, 1958).
- FIGURE 7-2: Index map of areas where gravity data has been acquired. The grid spacing for data points varies for areas A-E.
- FIGURE 7-3: Bouger gravity map of northeastern Kansas; one milligal contour interval.
- FIGURE 7-4: Bouger gravity map of southeastern Kansas; one milligal contour interval.

BOUGUER GRAVITY ANOMALY MAP OF KANSAS

by G. P. Woollard, 1958

BULLETIN 137 Plate 1

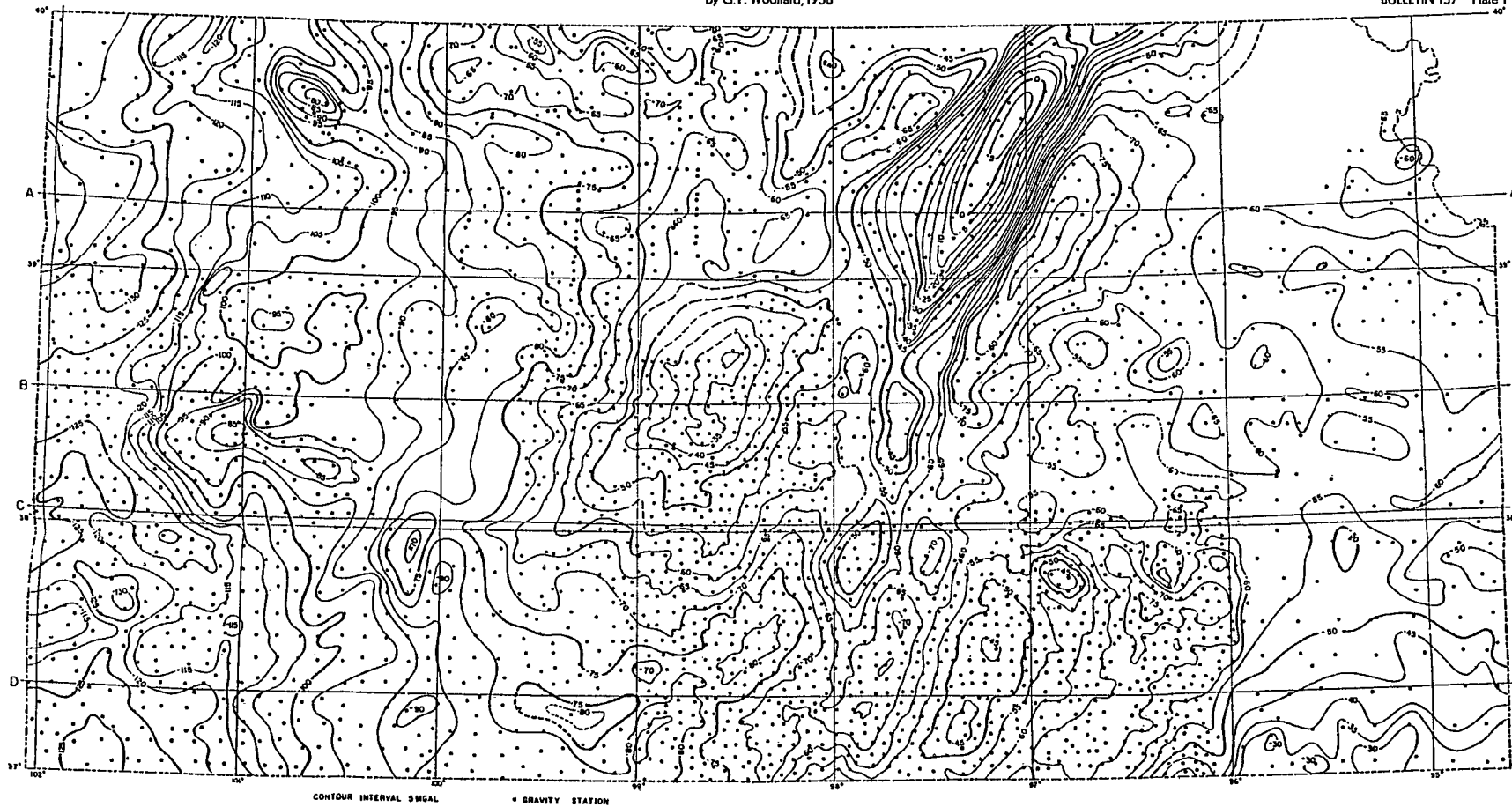


FIGURE 7-1

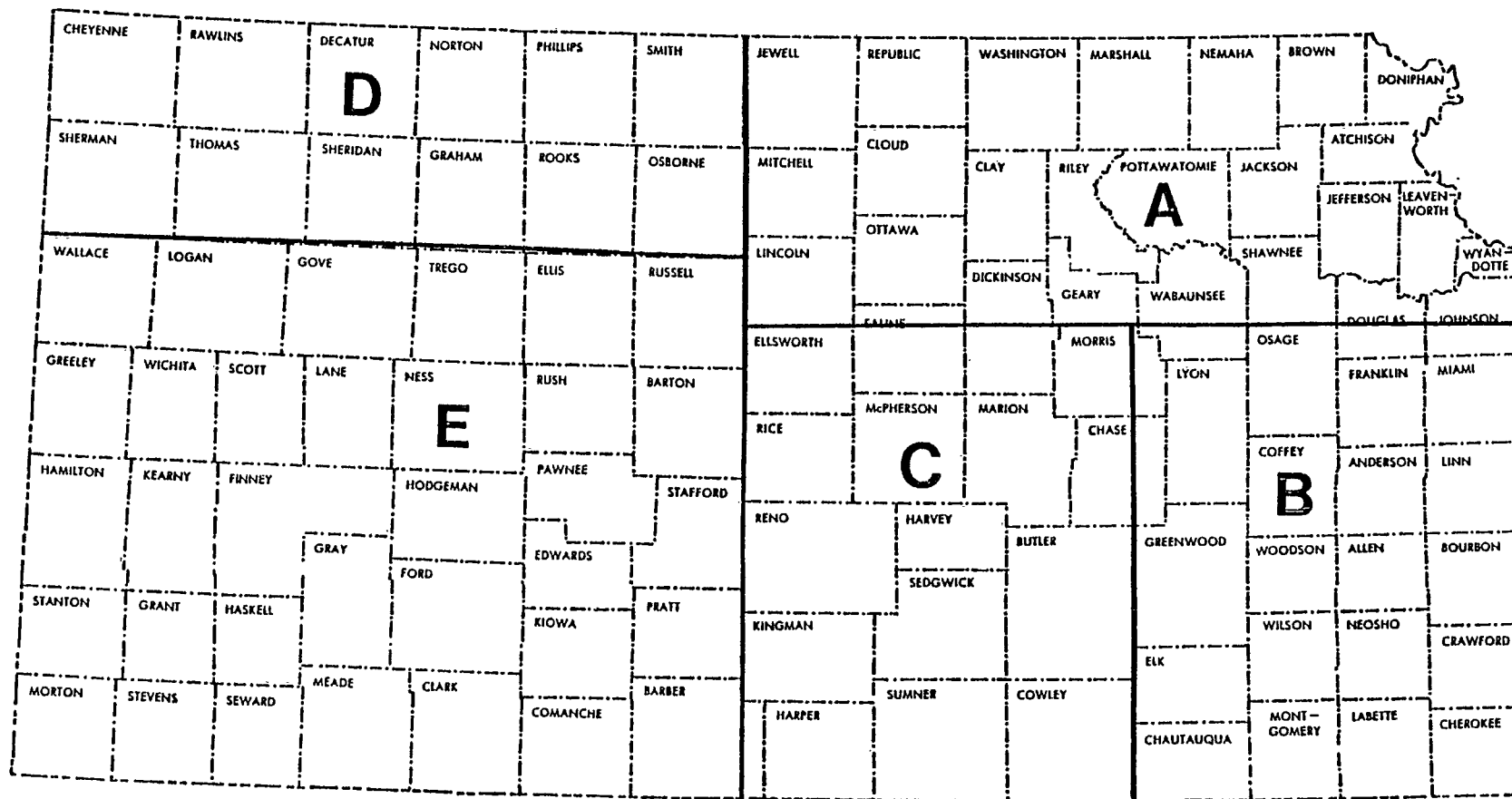
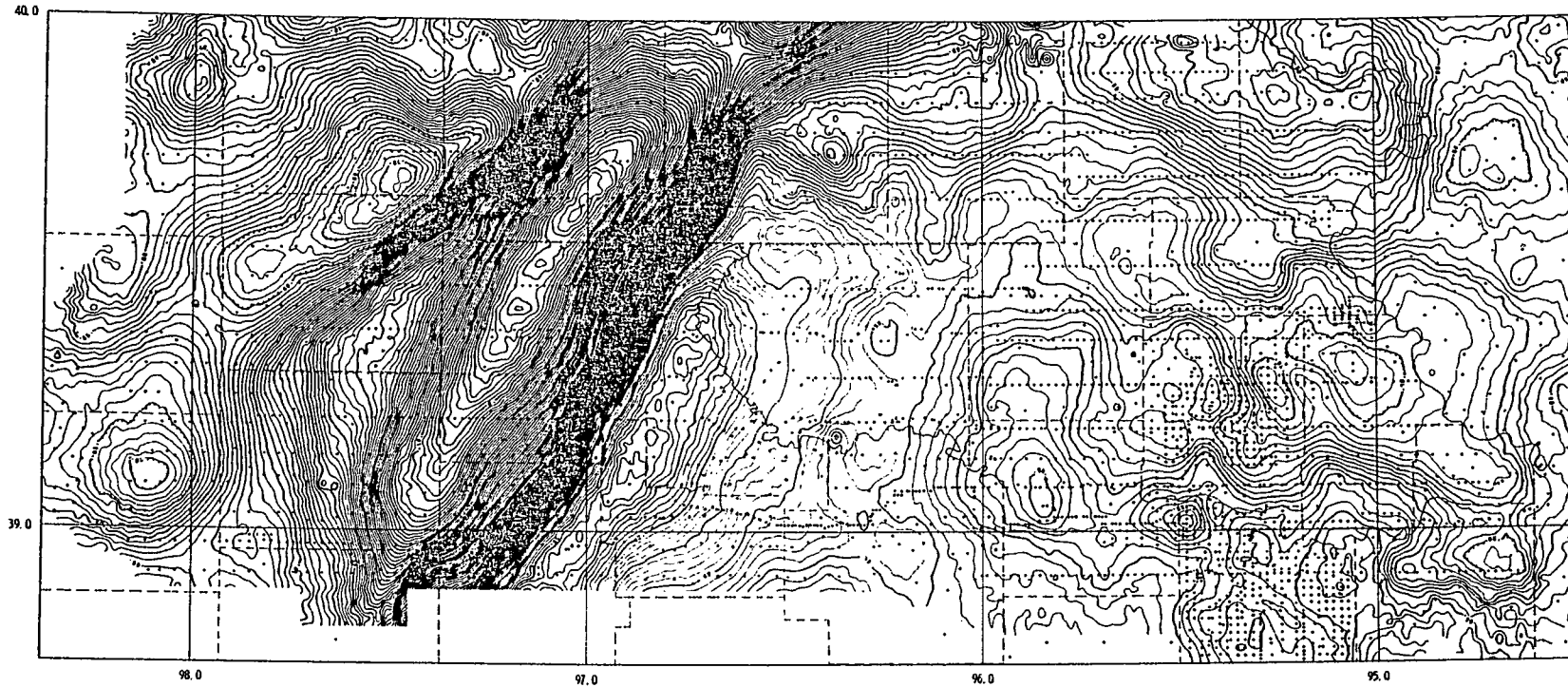


FIGURE 7-2

BOUGUER GRAVITY MAP OF NORTHEASTERN KANSAS

H. Yarger, K. Ng, R. Robertson, and R. Woods

OPEN FILE APRIL 1, 1980

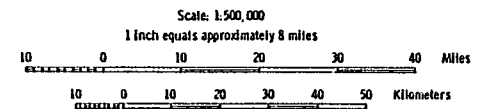


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Bouguer Gravity Field of the Earth in Milligals
 Contour Interval 1 Milligal
 Lambert Conformal Conic Projection
 Standard Parallels 33° and 45°
 Standard Deviation for Station Measurement = 0.3 Milligals

The absolute gravity field was referenced to the
 International Gravity Standardization Net 1971.
 The Bouguer gravity field was calculated using
 The Gravity Formula 1967 and a density of 2.67.

Supported principally by the Kansas Geological Survey.
 Supported in part by the U. S. Nuclear Regulatory
 Commission under Contract No. AT149-241-0256.

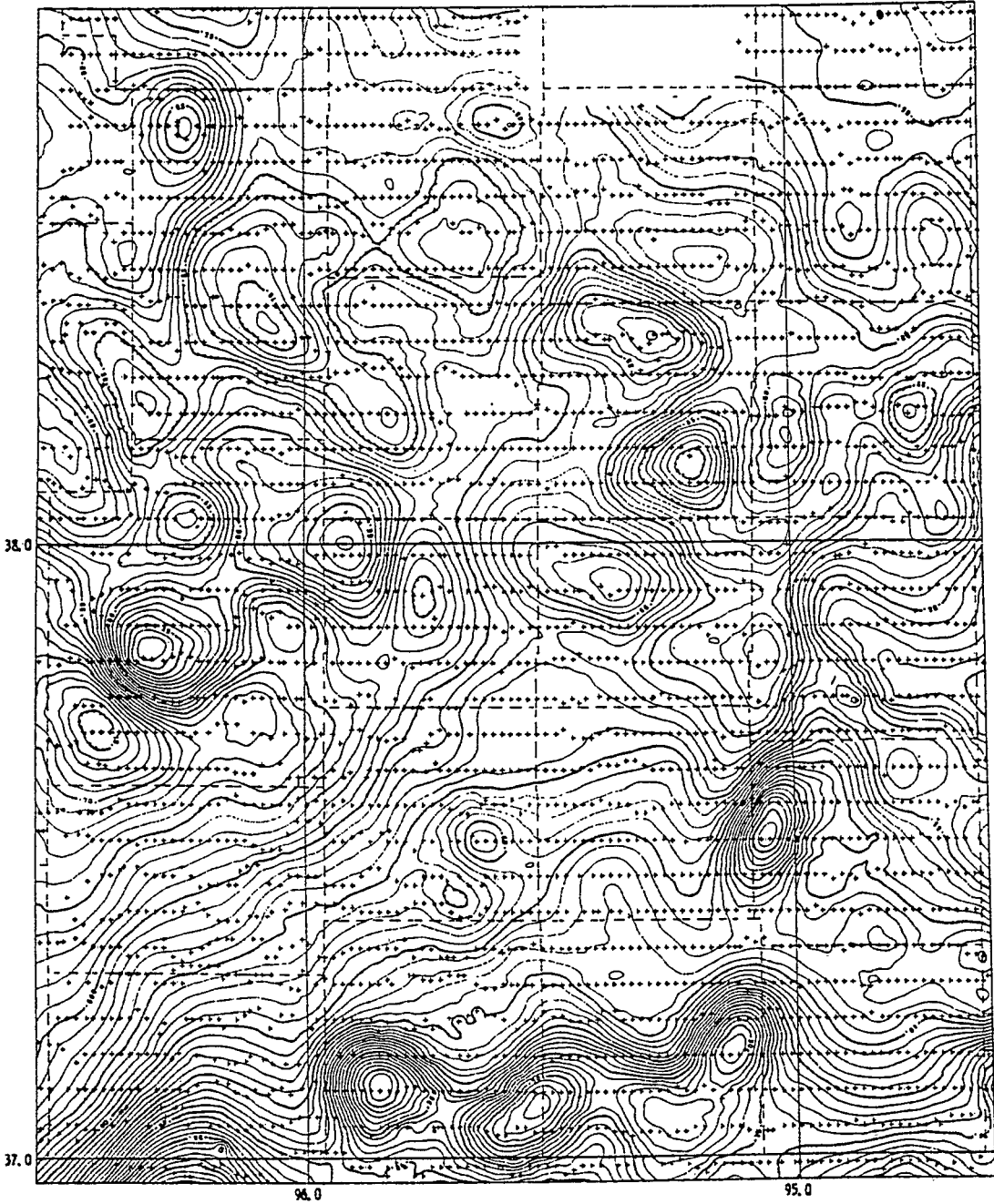


Index Map

FIGURE 7-3

BOUGUER GRAVITY MAP OF SOUTHEASTERN KANSAS

H. YARGER, C. LAM, R. SOOBY, A. MARTIN, G. ROTHE, D. STEEPLES



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Bouguer Gravity Field of the Earth in Milligals
Contour Interval 1 Milligal
Lambert Conformal Conic Projection

Standard Parallels 33° and 45°

The absolute gravity field was referenced to the International Gravity Standardization Net 1971. The Bouguer gravity field was calculated using The Gravity Formula 1967 and a density of 2.67.

Supported principally by the Kansas Geological Survey, Supported in part by the Department of Energy under Grant No. DE-AS07-19ET27204

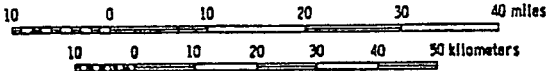


Index Map

FIGURE 7 - 4

Scale 1:500,000

1 inch equals approximately 8 miles



GEOHERMAL MAPPING OF WESTERN KANSAS BASED ON CHEMICAL GEOTHERMOMETERS

by

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INTRODUCTION

A study of the geothermal potential of the United States based on silica geothermometer temperatures was made by Swanberg and Morgan (1979). The temperatures were calculated from dissolved silica concentrations in subsurface waters. The geothermometer equation used assumes that the water in the geothermal reservoir is in equilibrium with quartz and that no silica precipitation occurs as the water flows from the reservoir to the shallower sampling location. The silica geothermometer map did not include results for Kansas, however, because data was lacking at that time in the WATSTORE file of water-quality data used by Swanberg and Morgan.

In the last several years L. R. Hathaway of the Kansas Geological Survey has directed investigations of the geochemistry of groundwaters used for irrigation in Kansas. The approximately 1,200 wells sampled are from the broad, unconfined aquifers of Kansas, the Ogallala aquifer in the western third of the state, the Great Bend Prairie in south-central Kansas, and the Equus Beds in McPherson, Harvey, and Sedgwick counties (Figure 8-1). The Arkansas River valley was also included in the study area, from western Kansas where it separates the central and southern portions of the Ogallala aquifer, along the northern part of

the Great Bend Prairie, to the southern portion of the Equus Beds. Sampling of each aquifer area was conducted during the middle of the summer, the period of greatest irrigation pumpage. Thus, seasonal variations were minimized. Careful control of the quality of the analytical data was maintained during these investigations through the use of various types of duplicate samples. Only a small portion of the data are in the WATSTORE file. These analyses provided for the computation of geothermometer temperatures for approximately half of Kansas.

A conspicuous feature of Swanberg and Morgan's (1979) map is the region of high temperatures given by the silica geothermometer for central and western Nebraska. This area appears to be coincident with the location of the Ogallala aquifer in Nebraska. The aquifer extends from southern South Dakota to northwestern Texas and the eastern edge of New Mexico. Geothermal temperatures were not computed in Swanberg and Morgan's map for the Oklahoma and Texas portions of the Ogallala aquifer, as well as for Kansas, due to lack of data. A possible explanation for higher geothermal temperatures is the leaching of ash and feldspar in the sediments of the Ogallala aquifer and ash in Upper Cretaceous rocks. The ash is primarily vitric tuff and contains amorphous silica. In the Ogallala Formation some silica has been leached and precipitated as opal cementing the sediment. Concentrations of silica dissolved from ash, opal, and feldspar weathering can be appreciably greater than those in equilibrium with quartz.

Other chemical geothermometers have been used to estimate temperatures in geothermal reservoirs. Another silica geothermometer is based on chalcedony, which is more soluble than quartz. Therefore, the resul-

tant geothermal temperatures are less than those calculated from the quartz geothermometer for the same dissolved silica content.

Cation geothermometers include an equation involving the ratio Na/K. Fournier and Truesdell (1973, 1974) developed a Na-K-Ca geothermometer that reportedly gives better values than the Na/K geothermometer, especially at lower temperatures. Paces (1975a, 1975b) modified the Na-K-Ca geothermometer for groundwater with temperatures below 75°C and partial pressures of carbon dioxide above 10^{-4} atm.

Mineralogic controls on cation concentrations within the shallow portions of sedimentary aquifers are probably much more important than chemical characteristics inherited from waters circulating from depth. Calcium contents in Ogallala aquifer waters are generally in equilibrium with calcite. Sources and controls on sodium and potassium vary from contributions by deeper saline waters or the Arkansas River, to changes caused by ion exchange on clays, and to the weathering of feldspar. Thus, waters circulating from deeper, warmer strata could have lost their diagnostic chemistry as used in chemical geothermometers.

The objectives of this study were as follows:

1. Determine and compare geothermal temperatures using various chemical geothermometers and groundwater quality data from Kansas.
2. Correlate geothermometer temperatures with measurements of subsurface temperatures and calculated geothermal gradients.
3. Evaluate the relative importance of mineralogic controls within the aquifer versus geothermal effects, on the composition of groundwater and, thus, temperatures derived from geothermometer calculations.

Towards the end of this study, a complete map of the heat flow of the United States based on the quartz geothermometer was published by Swanberg and Morgan (1981). An area of high heat flow is shown in northwestern Kansas. Although Swanberg and Morgan did not describe in the publication how they had treated data in the Great Plains, Swanberg personally communicated that data for wells shallower than 400 feet deep in the area of the Ogallala aquifer had been eliminated during the map preparation. This was based on an evaluation of the silica-geothermometer anomaly for Nebraska (Swanberg, 1980). The shallower well data give generally higher and more widely ranging temperatures than for the deeper wells. The map of Swanberg and Morgan (1981) appeared to have met objective (1) as stated above and its relation to the geothermal potential of Kansas. However, the other objectives were very useful for determining whether the area of higher heat flow below 400 feet affects the temperatures and geochemistry of the shallower strata. Also, an improved understanding of the mineralogic controls on the concentrations of dissolved constituents used in computing geothermal temperatures could allow improvement in the application and interpretation of geothermometer data for sedimentary systems.

PROCEDURE

Groundwater chemical analyses acquired by the Kansas Geological Survey as part of irrigation water studies (Hathaway, et al., 1975, 1977, 1978a, 1978b, 1979, 1981) were converted into the computer format used in the WATSTORE system. This system is managed by the U.S. Geological Survey and allows access to water resources data by federal, state, and other agencies.

Geothermal temperatures were calculated from the water quality data and five geothermometer equations. Two of the equations are based on the solubility of silica in the geothermal reservoir. The quartz geothermometer used by Swanberg and Morgan (1979, 1981) to construct silica temperature and heat flow maps of the United States assumes conductive cooling during the passage of the water to its nearer surface location and is applicable for temperatures of 125-250°C (Fournier, 1973, 1976),

$$T^{\circ}\text{C} = \frac{1315}{5.205 - \log(\text{SiO}_2)} - 273.15$$

where the concentration of SiO_2 is in mg/L. The chalcedony geothermometer of Fournier and Truesdell (1970) may be more applicable for lower temperatures.

$$T^{\circ}\text{C} = \frac{1015.1}{4.655 - \log(\text{SiO}_2)} - 273.15$$

The other three chemical geothermometers are based on cation concentrations. The Na/K geothermometer of White and Ellis (quoted in White, 1970) was reported to be applicable for temperatures of 100-275°C.

$$T^{\circ}\text{C} = \frac{855.6}{\log(\text{Na/K}) + 0.8573} - 273.15$$

where Na and K contents of the water are in mg/L.

Fournier and Truesdell (1973, 1974) formulated a Na-K-Ca geothermometer

$$T^{\circ}\text{C} = \frac{1647}{5.218 + \log(\text{Na}/\text{K}) + \beta \log([\sqrt{\text{Ca}}]/\text{Na})} - 273.15$$

where concentrations are in mg/L and $\beta = 4/3$ for temperatures of less than 100°C . Paces (1975a, 1975b) modified the Na-K-Ca equation for groundwaters with temperatures below 75°C and partial pressures of carbon dioxide above 10^{-4} atm.

$$T^{\circ}\text{C} = \frac{1647}{7.275 + \log(\text{Na}/\text{K}) + \beta \log([\sqrt{\text{Ca}}]/\text{Na}) - 0.253J} - 273.15$$

where, $J = \text{pH} - \log(\text{HCO}_3) - 4.22 \times 10^{-3}t - 3.54 \times 10^{-5}t^2$

t is the temperature of the groundwater samples in $^{\circ}\text{C}$ and concentration units are the same as for the Na-K-Ca equation.

An activity coefficient of 0.93 was used to adjust the bicarbonate concentration to activity units.

Silica concentrations, the ratio of K to total dissolved solids, and all geothermometer temperatures except those based on the Na/K equation were plotted and contoured with the digital graphics programs TERRA-PLOT (FELIX) (McCullagh, 1979) and GIMMAP (Ross, 1981; Brentano, 1982) of the Kansas Geological Survey. The patterns of the temperature contour maps were compared with each other and a map of subsurface temperatures and two maps of geothermal gradients from Stavnes (Plates 2-1,

2-2, 2-4). Staynes computed the subsurface temperatures for a depth of 1000 feet and geothermal gradients from oil and gas records for wells over 1000 feet. She also calculated geothermal gradients from her own temperature measurements below 400 feet in boreholes. The quartz geothermometer temperatures were also statistically compared with the subsurface temperatures and borehole geothermal gradients using linear correlation and regression. Graphs of the correlation were produced with the computer program SURFACE II (Sampson, 1978).

RESULTS AND DISCUSSION

COMPARISON OF TEMPERATURES FROM DIFFERENT GEOTHERMOMETERS

The geothermal temperatures computed for the two silica and three cation geothermometers are listed in Appendix I along with the well location and actual groundwater temperature during sampling. Ranges of the quartz and chalcedony geothermometer temperatures are 39.6-118.2°C and 4.6-88.1°C, respectively. Differences between the quartz and chalcedony temperatures range from 35-30°C from the low to the high values, and are consistent because the basic form of the equations is the same for both quartz and chalcedony solubility. The areas with higher silica geothermometer temperatures are located in the northwestern corner and the west-central part of Kansas (Figures 8-2 and 8-3). Nearly all of the quartz and chalcedony geothermometer temperatures were below 90°C and 60°C, respectively, in southwestern Kansas, the Great Bend Prairie and the Equus Beds, (see Figure 8-1 for location of aquifers). The region of higher heat flow indicated by Swanberg and Morgan's (1981) silica geothermometry map generally coincides with the areas of higher silica temperatures computed in this study, even though the data for their map was derived from water

samples below the Ogallala aquifer.

Temperatures calculated using the Na-K-Ca geothermometer range from 2.6-85.8°C and are both higher and lower than the chalcedony equation temperatures. The highest values ($>60^{\circ}\text{C}$) stretched along a west to east strip in northwestern Kansas along the border with Nebraska (Figure 8-4). Some higher temperatures were also present in the west central portion of the state and in alluvial valleys in western Kansas, particularly along the Arkansas River valley from the Colorado state line to Garden City. Except for the highs in the river valleys, the higher temperatures were in the same general areas as those for the silica geothermometer temperatures, even though the one to one correlation on a local basis within the high areas was low.

The modified Na-K-Ca geothermometer, (adjusted for dissolved carbon dioxide), gave the lowest temperatures (-39.0 to 30.9°C) of all five geothermometers. The below-zero temperatures indicate that this geothermometer is not appropriate for the aquifer systems investigated. The higher temperatures ($>20^{\circ}\text{C}$) were distributed mainly within the northwestern area and partly in the west-central portion in Kansas. The patterns were relatively similar to those for the Na-K-Ca geothermometer.

The Na/K geothermometer temperatures were unreasonably high (31.4 - 657°C). The Na/K equation has been found before to fail at temperatures below 100 to 120°C and to yield improbably high temperatures for solutions with high calcium concentrations (Truesdell, 1975).

CORRELATION OF GEOTHERMOMETER TEMPERATURES WITH TEMPERATURE MEASUREMENTS AND GEOTHERMAL GRADIENTS

Stavnes prepared contour maps of the geothermal gradients and

subsurface temperatures at a depth of 300 meters using bottom-hole temperatures (BHT) from oil and gas records (Plates 2-1 and 2-2 of Chapter 2 of this report). Although she stated that the data were subject to errors from drilling mud effects, and that the temperatures computed for extreme northwestern Kansas are not valid, the relative changes in the data were examined for patterns that could be associated with geothermometer temperatures. The BHT map shows temperatures range from 20-30°C in the western two-thirds of Kansas, except for a few isolated locations with temperatures above and below this range. Generally, larger areas of lower temperatures occur in the southwestern part of the state. There are no noticeable differences to distinguish the other aquifer areas studied, except for two small areas in the northwestern corner of Kansas which have temperatures greater than 32°C. No distinctive differences were observed on the geothermal gradient map for the western two-thirds of the state. Values range from 20-35°C.

The statistical correlations between the chalcedony geothermometer temperatures and BHT values interpolated for the same 1,200 points is highly significant. However, the correlation coefficient is 0.33, meaning that only 11 percent of the variation in the geothermometer temperatures is explained. A similar result is expected for a correlation between the geothermometer temperatures and the geothermal gradients computed from the BHT data.

Stavnes also prepared maps of the distribution of the geothermal gradients and subsurface temperatures at a depth of 300 meters from thermal logging of boreholes, 22 of which were located in the western two-thirds of the

state (Plates 2-3 and 2-5 in Chapter 2 of this report). Geothermal gradients and temperatures are relatively high (42-59 °C/km and 78-85 °C/km, respectively) in the northwestern and parts of west-central Kansas. In the rest of western and central Kansas gradients and temperatures are relatively uniform, fluctuating from 24-40 °C/km and 22-25 °C/km, respectively.

The associations between the chalcedony geothermometer temperatures and both gradients and subsurface temperatures from borehole measurements are statistically highly significant. Correlation coefficients are 0.68 in both cases, giving coefficients of determination of 0.46. A graph of the 22 points for each correlation shows two general groups of points, one group of five at high geothermometer temperatures and gradients and subsurface temperatures, and the other group with little apparent correlation. Four of the points with higher values represent locations in northwestern Kansas, the other point is in west-central Kansas. The associations between the geothermometry and borehole data can also be observed visually by comparing the maps of both silica geothermometers with those for subsurface temperatures and gradients.

RELATIONSHIP BETWEEN GEOTHERMOMETER TEMPERATURES AND AQUIFER GEOCHEMISTRY

The areas of highest temperatures given by the quartz, chalcedony, and Na-K-Ca geothermometers are all located in northwestern Kansas and extend into the west-central regions of the state. Chemical data used for these areas of highs are for waters from the Ogallala aquifer. The sediments of this aquifer are composed mainly of arkosic gravel, sand, and silt of predominantly Pliocene age, although some Pleistocene sediments are present, especially in alluvial valleys. The sediments also contain calcite, volcanic ash, diatomaceous marl, opaline sandstone, and

bentonitic clay. The ash, opal, bentonite (indicating previous ash that has been weathered), and feldspar could be the major sources of higher concentrations of dissolved silica (Figure 8-5), rather than waters circulating from deeper strata with higher temperatures. The ash contains amorphous silica and the opal comprises hydrated, poorly-crystalline cristobalite, both of which are appreciably more soluble than quartz, the major component of the silts, sands, and gravels constituting the major aquifers of Kansas.

Volcanic ash was deposited in both the Pliocene and Pleistocene sediments of the aquifers. The ash layers are discontinuous, having been redistributed during erosion, mainly by water, into ponds and undrained depressions (Carey, et al., 1952). Thus, deposits are generally widely separated, commonly of lenticular shape, and vary in thickness up to nearly ten meters. The ash beds are often crossbedded and may show banding due to alternating coarse and fine layers. Locations of the larger beds are shown in Figure 8-6. Many of these deposits have been mined or listed as potential economic sources of ash. Average thicknesses of the economic lenses are generally between two and five meters at the center.

The ash beds of Kansas are classified predominantly as vitric tuff, at times containing trace amounts of quartz, sanidine, and biotite (Swineford and Frye, 1946; Swineford, et al., 1955). Differentiation of ash falls has been based on characteristics of the glass shards: index of refraction, particle size, shape, color, chemical composition, and presence or absence of second order vesicles. Pliocene ash is generally gray, has a greater specific gravity, and exhibits thin, slightly

curved, platy shards relatively free of vesicles compared to the nearly white Pleistocene ash which contains sharply curved shards with elongate vesicles.

Several petrographically distinct ash beds have been found in the Pliocene Ogallala Formation of Kansas (Swineford, et al., 1955). They occur primarily in the middle and lower members of the formation and comprise an estimated three percent of the total sediment volume. The deposits are located primarily in the northwestern part of the state (Carey, et al., 1952). Essentially all of the volcanic ash layers occurring in Pleistocene sediments were deposited within one stratigraphic member, but are distributed throughout much of Kansas as shown by Figure 8-6.

The source of the Pleistocene ash in Kansas has been attributed to volcanoes in north-central New Mexico (Swineford, 1949) and in the Yellowstone Park area of Wyoming and Idaho (Boellstorff, 1976). Landes (1928) found that coarser or heavier ash generally lies in the southwestern part of the state, while finer ash is located to the north and east, thereby suggesting a source to the southwest. Although little is known about the source area for pyroclastic material in the Ogallala Formation, most workers agree that the volcanic vents were west of the High Plains, probably in Wyoming, Colorado, or the Cordillera farther west (Stanley, 1976).

Silicified rock in the Ogallala Formation of Kansas can be directly linked to the Pliocene and Pleistocene ash. The rock consists of two major types: quartzite composed of sandstone and conglomerate with opaline cement, and chert consisting of opal, chalcedony, various

amounts of calcite and scattered sand grains (Frye and Swineford, 1946). The silicified rock is distributed widely with the largest deposits occurring in the northwestern and north-central parts of the state (Figure 8-6).

The quartzite occurs predominantly in the lower member of the Ogallala Formation. Irregular opal concretions and bentonitic clays are also present in the lower member. Opaline cement is widely distributed throughout the middle member of the Ogallala as discontinuous zones. Both the middle and lower members of the Ogallala contain most of the Pliocene ash. The leaching of this ash is thought to be the silica source forming the opaline cement in the quartzite. The water table is believed to have been high during the deposition of the Ogallala Formation (Frye and Swineford, 1946). Ash layers would have been subject to hydration and leaching shortly after accumulation. Subsequently, the dissolved silica precipitated as opaline cement. The presence of green quartzite containing ferrous iron in the lower Ogallala supports the theory of underwater formation of the opal. As the water table declined, the ash was often eroded, or, in some cases, an advanced state of leaching was reached before a return to normal groundwater conditions. Thus, much of the parent ash was removed.

The uppermost member of the Ogallala Formation contains discontinuous opal and chert composed of silt-sized clastics which are secondary replacements of calcium carbonate (Frye and Swineford, 1946). The source of this silica is considered to be the younger Pleistocene ash overlying the Pliocene sediments, the opal having been deposited by downward percolating waters in the vadose zone during a period of

arid climate in which caliche had formed.

The distribution of the dissolved silica concentrations in Figure 8-5 therefore appears to be consistent with the presence of volcanic ash and opaline cement. The higher silica concentration in groundwaters occur in the Ogallala aquifer, where the Pliocene ash and opal comprise a greater percentage of the sediment than in the Pleistocene deposits. The discontinuous nature of the ash and opaline cemented rocks could explain the variations in silica concentrations within regions of Kansas.

Although the main component of the volcanic glass constituting most of the ash is silica, relatively large amounts of potassium are present. For example, Swineford, et al. (1955) reported the mean silica content of 48 samples of late Tertiary ash deposits in western Kansas and western Nebraska to be 71.0 percent by weight (as SiO_2). The mean K_2O concentration of these samples is 5.53 percent which substantially exceeds the mean Na_2O content of 1.62 percent. Leaching of the ash could release much potassium. Although some of the potassium could be adsorbed by clays present in the sediments or formed from the ash weathering (bentonite), much would remain in solution due to competition for exchange sites by calcium, magnesium and sodium present in the groundwater. Feldspar in the Pliocene and Pleistocene sediments of Kansas is predominantly potassic and its weathering could also be a source of potassium as well as of dissolved silica in groundwaters. Therefore, the Na/K ratios derived from the ash and feldspar leaching would be higher in sediments with greater amounts of these materials and give high temperatures computed from the

Na/K and Na-K-Ca geothermometers.

A map (Figure 8-7) of the weight ratio of dissolved potassium to total dissolved solids (TDS) shows a distribution of high and low values somewhat similar to those for dissolved silica concentrations (Figure 8-5) and the Na-K-Ca geothermometer temperatures (Figure 8-4). Nearly all of the higher K/TDS ratios (>0.016) are located in northwestern and parts of west-central Kansas, with the highest values (>0.24) in a zone near the Nebraska border. Low ratios are found in the Arkansas River valley, the Equus Beds, and the eastern half of the Great Bend Prairie. Thus, the distribution of Na-K-Ca geothermometer temperatures could also be explained largely on the basis of sediment geochemistry rather than the circulation of deeper, warmer waters.

CONCLUSIONS

1. Geothermal temperatures computed from five chemical geothermometers for irrigation well waters from Kansas ranged widely. The chalcedony and Na-K-Ca geothermometers gave the most reasonable temperatures, ranging from $5-88^{\circ}\text{C}$ and from $3-86^{\circ}\text{C}$, respectively. Higher temperatures computed from both equations were distributed throughout northwestern Kansas and extended into the west-central part of the state. Quartz geothermometer temperatures were too high, Na/K equation temperatures much too high, and temperatures from a Na-K-Ca geothermometer modified for carbon dioxide generally much too low to be reasonable, including many values below 0°C .

2. The correlations between chalcedony geothermometer temperatures and both subsurface temperatures and geothermal gradients at 300 meters

derived from thermal logging of boreholes are statistically highly significant. Correlation coefficients are 0.68 in both cases. The distribution of the subsurface temperatures and geothermal gradients is similar to that for the geothermometer temperatures; higher values occur in northwestern and extend into west-central Kansas. The association between the chalcedony geothermometer temperatures and subsurface temperatures at 300 meters computed from bottom-hole temperatures of oil and gas wells is highly significant, but has a correlation coefficient of only 0.33.

3. The geochemistry of sediments in the aquifers, which are less than 200 meters in depth, appears to be the major control on dissolved silica and cation concentrations and, thus, the geothermometer temperatures computed from these concentrations. 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 in the northern part than elsewhere in the Ogallala Formation of western Kansas. The greater volumes of ash and opal (both 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 explain a similar distribution of higher ratios of dissolved potassium to total dissolved solids.

The areas of greater dissolved silica and K/TDS values also coincide with the regions of higher subsurface temperatures and heat flows under the Ogallala aquifer as determined from the measurements of Stavnes

(Chapter 2, this report) and the calculations of Swanberg and Morgan (1981), respectively. The higher temperatures underneath the northern half of the Ogallala may have increased the leaching of siliceous sediments. Thus, the effects of greater amounts of more soluble siliceous sediments and higher subsurface temperatures may have combined to give the areas of higher geothermometer temperatures. If the locations of larger ash and opal volumes in the aquifer sediments did not coincide with the region of higher temperatures, the distribution of geothermometer temperatures would be expected to conflict with the temperature distribution, for the sediment geochemistry is the more important control on groundwater composition.

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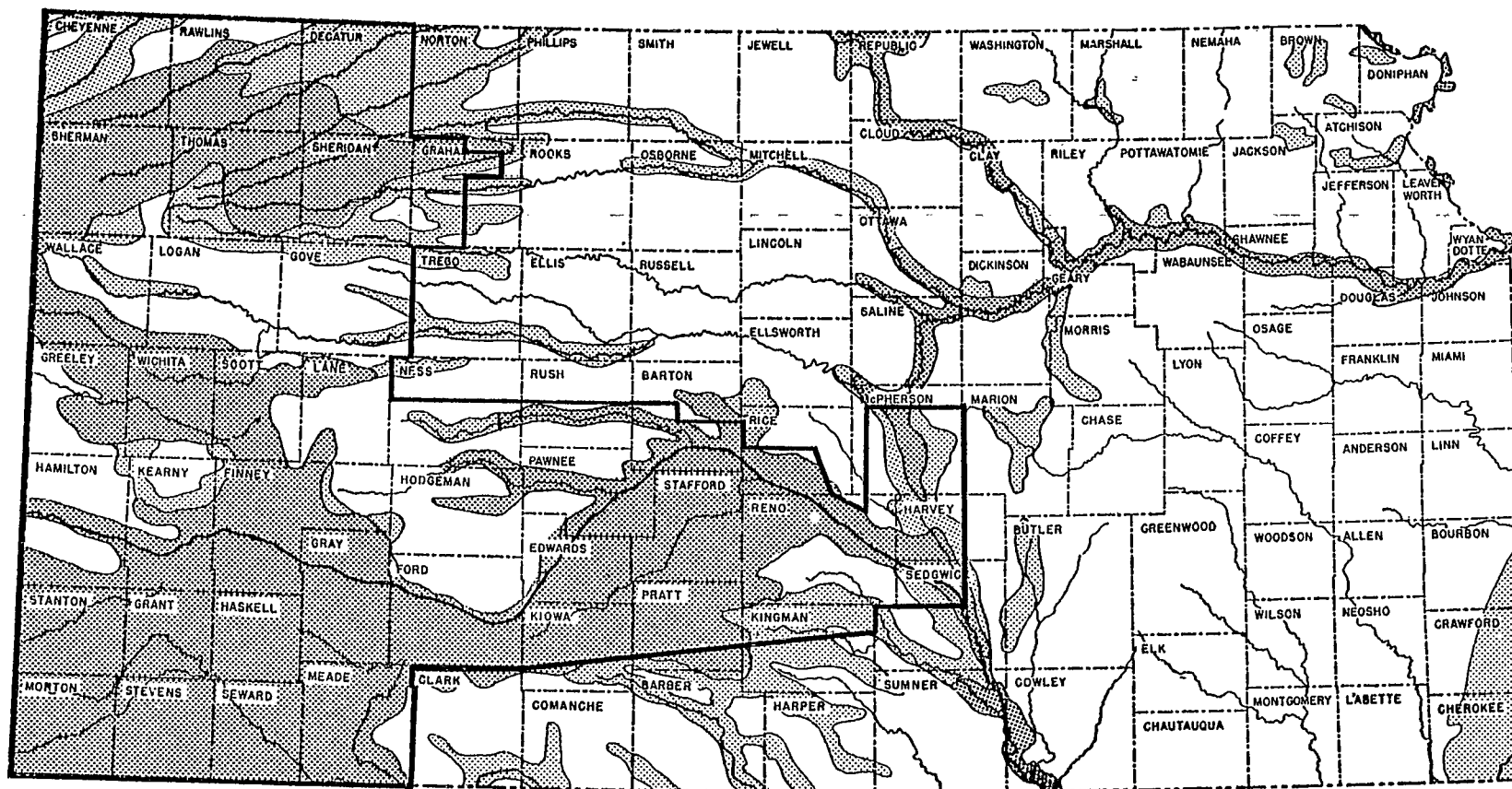
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FIGURE CAPTIONS

- FIGURE 8-1: Area of study.
- FIGURE 8-2: Distribution of quartz geothermometer temperatures.
- FIGURE 8-3: Distribution of chalcedony geothermometer temperatures.
- FIGURE 8-4: Distribution of Na-K-Ca geothermometer temperatures.
- FIGURE 8-5: Distribution of dissolved silica concentrations.
- FIGURE 8-6: Volcanic ash, siliceous rock, and related deposits of Kansas. Information compiled from Jewett and Schoewe, 1942; Carey, et al., 1952.
- FIGURE 8-7: Distribution of the weight ratio of dissolved potassium to total dissolved solids.

GENERAL AVAILABILITY OF GROUND WATER IN KANSAS



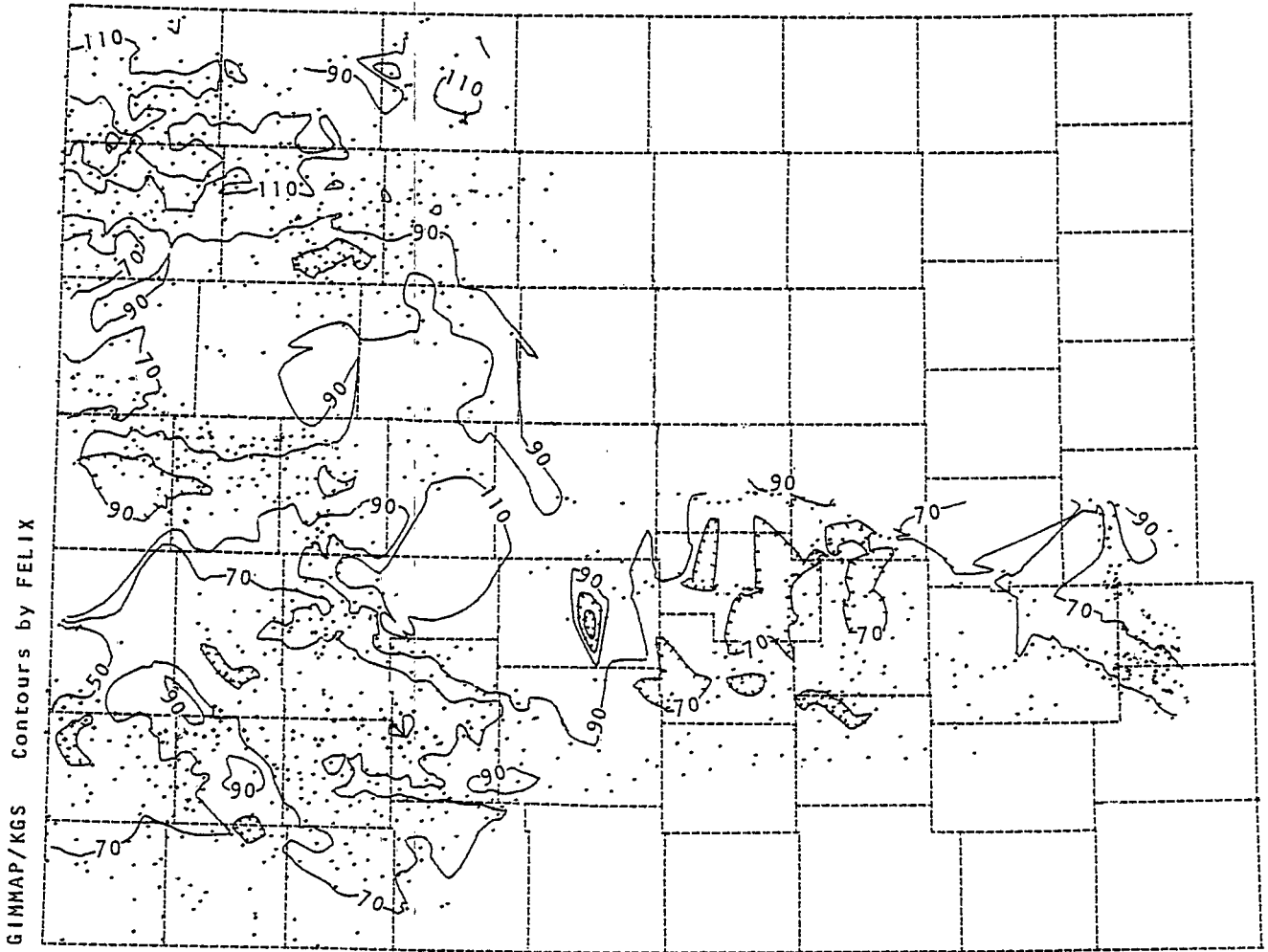
U.S. Geological Survey and State Geological Survey of Kansas

Revised February 1968

- Yield of less than 100 gallons of water a minute
- Yield of 100 to 500 gallons of water a minute
- Yield greater than 500 gallons of water a minute

FIGURE 8-1

QUARTZ GEOTHERMOMETER TEMPERATURES, °C



Western 2/3 of Kansas is shown
Contour Interval 20°C
Lambert conformal conical projection

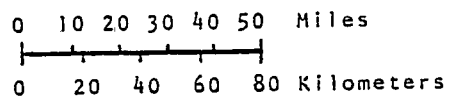
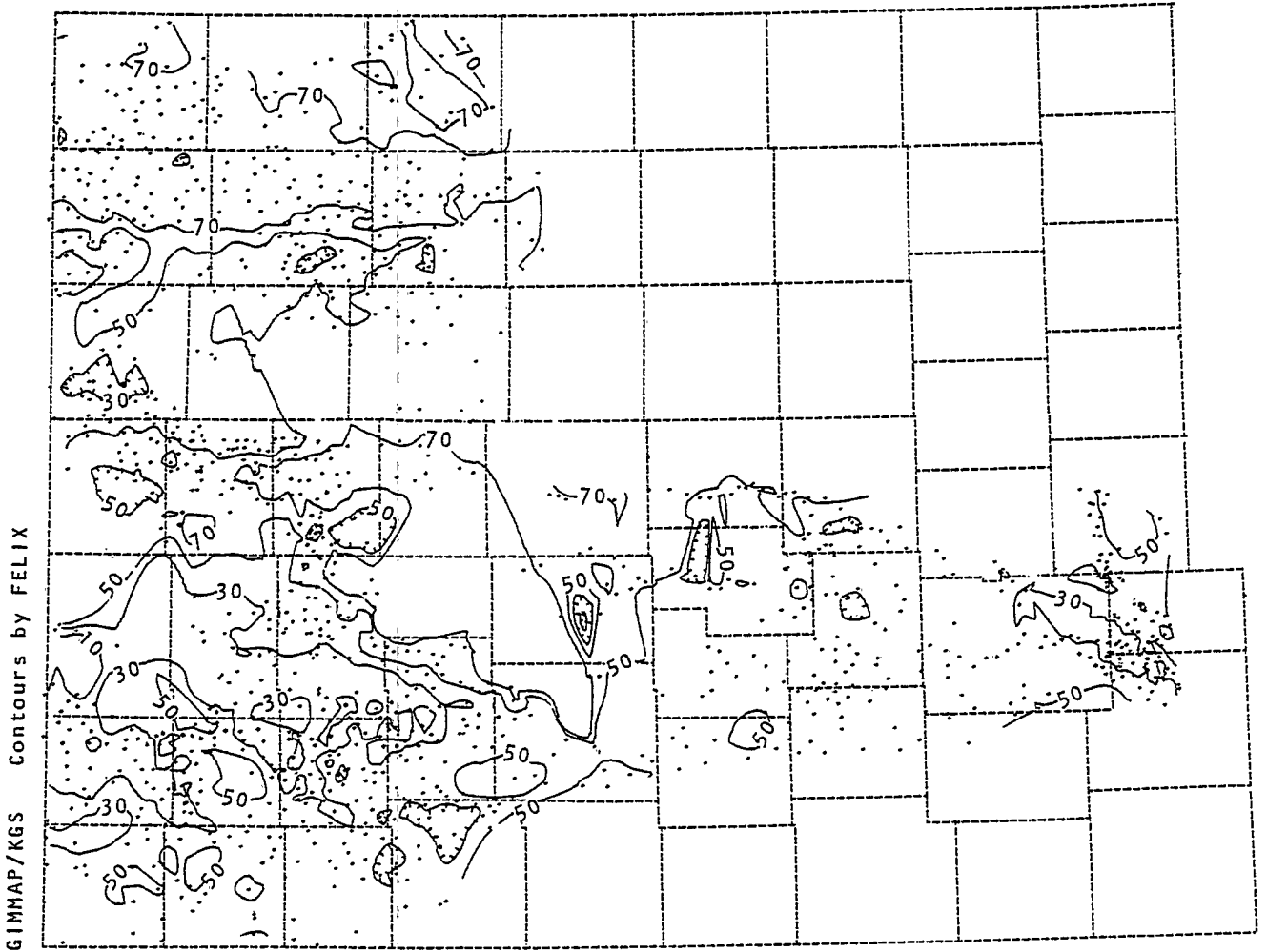


FIGURE 8-2

CHALCEDONY GEOTHERMOMETER TEMPERATURES, °C

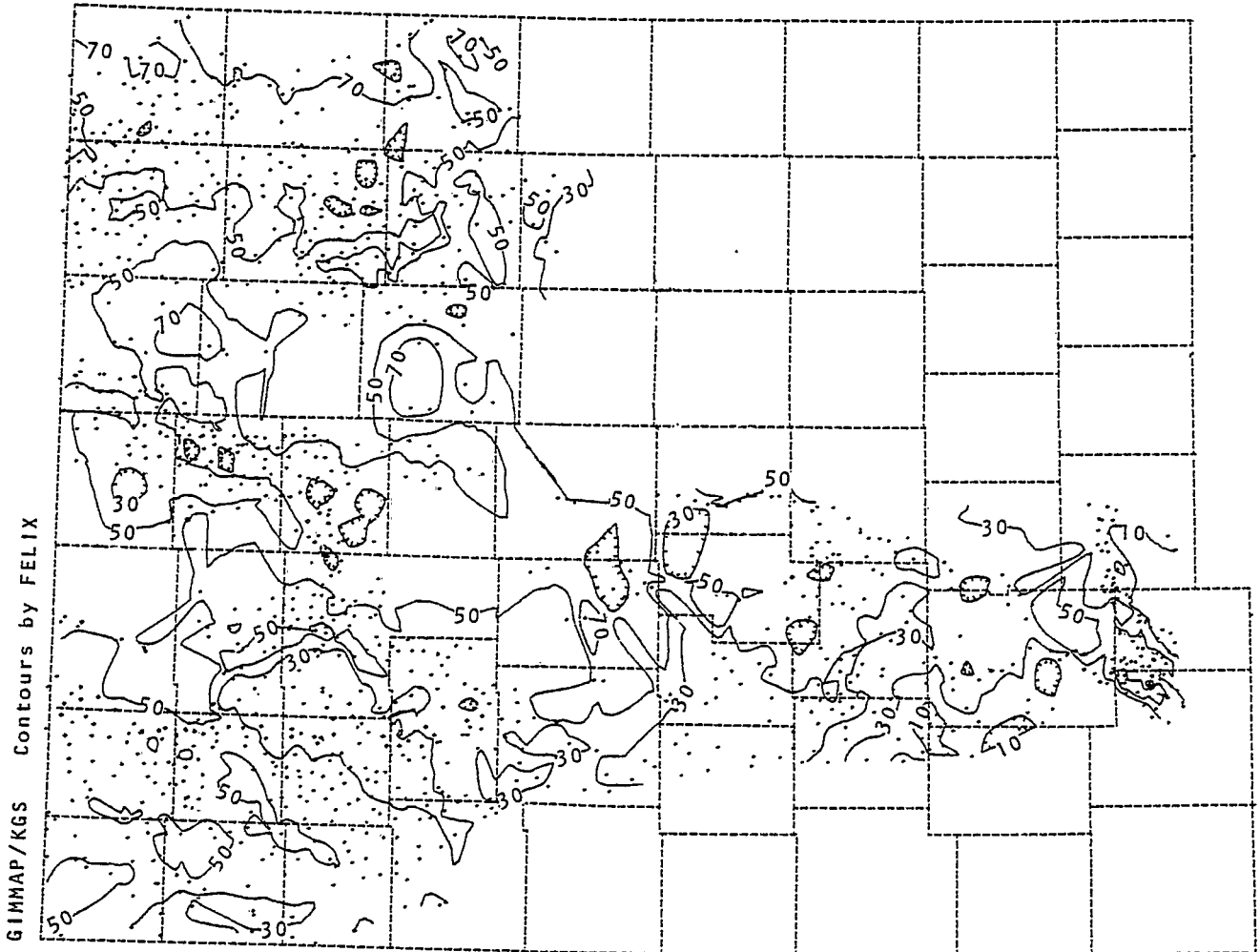


Western 2/3 of Kansas is shown
Contour Interval 20°C
Lambert conformal conical projection

0 10 20 30 40 50 Miles
0 20 40 60 80 Kilometers

FIGURE 8-3

NA - K - CA GEOTHERMOMETER TEMPERATURES, °C



Western 2/3 of Kansas is shown

Contour Interval 20°C

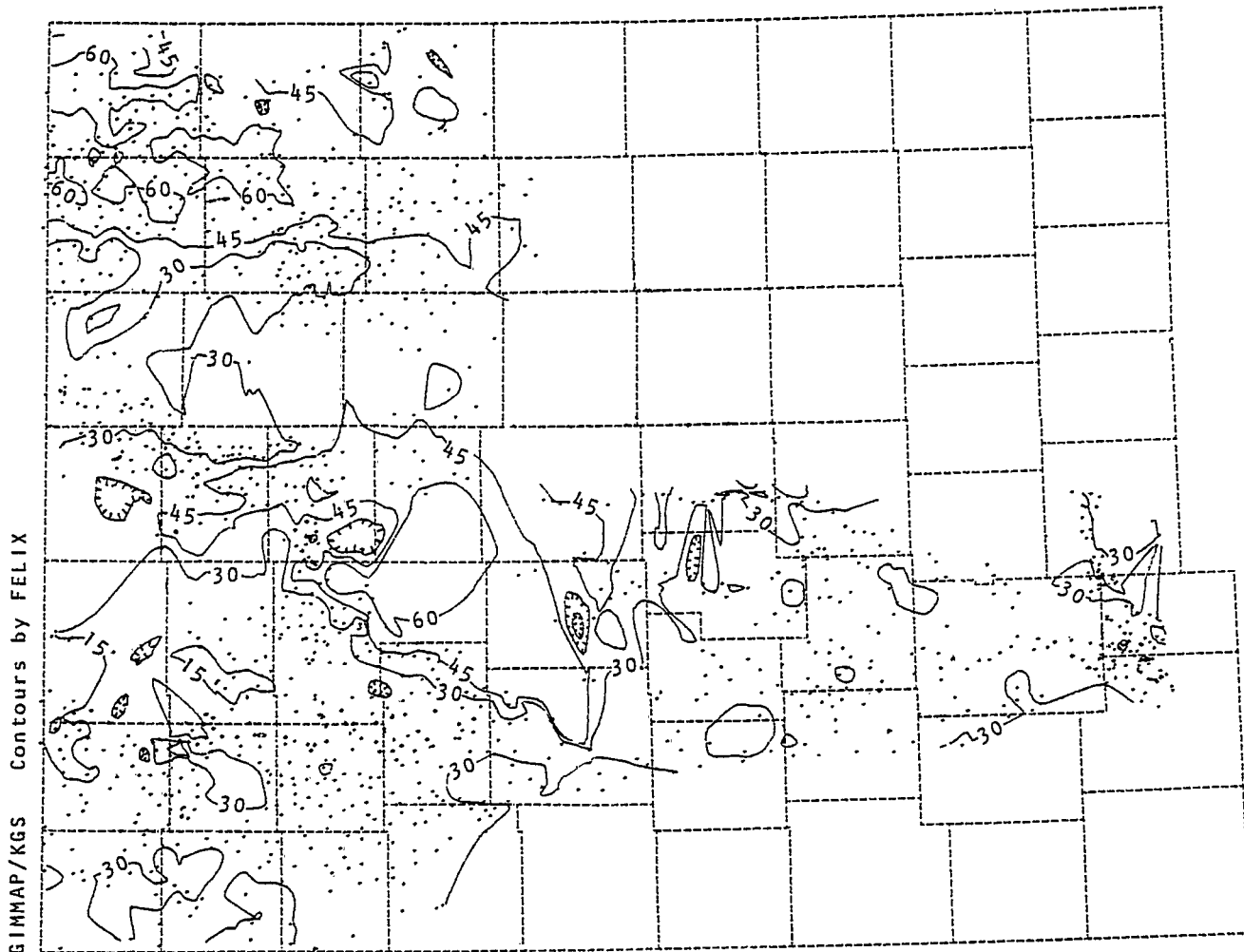
Lambert conformal conical projection

0 10 20 30 40 50 Miles

0 20 40 60 80 Kilometers

FIGURE 8-4

SILICA CONCENTRATIONS, mg/L



Western 2/3 of Kansas is shown
Contour Interval 15 mg/L
Lambert conformal conical projection

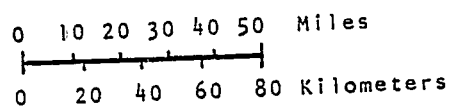


FIGURE 8-5

VOLCANIC ASH, SILICEOUS ROCK AND RELATED DEPOSITS OF KANSAS

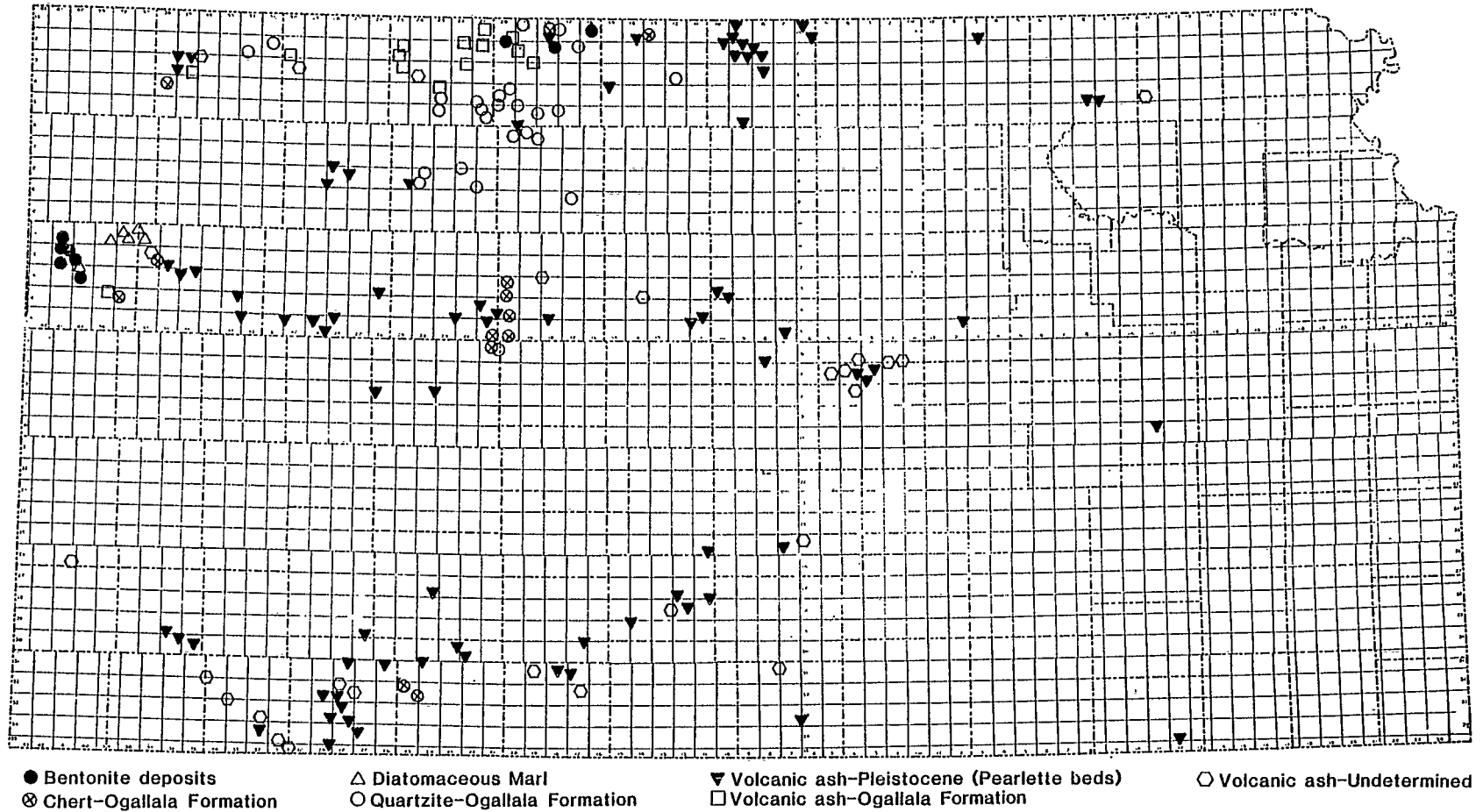
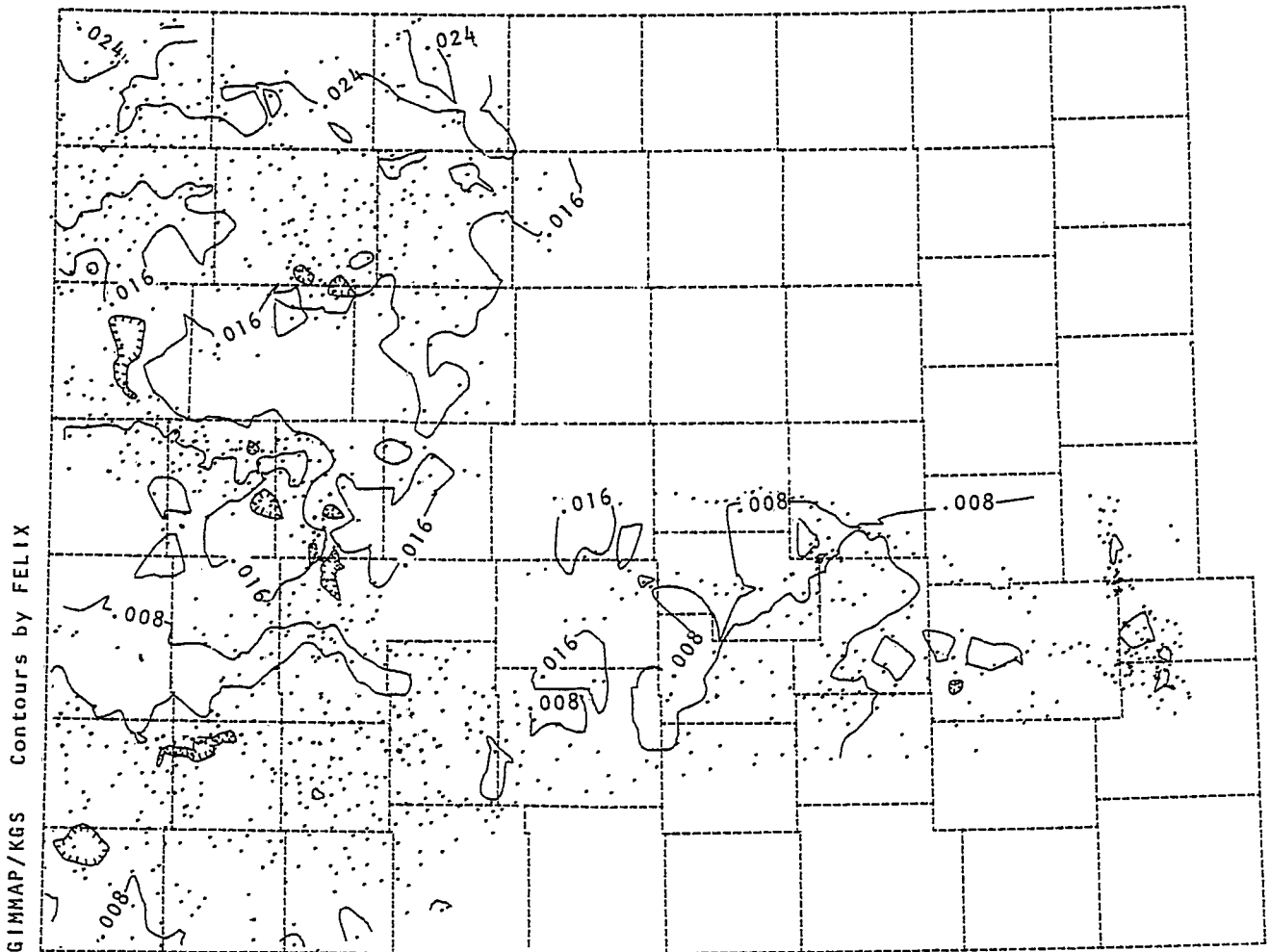


FIGURE 8-6

RATIO OF POTASSIUM, mg/L, TO TOTAL DISSOLVED SOLIDS, mg/L



Western 2/3 of Kansas is shown
Contour Interval .008
Lambert conformal conical projection

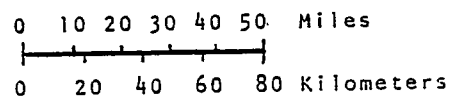


FIGURE 8-7

CONCLUSIONS

Geothermal gradients measured for this report and data from oil well records indicate that geothermal resources in Kansas are of a low-grade nature. However, considerable variation in the gradient is noted statewide within the upper 500 meters of the sedimentary section; this suggests the feasibility of using groundwater for space heating by means of heat pumps.

The silica geothermometer data indicate an area of high dissolved silica content in northwestern Kansas that is consistent with silica content derived from volcanic ash deposits or, perhaps, from the siliceous Ogallala aquifer. The presence of a high temperature source for subsurface waters in northwestern Kansas cannot be inferred from their silica geothermometry.

The gravity and aeromagnetic data are valuable assets in basement geologic interpretation. Yarger has shown in his reports that a complex Precambrian history is recorded in the Kansas crust. His conclusions suggest that the Wichita aeromagnetic low and the southern extension of the MGA are possible future sites for deep geothermal exploration if the Hot Dry Rock Project is shown to have long-term profit potential.

Preliminary analyses of data from the Consortium for Continental Reflection Profiling (COCORP) indicate a probable thickness of as much as 3 to 4 km for the Rice Formation, a Precambrian arkosic unit that flanks the MGA. Yarger's modeling of gravity and aeromagnetic data indicates a similar thickness for the Rice Formation as the COCORP data. The possible development of the Rice Formation as a geothermal aquifer cannot be ruled out at this time. The water quality and transmissivity of the aquifer are, however, unknown.

None of the presently available data lead us to believe that geothermal gradients below 1 km depth exceed 30 to 40 °C/km.

Additional conclusions are enumerated by individual authors.