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HEAT FLOW AND GEOTHERMAL POTENTIAL OF KANSAS

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ABSTRACT

Temperature, thermal conductivity measurements and heat flow values are presented for four holes originally drilled for water resources investigations by the U.S. Geological Survey. 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 5 wells are also presented. Temperature gradients in the sedimentary section vary over a large range (over 4:1), and there are significantly different temperatures at the same depth in different portions of the state. Temperatures as high as 34°C occur at a depth of 500 m in the south-central portion of the state and 28°C or lower in other parts of the state. In addition to cuttings measurements, thermal conductivities were estimated from geophysical well log parameters; the results are useful and more use of the technique is suggested. Using these results geophysical well logs can be used to predict temperatures as a function of depth in areas for which no temperatures are available if heat flow is assumed. The extreme variation in gradients observed in the holes occur because of the large contrast in thermal conductivity values. Shale thermal conductivity values appear to have been overestimated in the past and the Paleozoic shales in Kansas have thermal conductivity values of about 1.18 ± 0.03 $Wm^{-1}K^{-1}$. On the high side, evaporite and dolomite units have thermal conductivities of over 4 $Wm^{-1}K^{-1}$. In spite of the large variations of gradient the heat flow values throughout the

holes do not vary more then 10% and any water flow effects which might be present due to the lateral motion on any of the aquifers are less than 10%. 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 suggest that the heat flow-heat production line postulated for 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 then 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.

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+ 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; see 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 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 are 12S/17E-13bbd, 13S/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 portable hand operated equipment. Most of the holes were logged with a digital recording system attached to the output of the digital 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 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 A 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. Geological Survey. These results are given in Appendix B. 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 $Wm^{-1}K^{-1}$ for the bottom part of hole 13S/2W-32ccc (see Robertson, 1975).

GEOTHERMAL 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 1 and on Figure 1, a generalized index map of Kansas. The holes will be individually discussed preceding 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 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 2a and 2b are the shales. The water table was just above 100 m and the first reliable gradients are below 105 m.

TABLE 1. Location data for holes logged.

Township/Range -Section	North Latitude	West Longitude	Hole Name	Date Logged	Collar Elevation	Depth Logged
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).

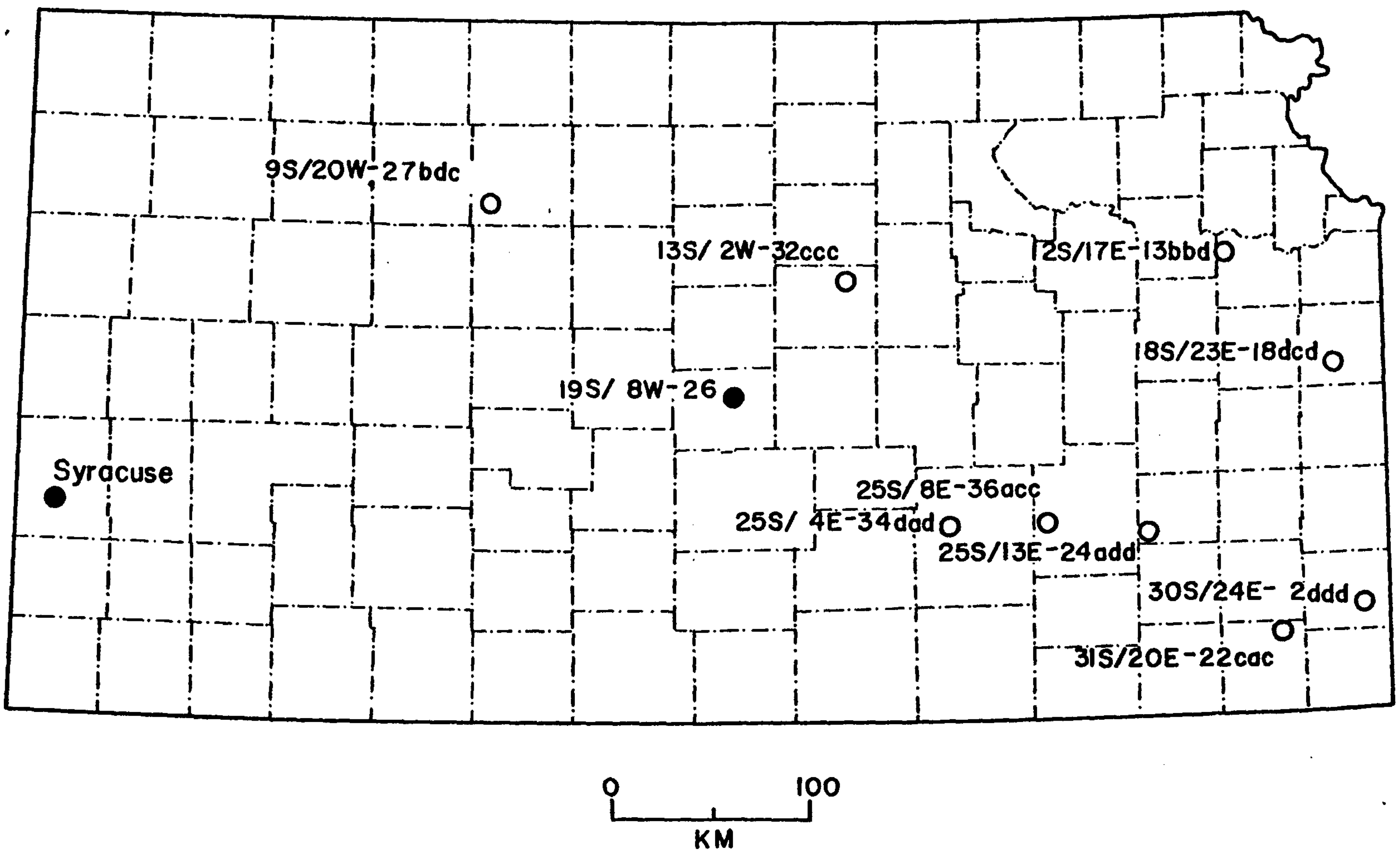


FIGURE 1. Index map of sites of published heat flow values (solid circles) and sites of holes discussed in this report (open circles).

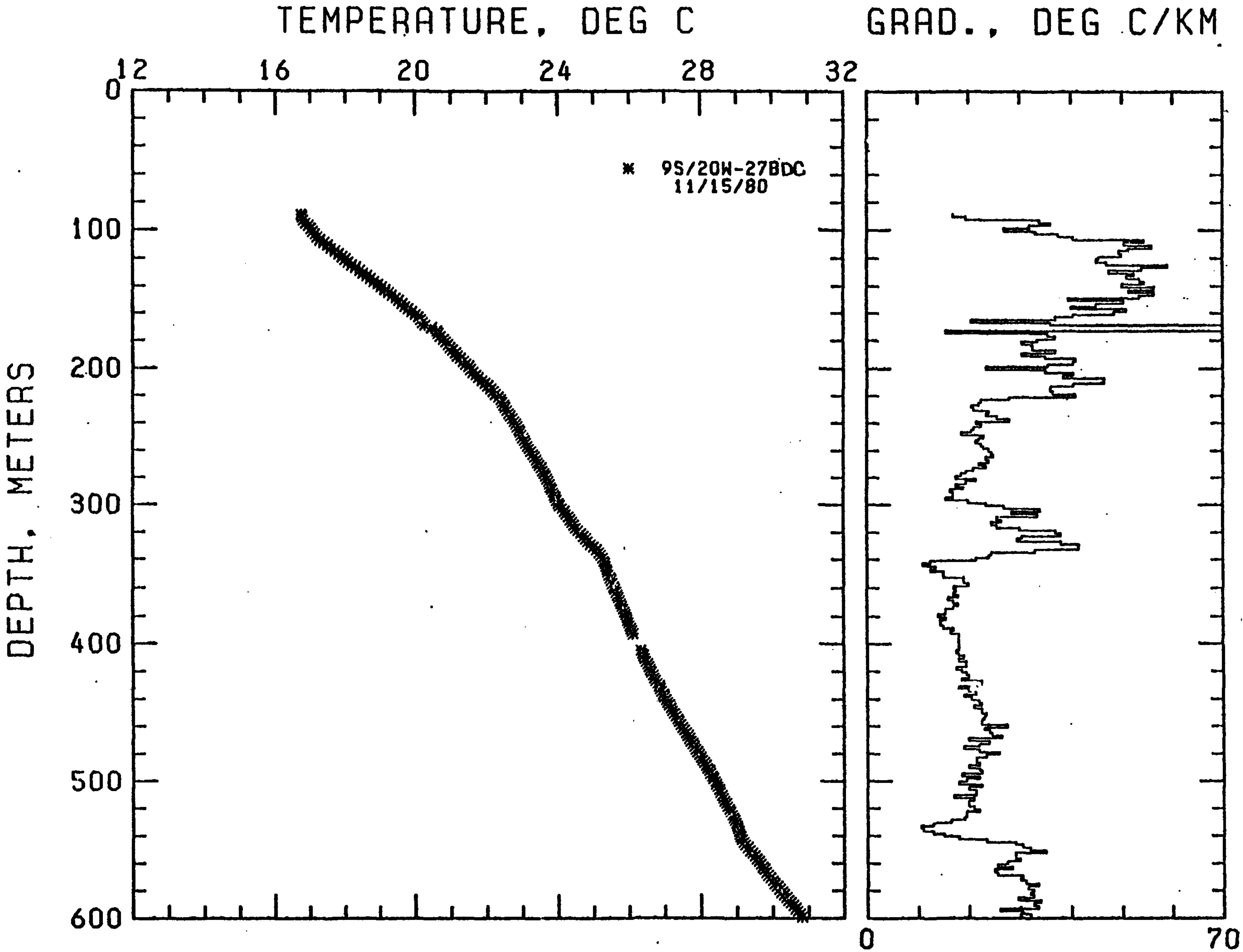


FIGURE 2A. Temperature-depth and gradient-depth curves for hole 9S/20W-27bdc. Two-meter gradient intervals are plotted.

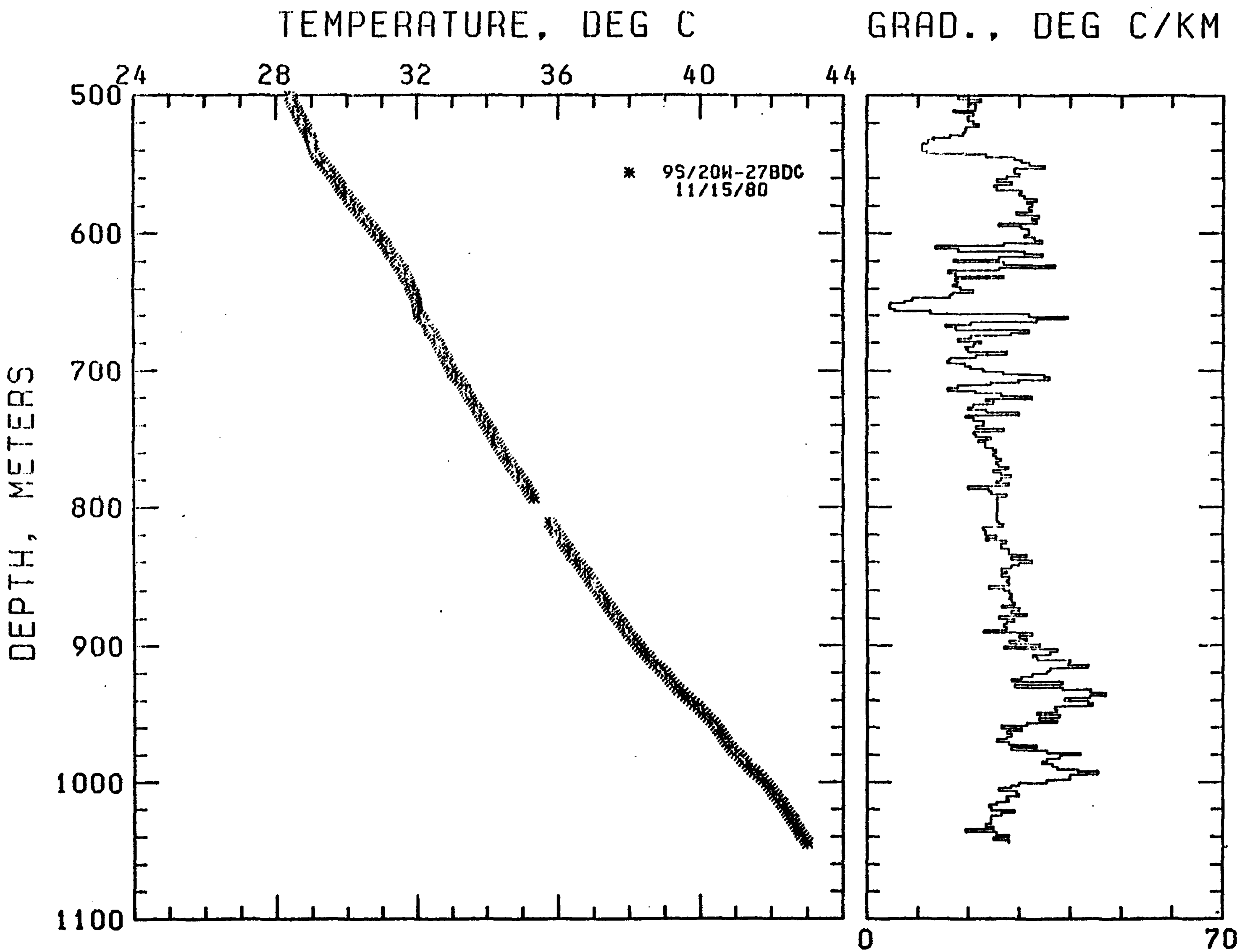


FIGURE 2B. Temperature-depth and gradient-depth curves for hole 9S/20W-27bdc. Two-meter gradient intervals are plotted.

There a section 60 m thick between 105 m and 165 m has a mean gradient of 50.5 ± 0.3°C/km. Below that section the gradient drops to approximately 37.5 ± 0.5°C/km to a depth of 221 m at which point the gradient drops to values generally less than 30°C/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 ± 1.8°C/km. In the Permian section (450-900 m) the mean gradient is 24.2 ± 0.3°C/km and in the Pennsylvanian section (900-1045 m) the mean gradient is 33.6 ± 0.3°C/km. In the Pennsylvanian section the gradients are variable ranging from 45°C/km in the predominantly shale units to 25°C/km in the more limestone rich units. Temperatures are somewhat lower in this hole then 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. The gradient in the Pennsylvanian section between 120 m and 521 m ranges

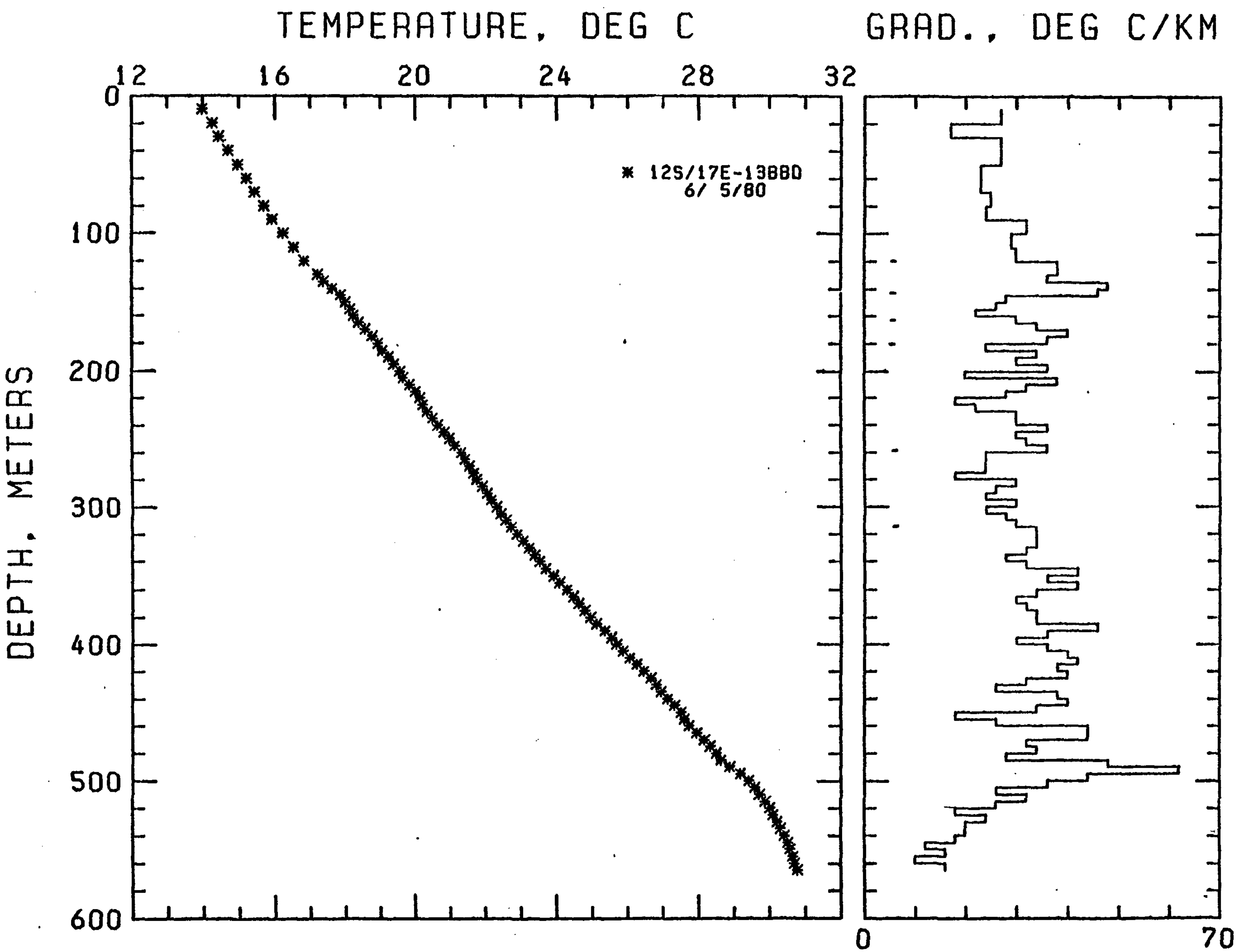


FIGURE 3. Temperature-depth and gradient-depth curves for hole 12S/17E-13bbd. Five-meter gradient intervals are plotted.

from 25°C/km to just over 40°C/km and averages 32.1 ± 1.0°C/km. In the Pre-Pennsylvanian carbonate section below 520 m(to 565 m) the mean gradient is 17.1 ± 0.1°C/km.

Temperature-depth curves and bar graphs of gradient for hole 13S/12W-32ccc are shown in Figure 4. This hole was drilled for the U.S. Geological Survey 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 (see Figure 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 ± 0.6°C/km. The mean gradient in the Pennsylvanian section (280-792 m) is 31.9 ± 0.6°C/km. Below 792 m in the Pre-Pennsylvanian section the units are more monolithologic and there is a good correlation between lithology and gradient (Figure 4c). The section of high gradient between 558-598 m corresponds to the Lawrence shale. The gradient in this section is 48.6 ± 0.1°C/km. The mean gradient between 736 and 796 m in the Cherokee shale is 36.9 ± 0.2°C/km while the mean gradient in the Chattanooga shale between 862 and 912 m is 52.1 ± 0.1°C/km.

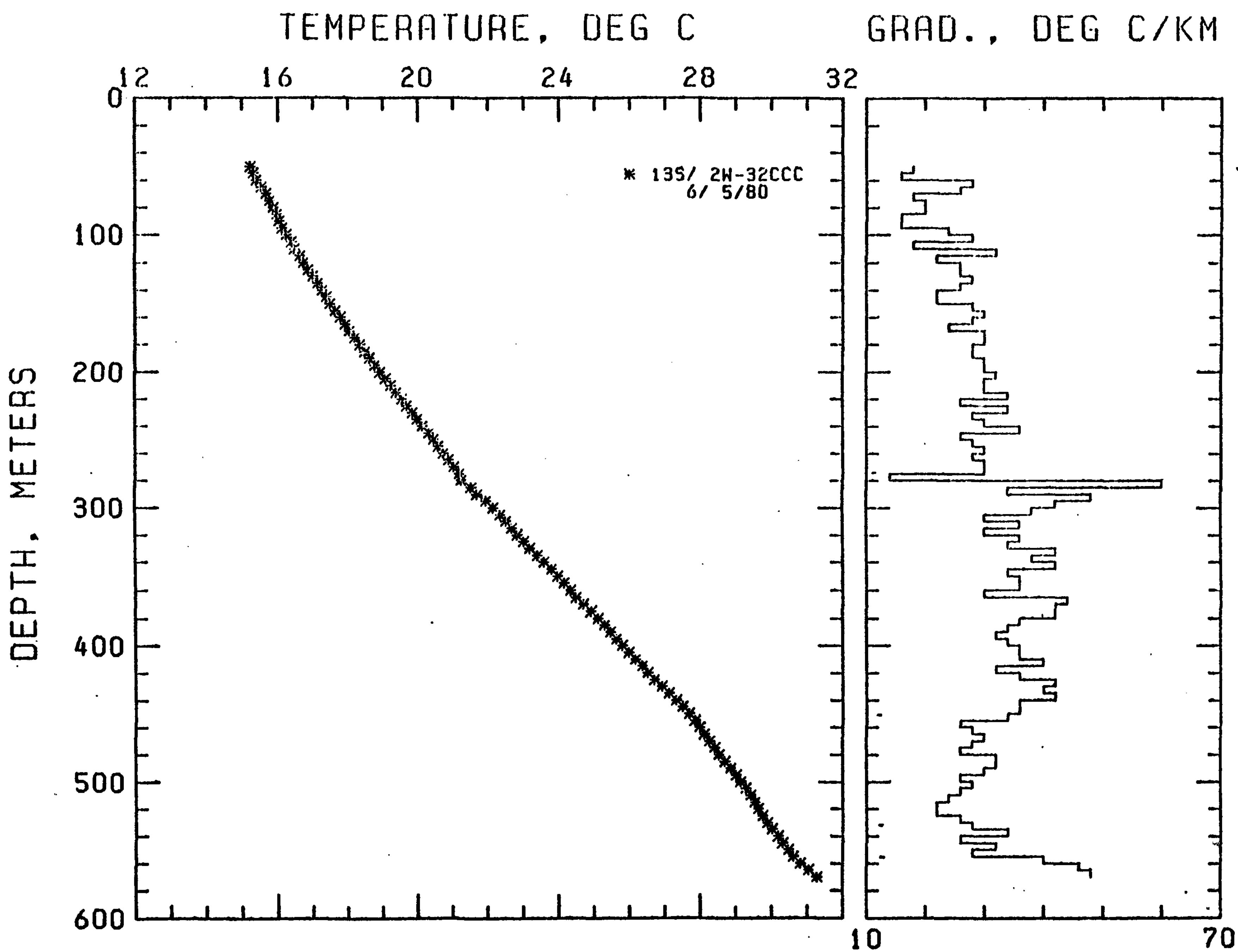


FIGURE 4A. Temperature-depth and gradient-depth curves for hole 13S/2W-32ccc. Five-meter gradient intervals are plotted.

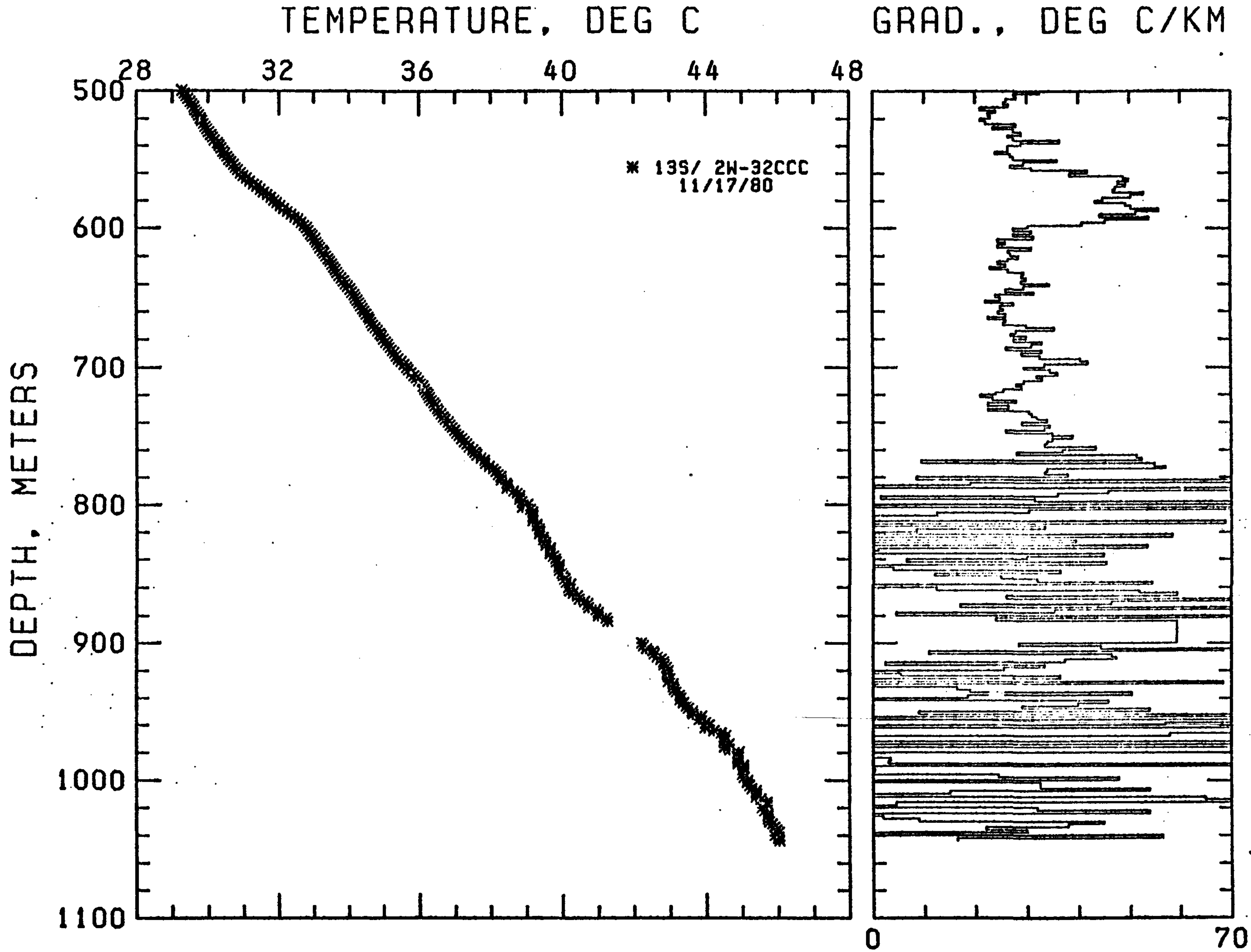


FIGURE 4B. Temperature-depth and gradient-depth curves for hole 13S/2W-32ccc. Two-meter gradient intervals are plotted.

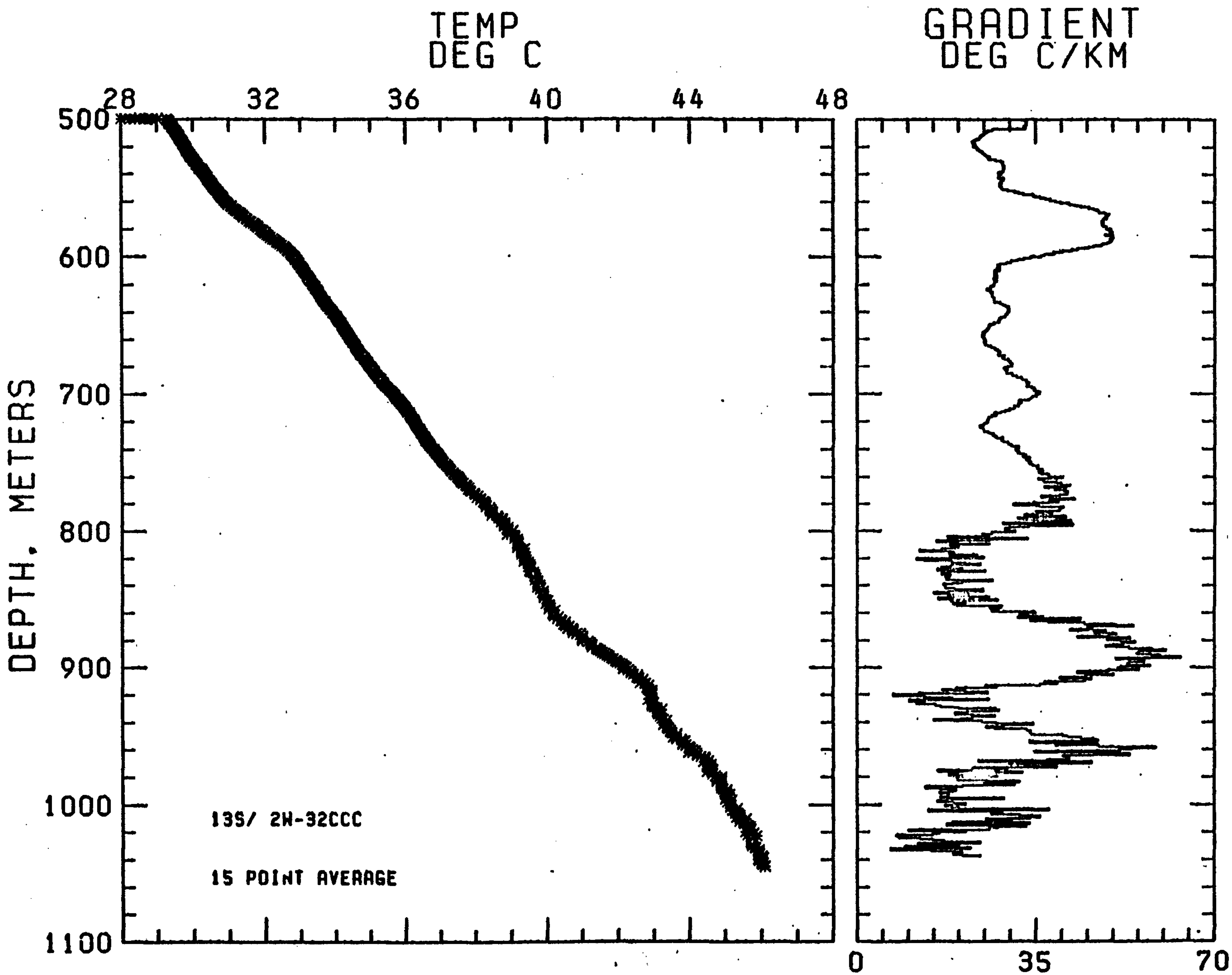


FIGURE 4C. Temperature-depth and gradient-depth curves for hole 13S/2W-32ccc. Fifteen-meter running average gradient values are plotted.

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. Geological Survey. 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 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 predominately 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 6;

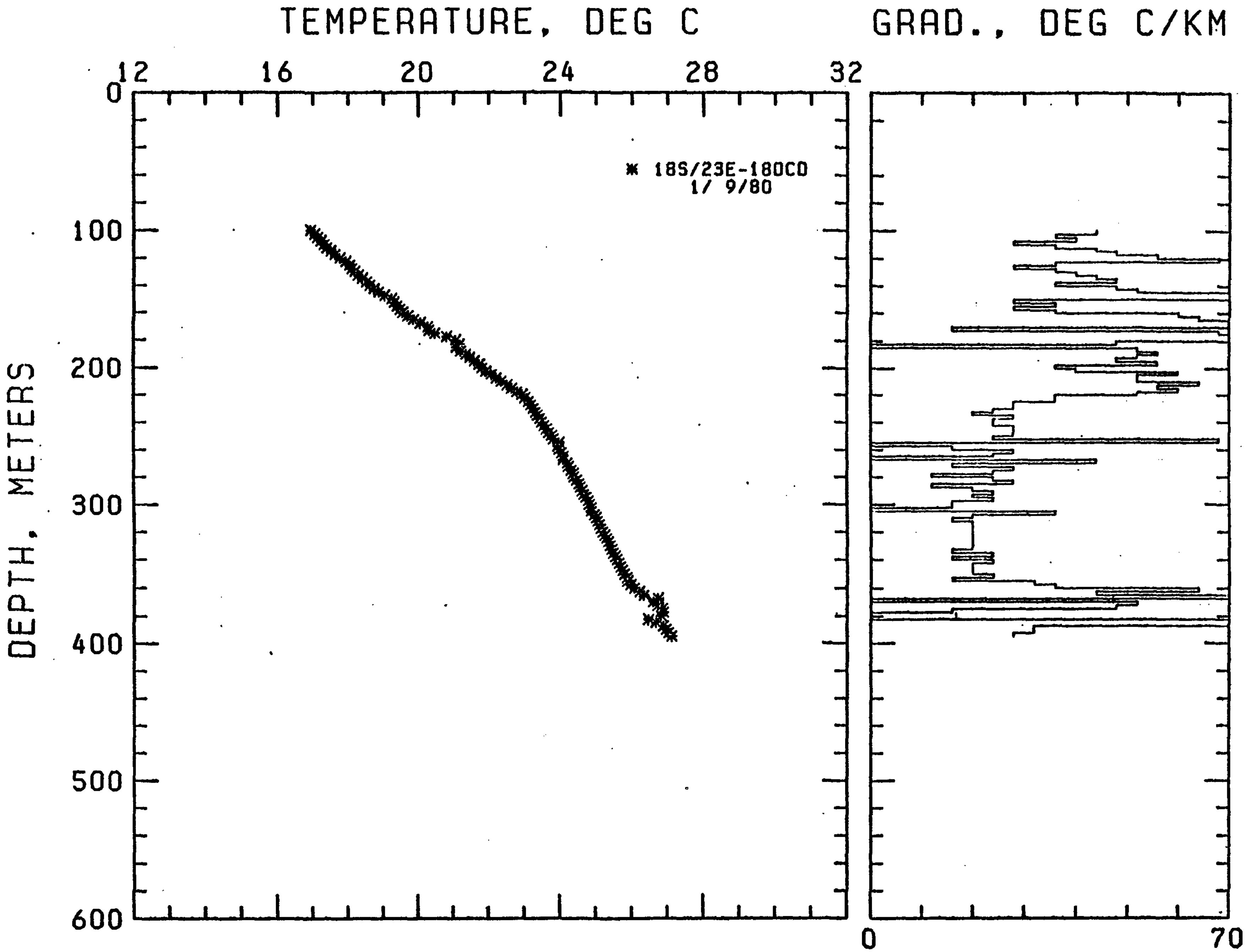


FIGURE 5. Temperature-depth and gradient-depth curves for hole 18S/23E-18dcd. 2.5-meter gradient intervals are plotted.

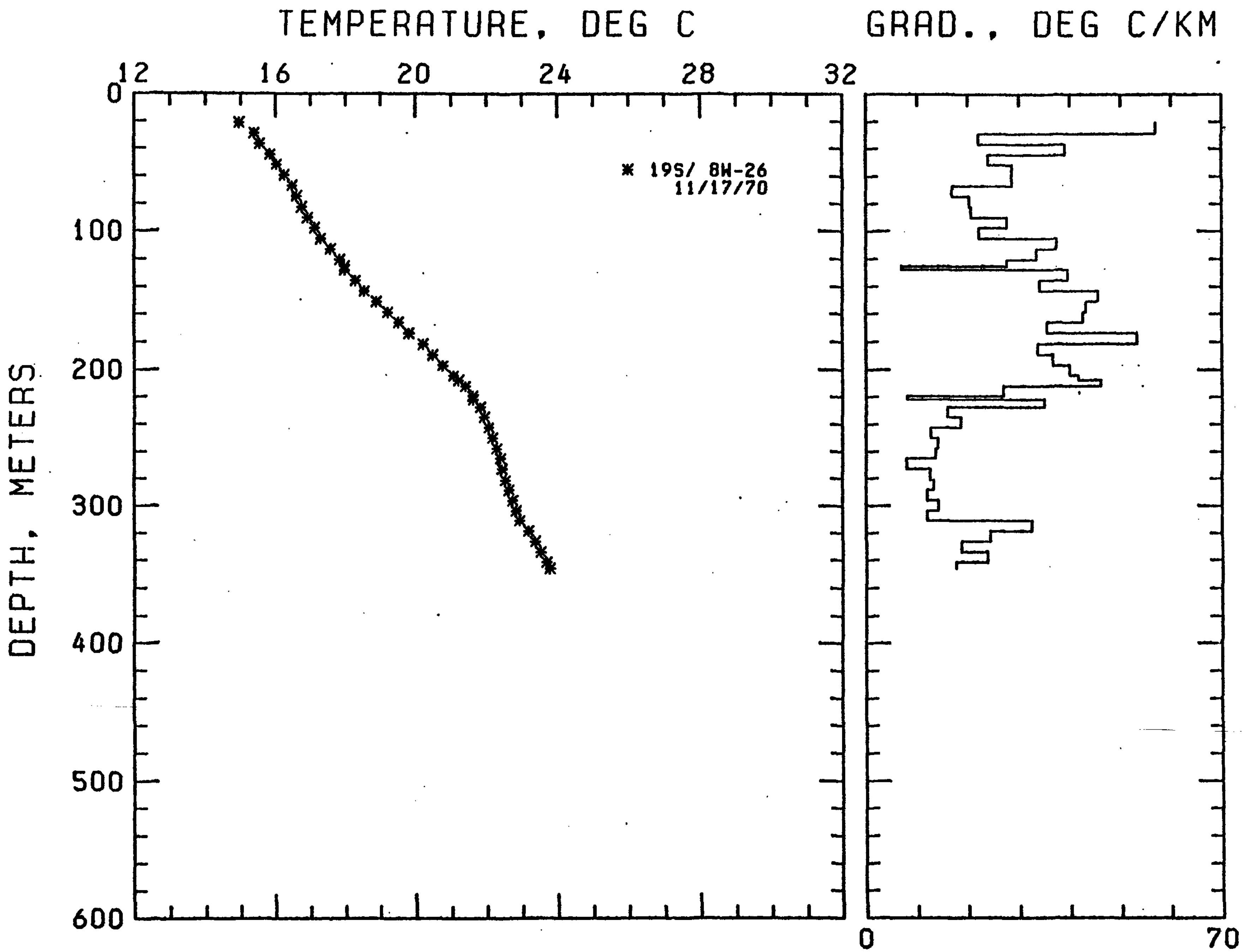


FIGURE 6. Temperature-depth and gradient-depth curves for hole 19S/8W-26 (Sass et al., 1971a).

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 south center part of the state, holes 25S/4E-34dad, 25S/8E-36acc and 25S/13E-23add. These holes are predominately 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 7a and 7b and 8. The mean gradient for hole 25S/4E-34dad between 200 and 737 m is 35.6 ± 0.6°C/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 ± 0.4°C/km between 200 and 390 m.

A temperature-depth curve and a gradient bar graph for hole 25S/13E-24add are shown in Figure 9. In this hole there is a variation of 10-20 m interval gradients from about 25 to 55°C/km. From a comparison

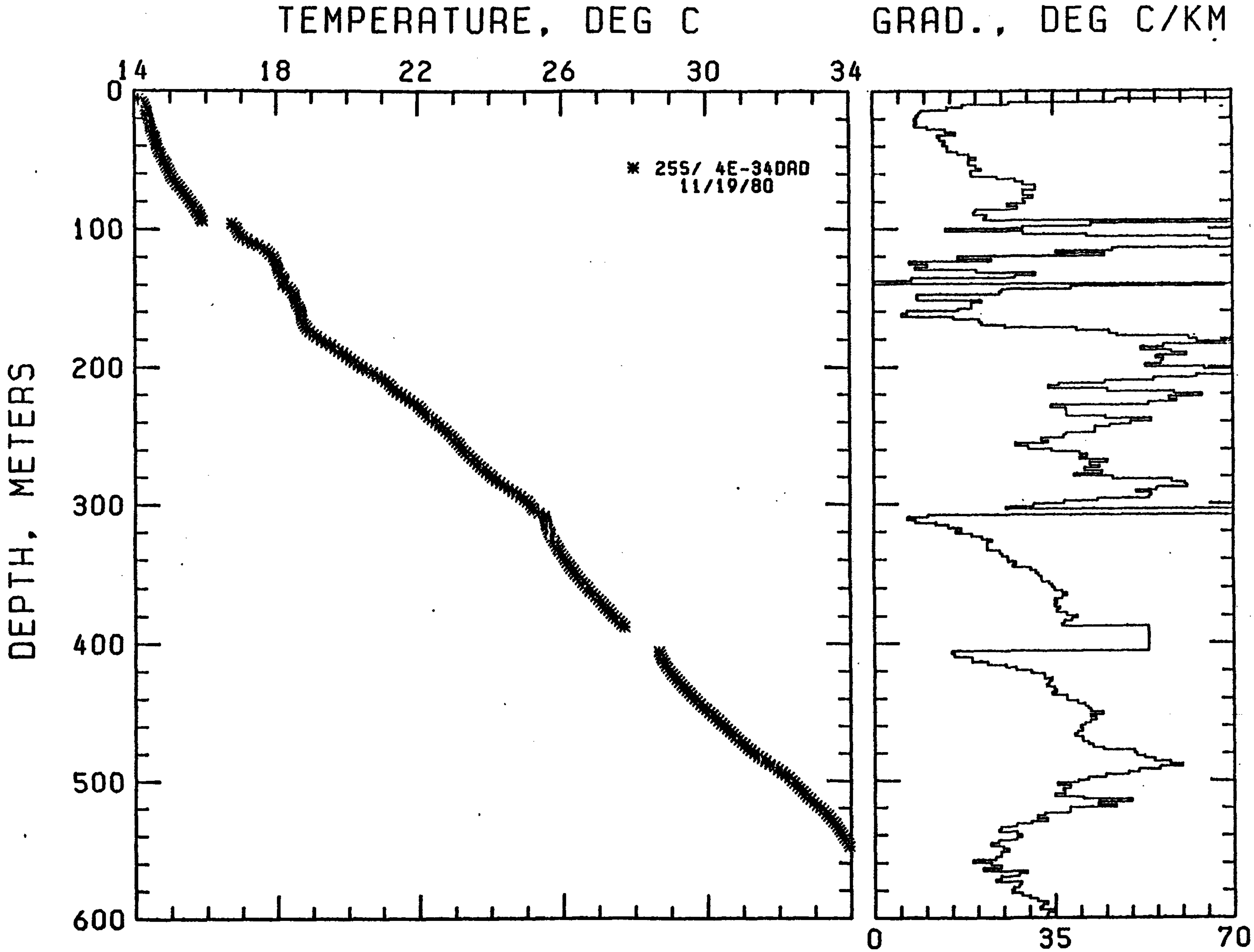


FIGURE 7A. Temperature-depth and gradient-depth curves for hole 25S/4E-34dad. Two-meter gradient intervals are plotted.

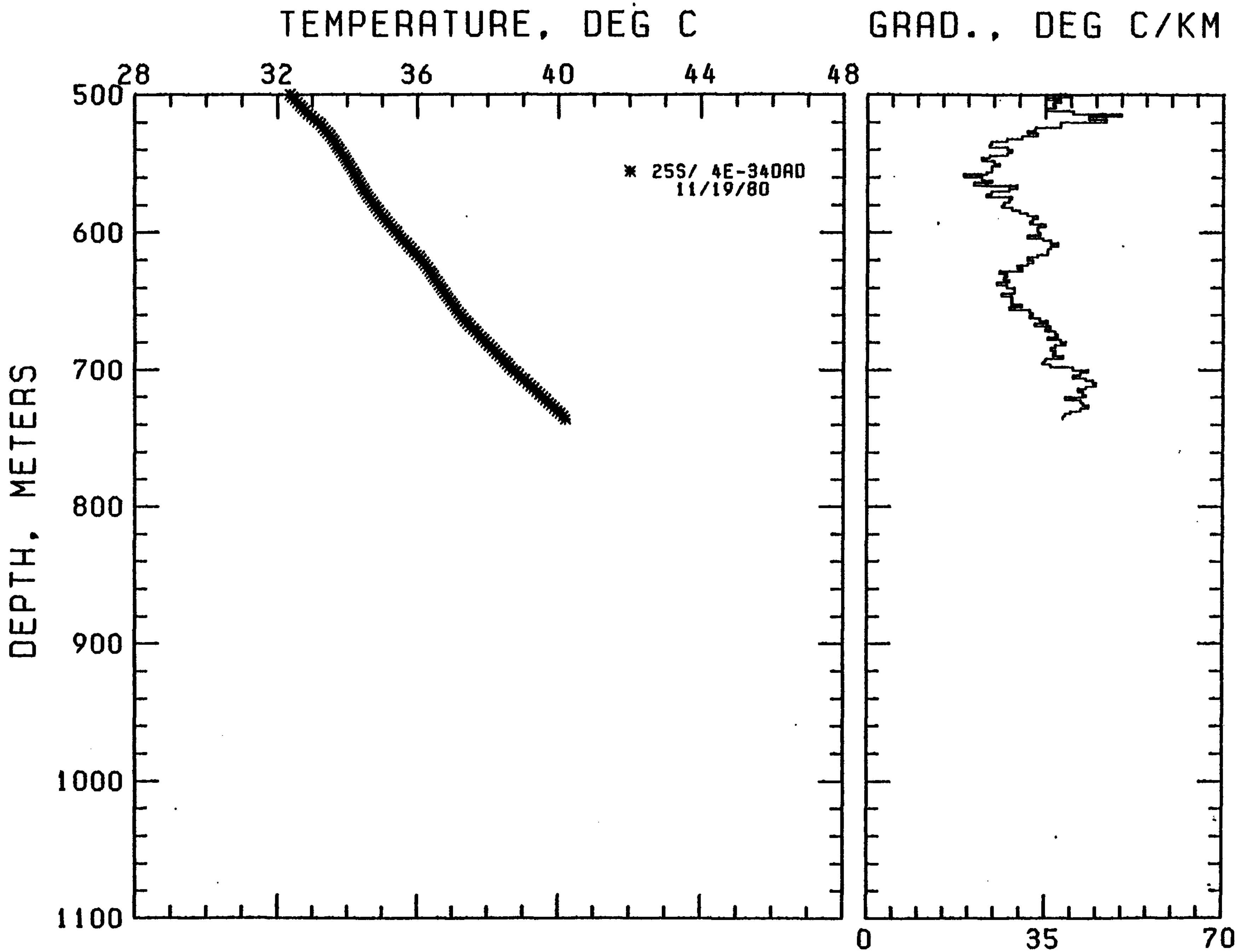


FIGURE 7B. Temperature-depth and gradient-depth curves for hole 25S/4E-34dad. Two-meter gradient intervals are plotted.

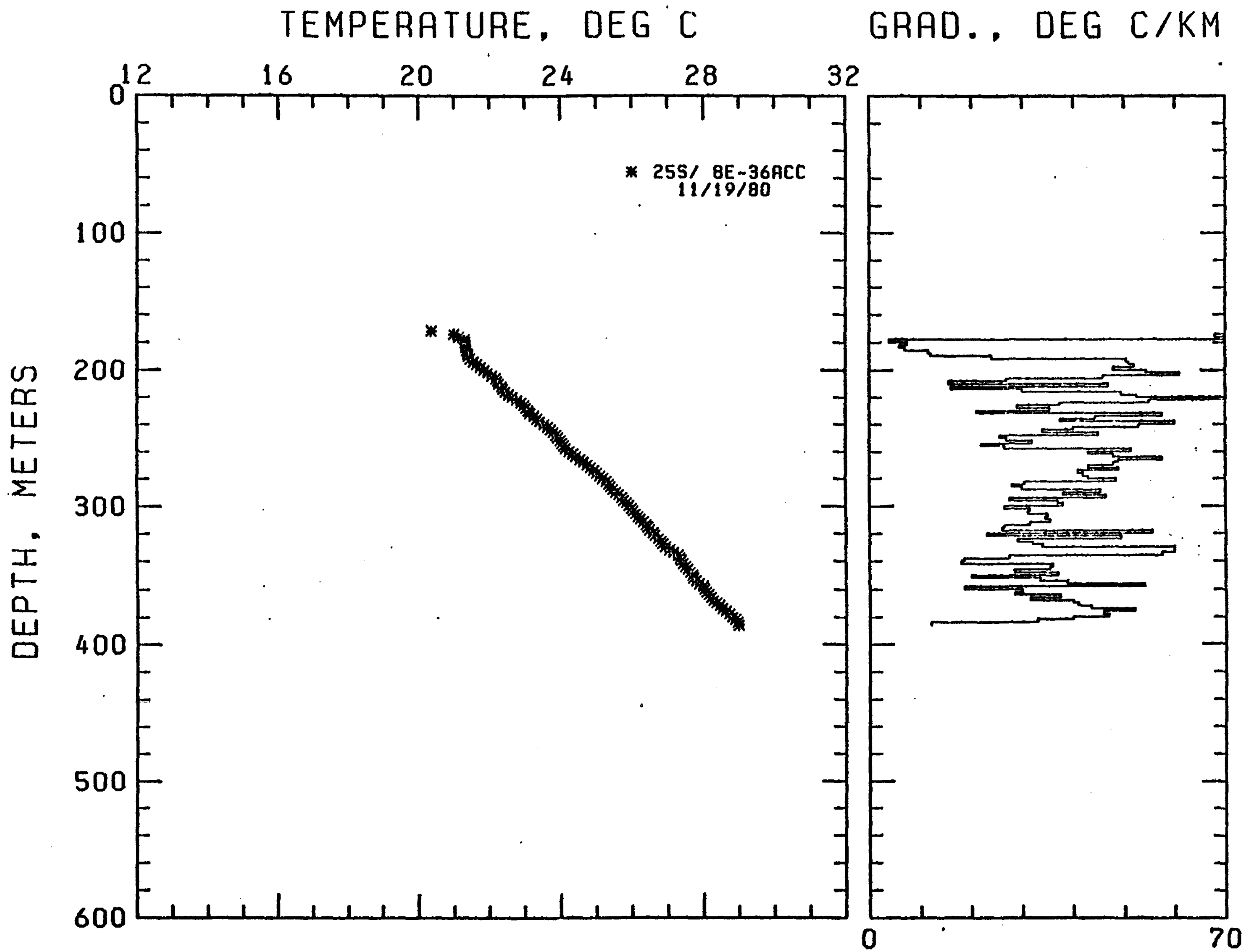


FIGURE 8. Temperature-depth and gradient-depth curves for hole 25S/8E-36acc. Two-meter gradient intervals are plotted.

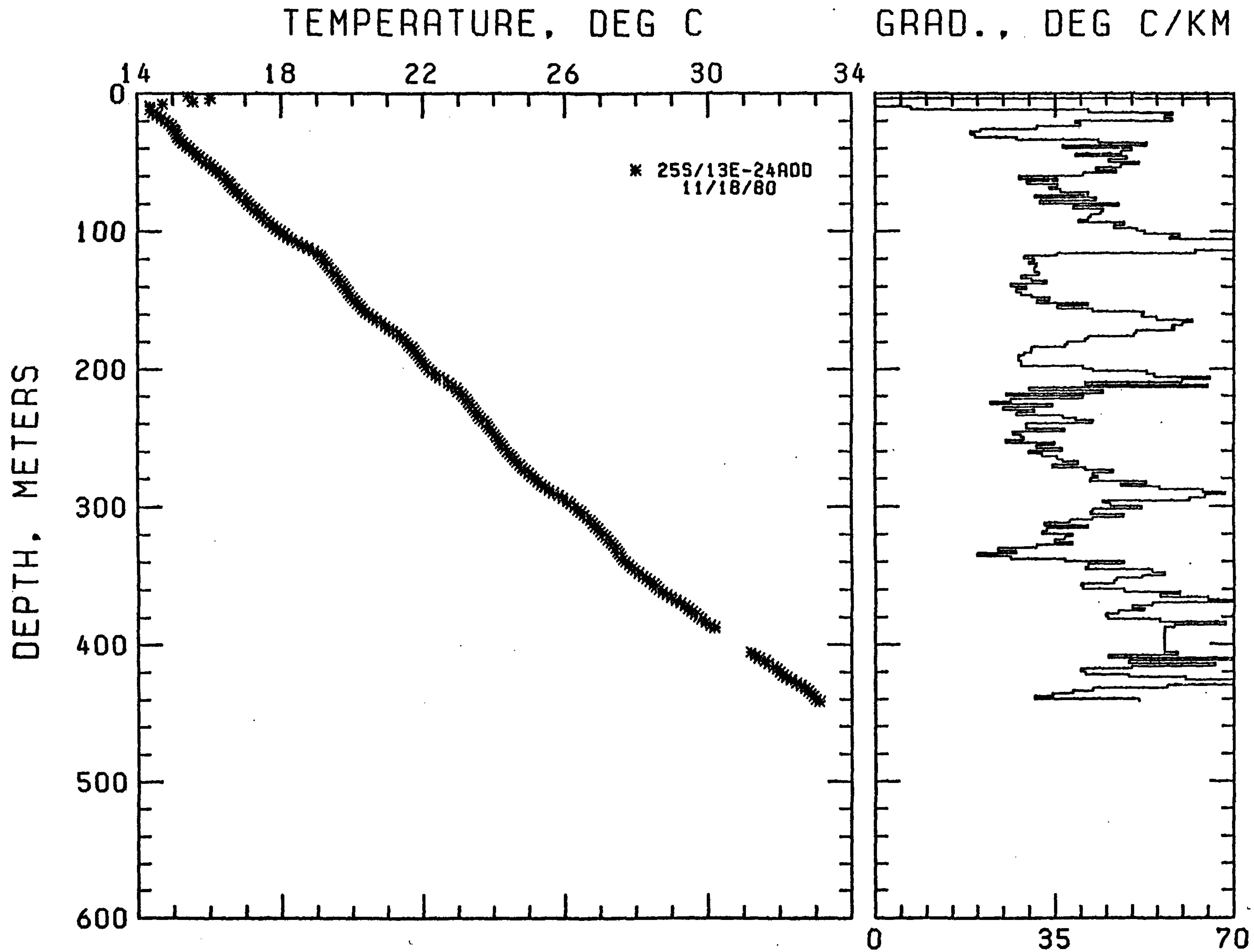


FIGURE 9. Temperature-depth and gradient-depth curves for hole 25S/13E-24add. Two-meter gradient intervals are plotted.

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 predominately 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 ± 0.9°C/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 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 holes furthest to the east where the Pennsylvanian section is thinnest. The mean gradient between 105 and 340 m is 19.7 ± 1.6°C/km.

Extensive data are available for hole 31S/20E-22cac, one of the holes drilled by the U.S. Geological Survey. This hole was logged to the drilled depth of 550 m (1804 ft.). The results are shown in Figure 11.

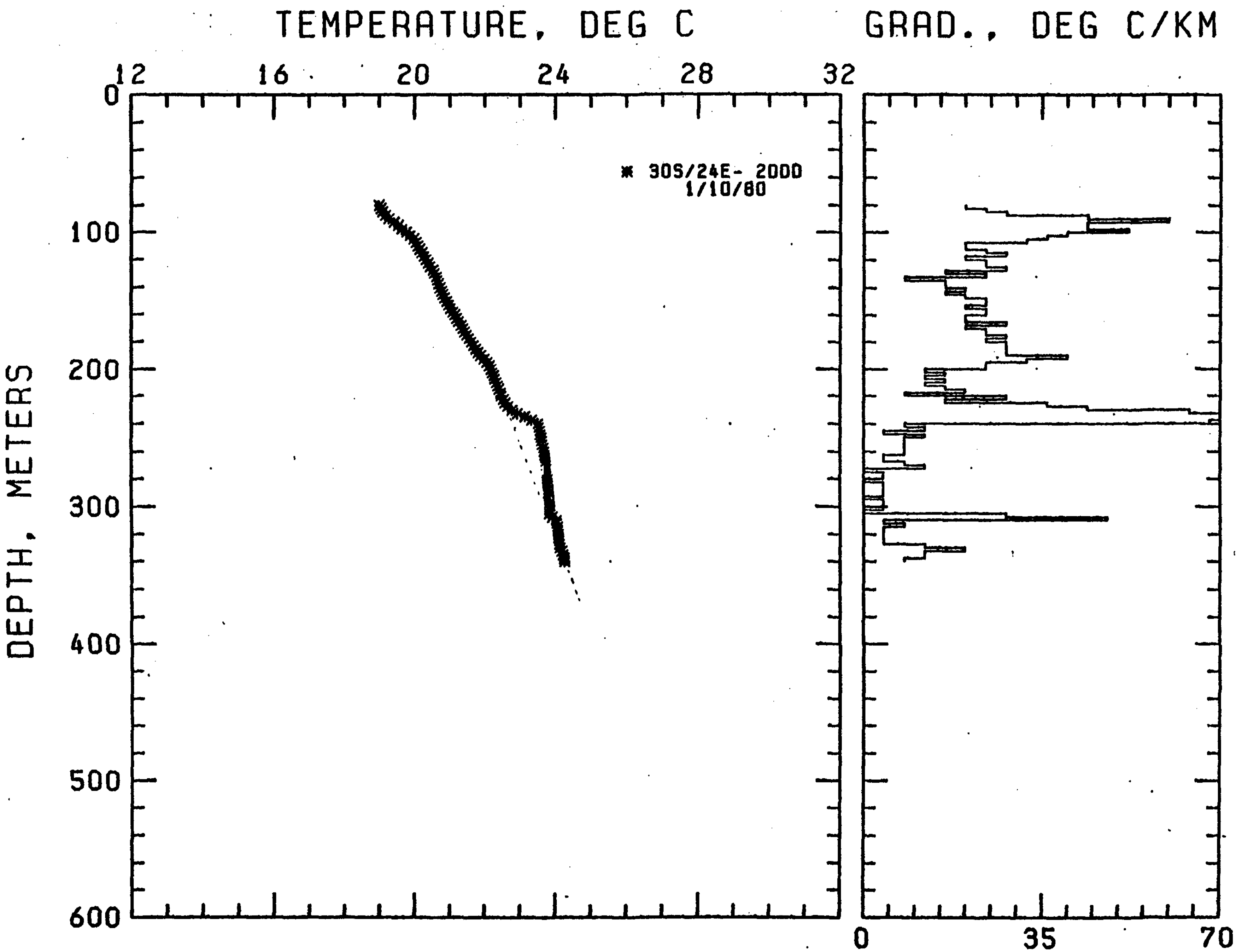


FIGURE 10. Temperature-depth and gradient-depth curves for hole 30S/24E-2ddd. 2.5-meter gradient intervals are plotted.

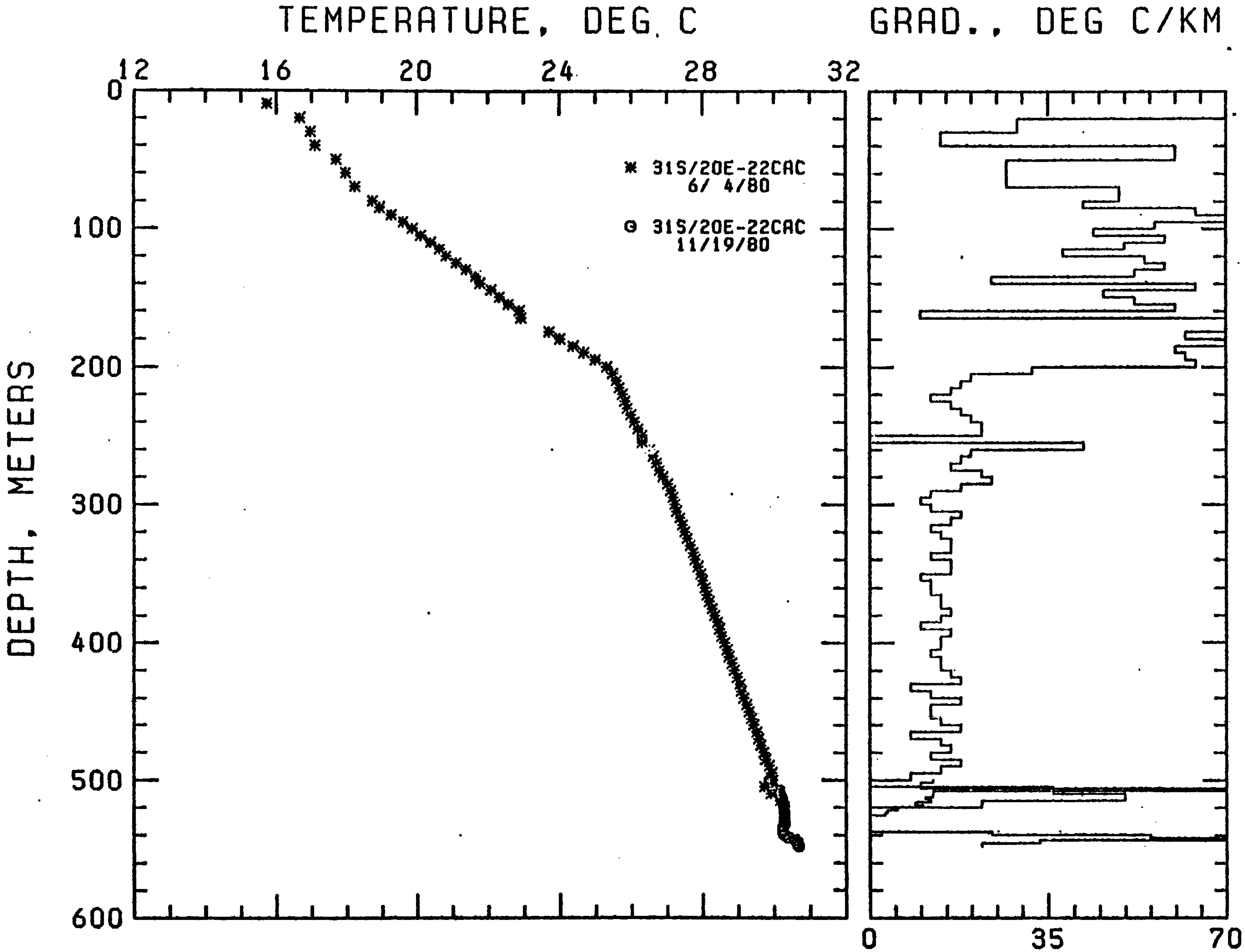


FIGURE 11. Temperature-depth and gradient-depth curves for hole 31S/20E-22cac. Five-meter gradient intervals are plotted.

The gradients between 95 m and 205 m are quite high, averaging 53.4 ± 1.5°C/km. Below 205 m the gradients average less then 20°C/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 conductivity 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 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 12. At this depth temperatures are highest in the southern third of the state except along the Missouri boundary. 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

TABLE 2. Temperatures (°C) measured at selected depths. Extrapolated temperatures are in parentheses.

Location	Depth (meters) 0	400	500	750	1000
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		

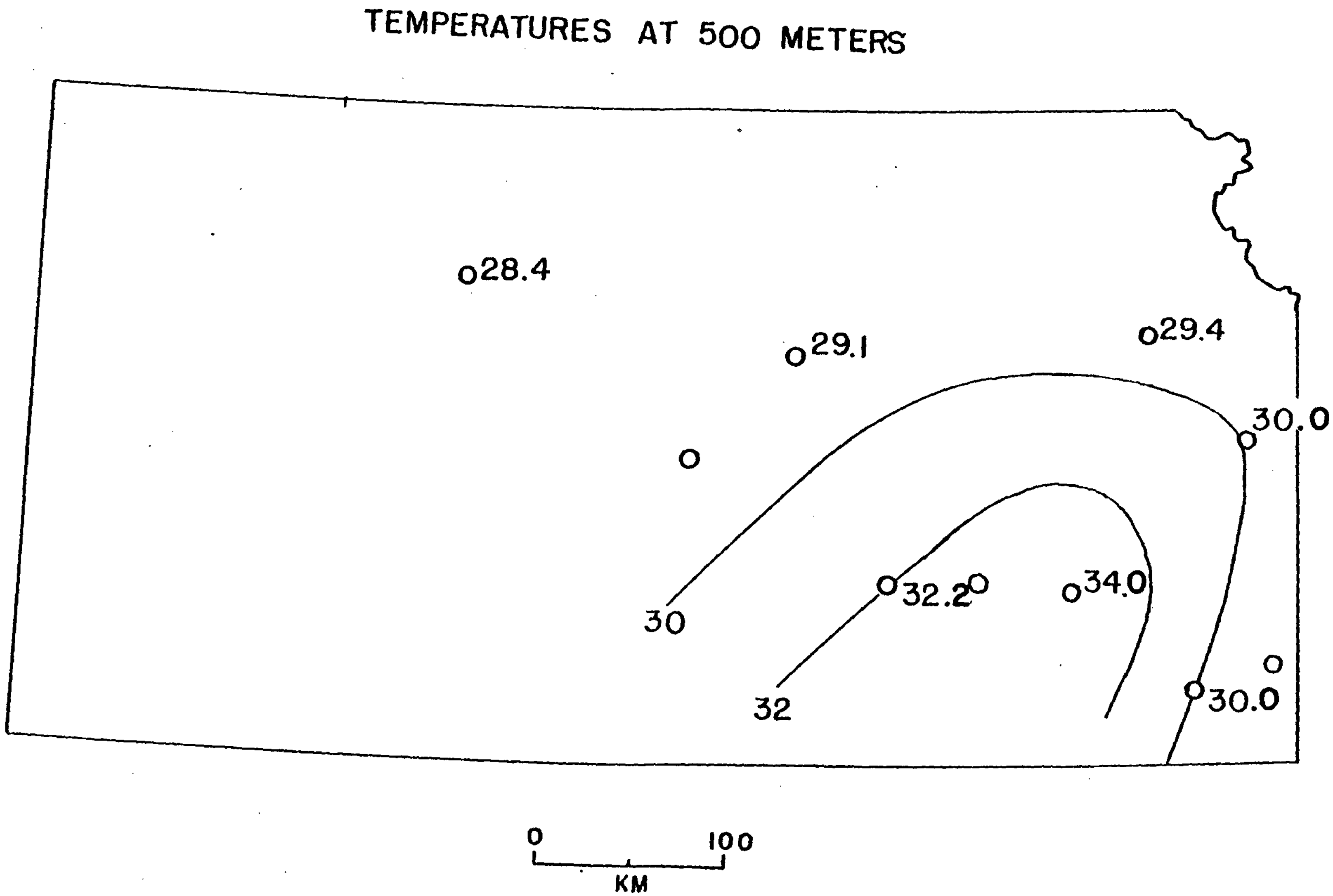


FIGURE 12. Isotherms at 500 meters. Temperatures are in °C.

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. Geological Survey. 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 B. 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 monolithologic 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 through 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. 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-22ccc are shown in Table 4. Heat flow values calculated for the various carbonate sections range from 49-60 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 49-60 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 $Wm^{-1}K^{-1}$ and the conductivity of the Sylvan shale is about 1.3 $Wm^{-1}K^{-1}$. The data for hole

TABLE 3. Interval thermal conductivity, geothermal gradient and heat flow for hole 12S/17E-13bbb. The thermal conductivity in column (2) is the value inferred from the best average heat flow divided by the gradient for that interval. Standard error listed under values.

Depth Interval meters	N	ϕ	Thermal Conductivity $Wm^{-1}K^{-1}$ (1)	Thermal Conductivity $Wm^{-1}K^{-1}$ (2)	Gradient mKm^{-1}	Heat Flow mWm^{-2}	Generalized Lithology
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 4. Interval thermal conductivity, geothermal gradient and heat flow for hole 13S/2W-32ccc. The values included in the heat flow averages are indicated by the asterisks. The thermal conductivity in column (2) is the value inferred from the best average heat flow divided by the gradient for that interval. Standard error listed under values.

Depth Interval meters	N	ϕ	Thermal Conductivity $Wm^{-1}K^{-1}$ (1)	Thermal Conductivity $Wm^{-1}K^{-1}$ (2)	Gradient mKm^{-1}	Heat Flow mWm^{-2}	Generalized Lithology
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	

18S/23E-18dcd are shown in Table 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 ± 0.5 $Wm^{-1}K^{-1}$ 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 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%) 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 over 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 (1968b) was based on thermal conductivity measurements of core samples from Precambrian basement rocks.

TABLE 5. Interval thermal conductivity, geothermal gradient and heat flow for hole 18S/23E-18dcd. The values included in the heat flow averages are indicated by the asterisks. The thermal conductivity in column (2) is the value inferred from the best average heat flow divided by the gradient for that interval. Standard error listed under values.

Depth Interval meters	N	ϕ	Thermal Conductivity $Wm^{-1}K^{-1}$ (1)	Thermal Conductivity $Wm^{-1}K^{-1}$ (2)	Gradient mKm^{-1}	Heat Flow mWm^{-2}	Generalized Lithology
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 6. Interval thermal conductivity, geothermal gradient and heat flow for hole 31S/20E-22cac. Thermal conductivity value estimated as discussed in text. Standard error listed under values.

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

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 PrePennsylvanian 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% ± 5%, are 1.8 to 2.25 $Wm^{-1}K^{-1}$. These values taken together with typical gradients of 45 to 55°C/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 the 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, resulting in either lower or higher heat flow values above the aquifer and also effecting heat flow values below the aquifer. The second possiblitity 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 gradient within the Pennsylvanian section ranges from 25°C/km to 50°C/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% higher then those in the PrePennsylvanian carbonate section. Since most of the limestonesin 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 range of thermal conductivity for at least some of the shales encountered in the holes is between 1.1 and 1.3 $Wm^{-1}K^{-1}$. Thus there is an approximate ratio of 2½:1 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 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 $Wm^{-1}K^{-1}$ (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% too high in the Ordovician shale section (Collingwood Formation). If a value of 1.1 $Wm^{-1}K^{-1}$ is assumed, as determined 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.

CALCULATION 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 log 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. Geological Survey are shown in Figures 13, 14, 15 and 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 accompanyed by gamma-ray log from a nearby hole (Figure 16). The geophysical logs are based on

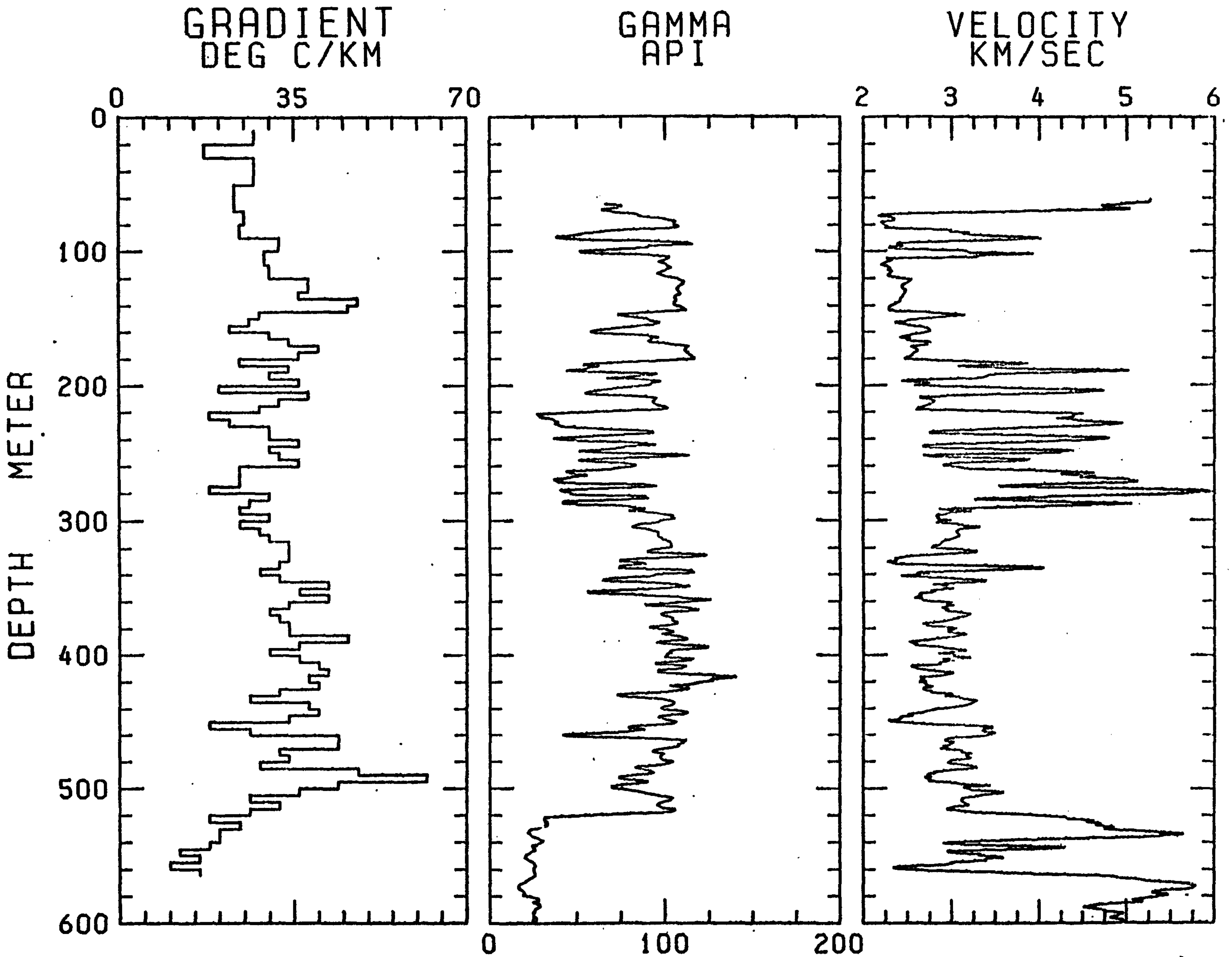


FIGURE 13. Comparison of geothermal gradient, γ-ray activity and P-wave velocity for hole 12S/17E-13bbd. The γ-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 3.

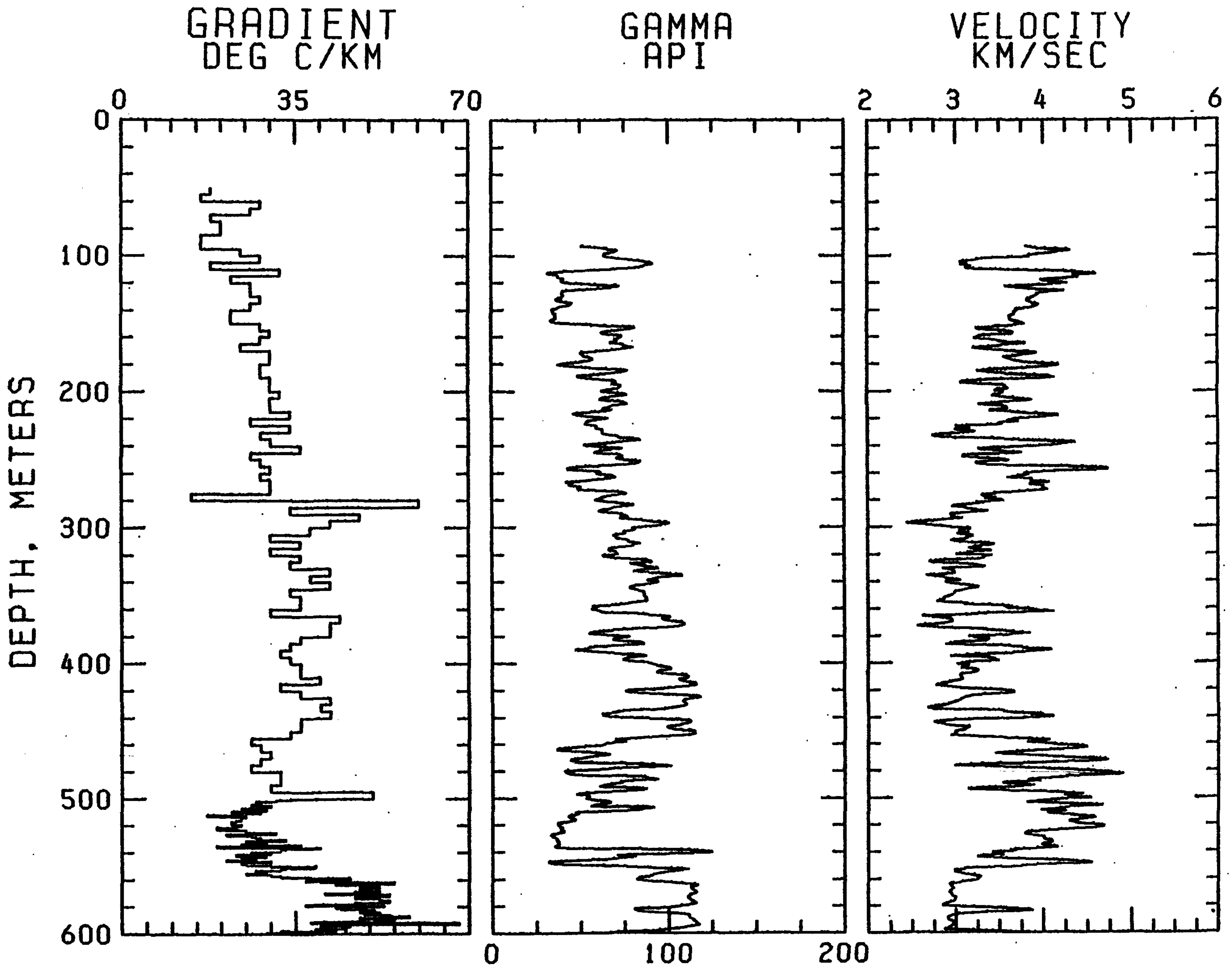


FIGURE 14A. Comparison of geothermal gradient, γ-ray activity and P-wave velocity for hole 13S/2W-32ccc. The γ-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 4A.

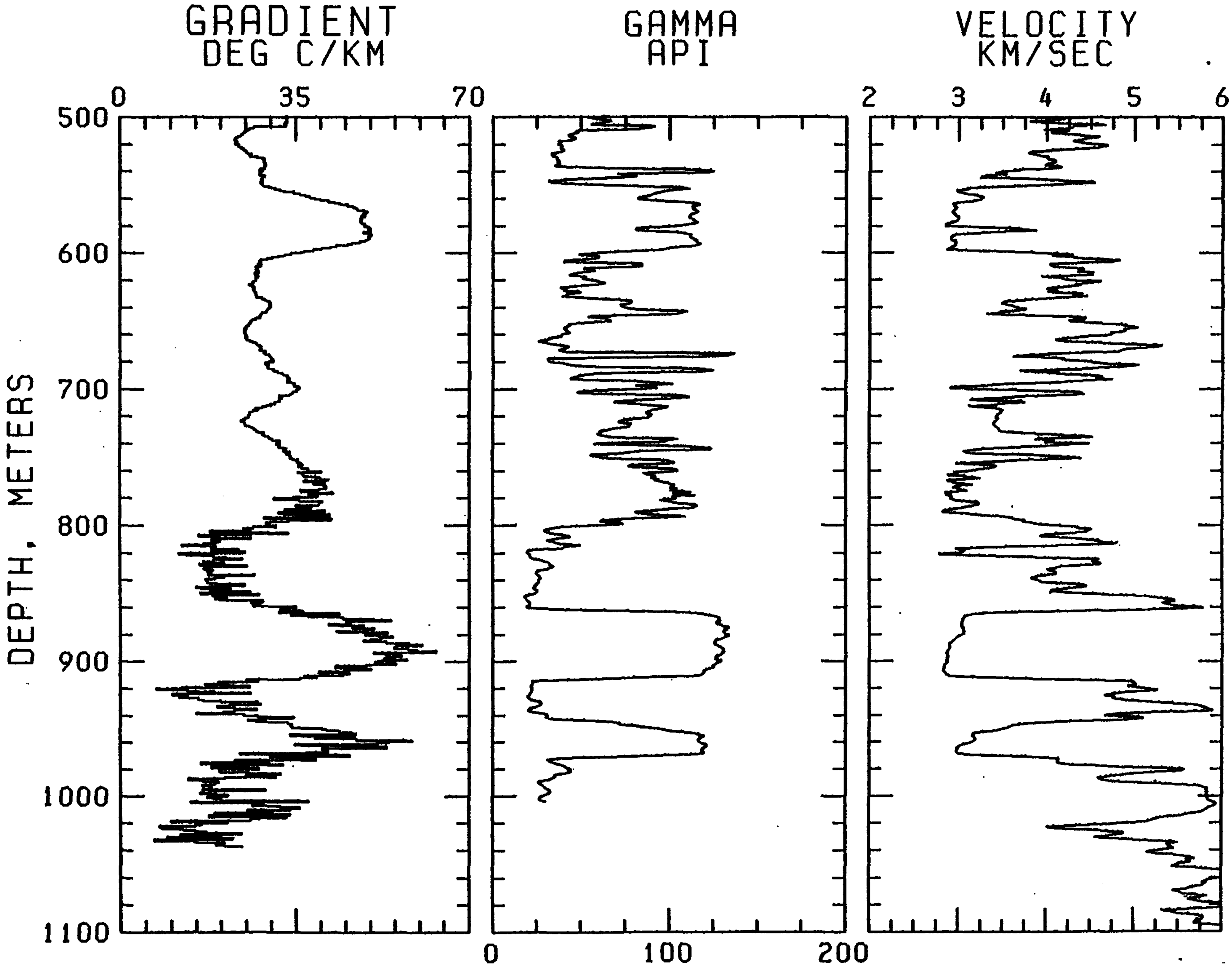


FIGURE 14B. Comparison of geothermal gradient, γ-ray activity and P-wave velocity for hole 13S/2W-32ccc. The γ-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient values are fifteen-meter running average values.

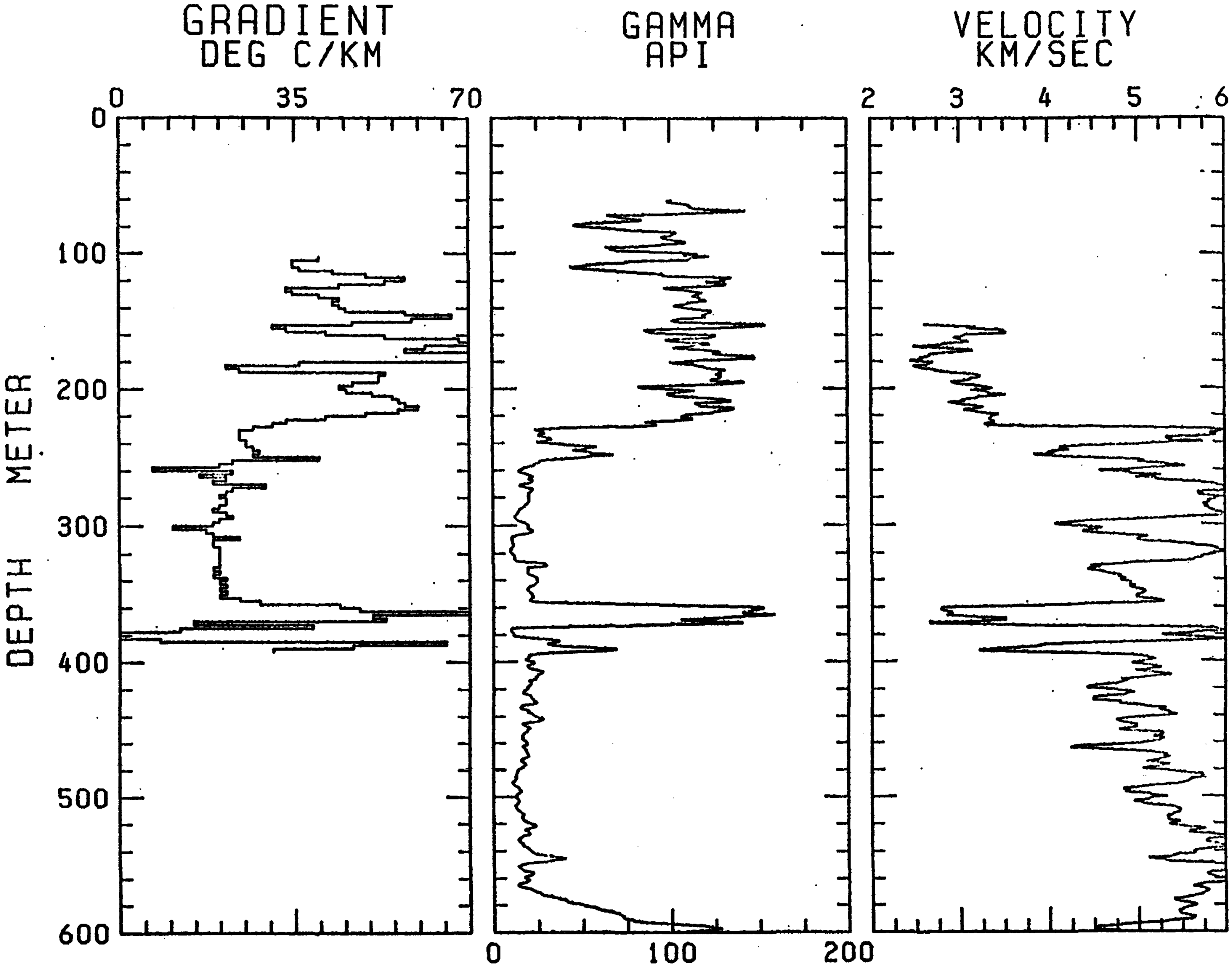


FIGURE 15. Comparison of geothermal gradient, γ-ray activity and P-wave velocity for hole 18S/23E-18dcd. The γ-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 5.

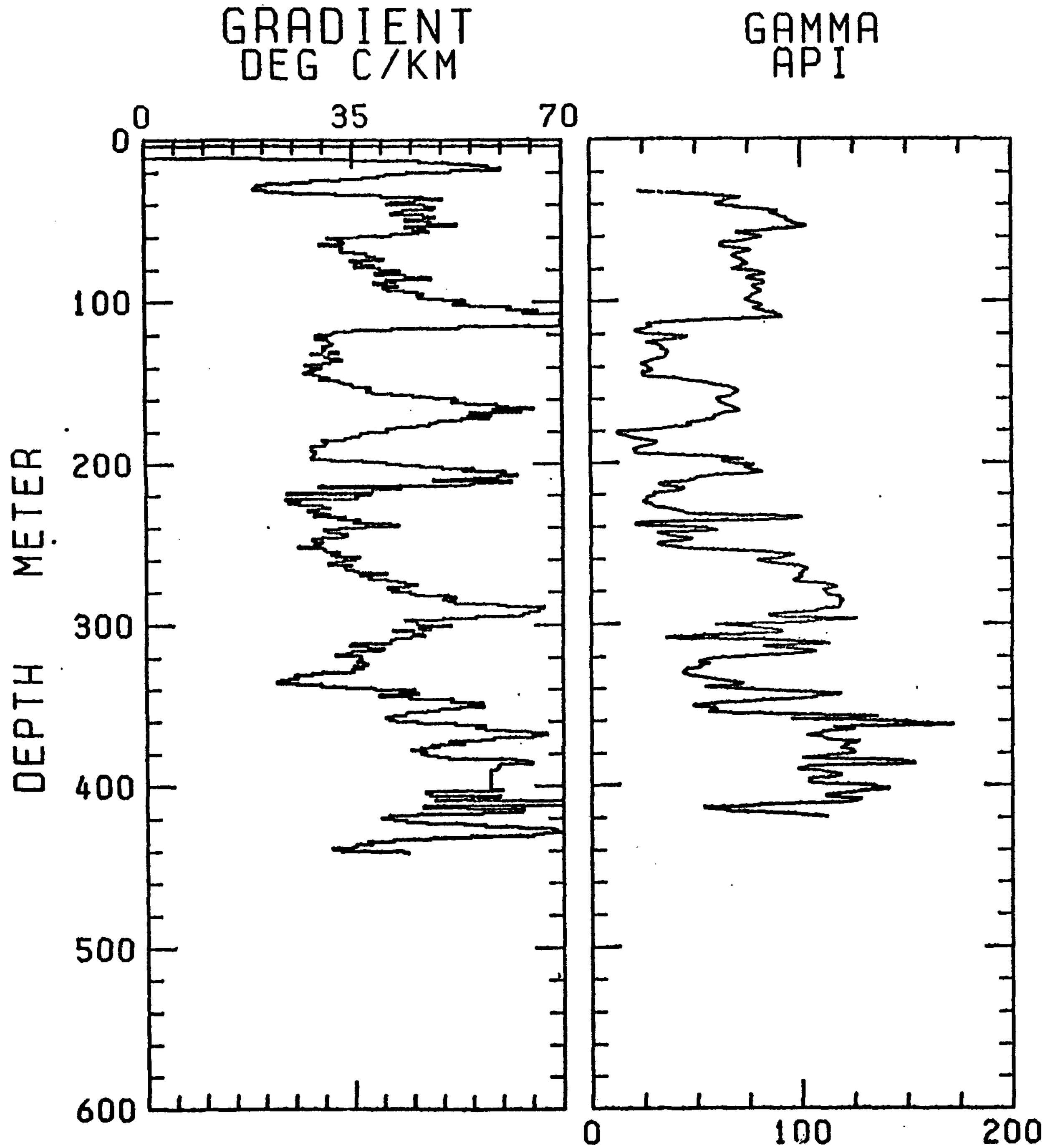


FIGURE 16. Comparison of geothermal gradient and γ-ray activity for hole 25S/13E-24add. The γ-ray data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient values are three-meter running average values. The γ-ray log is for hole 25S/13E-24dbb.

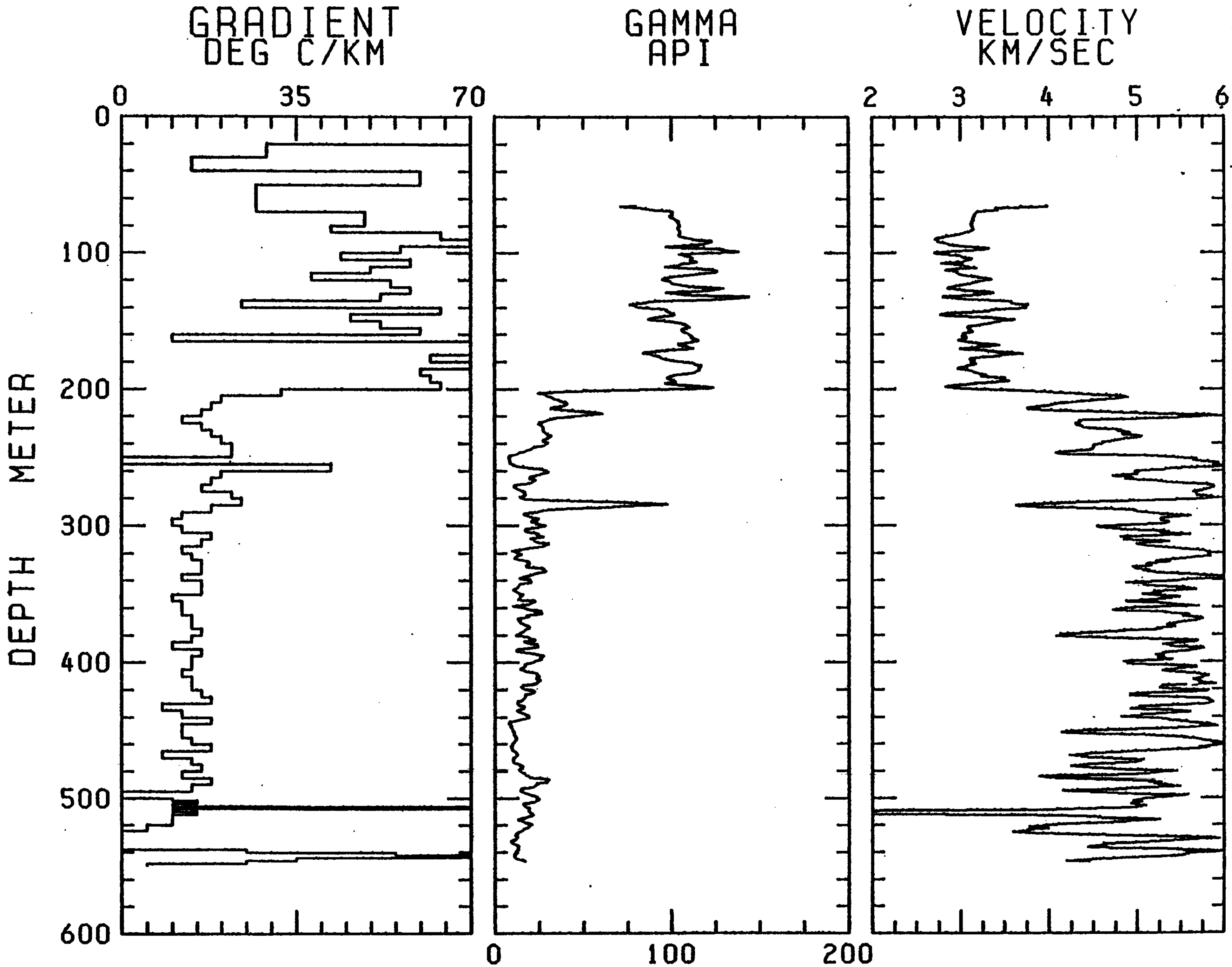


FIGURE 17. Comparison of geothermal gradient, γ-ray activity and P-wave velocity for hole 31S/20E-22cac. The γ-ray and P-wave data are based on 0.5 m digitized well logs smoothed by a 7-point average. Gradient plot from Figure 11.

a 0.5 m digitization of paper copies at a 5" = 100 ft. 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 gradient, these are shown in Figures 18 through 21. Shown are the least

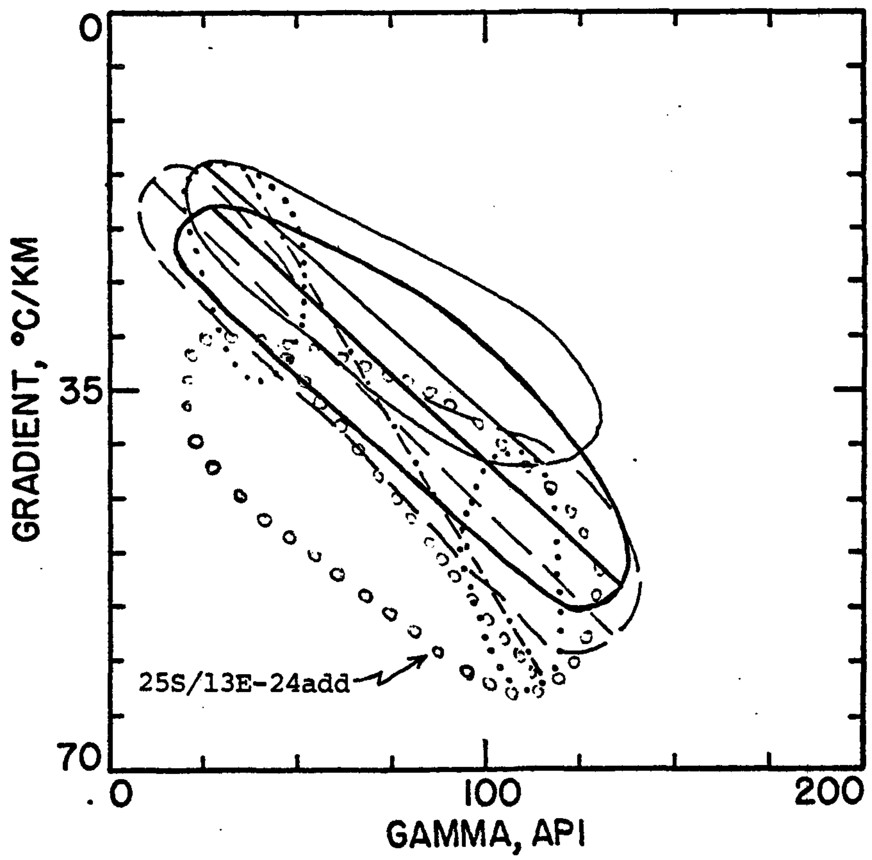
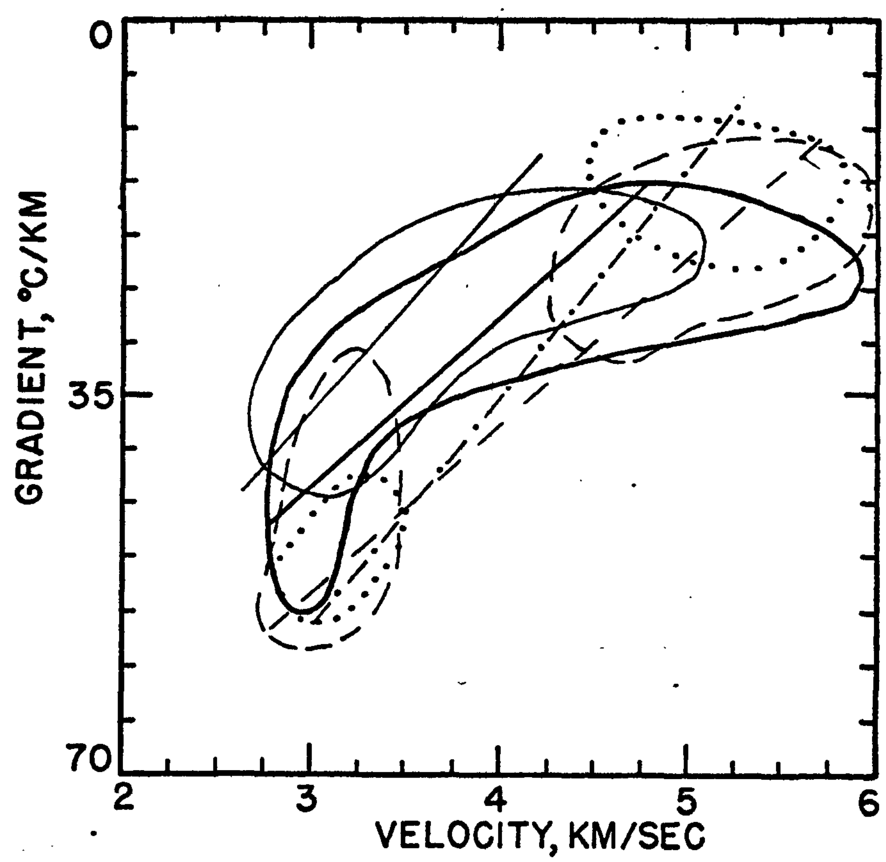


FIGURE 18. Crossplot of 10 m averages of gamma-ray activity and geothermal gradients. Least square straight lines fit to data and range of data are shown for each hole. Data from hole 12S/17E-13bbd are shown as the light solid line, data from 13S/2W-32ccc are shown as the heavy solid line, data from hole 18S/23E-18dcd are shown as the dashed line and data from hole 31S/20E-22cac are shown as the dotted lines.

FIGURE 19. Crossplots of 10 m averages of compressional velocity and geothermal gradient. The key is the same in Figure 18.



square straight lines fit to crossplots of the data averaged over a 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 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°C/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 (see Figure 19). Here again, almost exactly the same array of data is seen, i.e., similar slopes and with about a 10°C/km offset in the lines. However, the total data envelope is not as clearly linear as is the case in Figure 18,

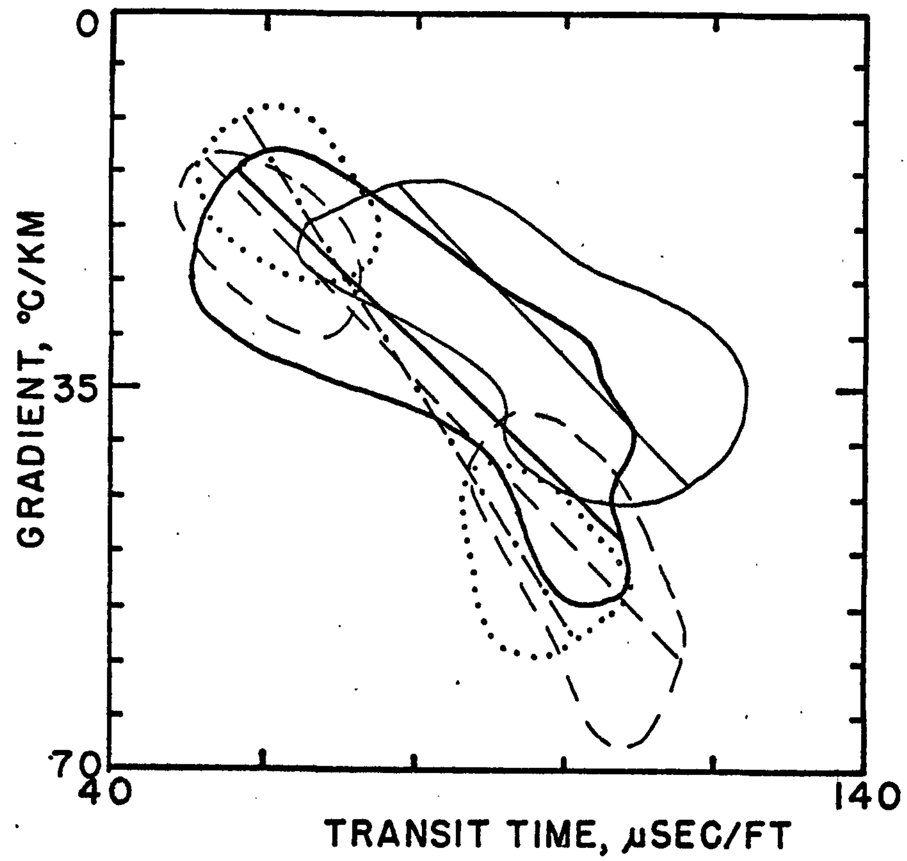
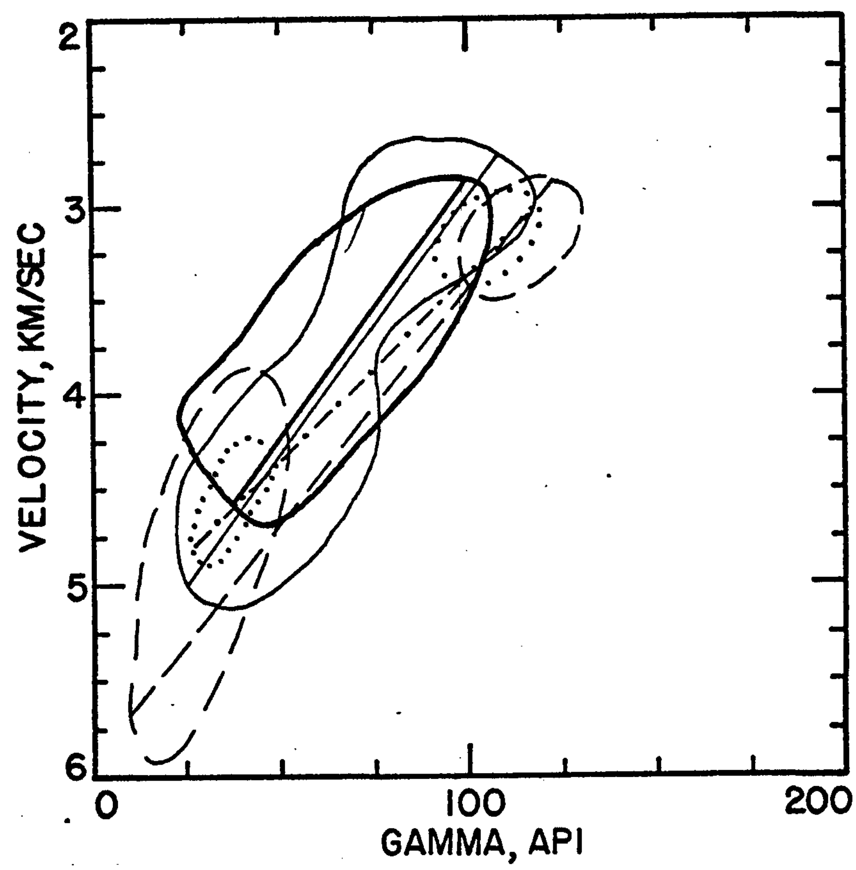


FIGURE 20. Crossplot of 10 m averages transit time (μsec/ft.) and geothermal gradient. Least square straight lines fit to data and range of data are shown for each hole. Data from hole 12S/17E-13bbd are shown as the light solid line, data from 13S/2W-32ccc are shown as the heavy solid line, data from hole 18S/23E-18dcd are shown as the dashed line and data from hole 31S/20E-22cac are shown as the dotted lines.

FIGURE 21. Crossplot of 10 m averages of gamma-ray activity and compressional velocity. The key is the same as in Figure 20.



especially for holes 12S/17E-13bbd and 13S/2W-32ccc. The crossplots of gradient and transit time are shown in Figure 20. The envelopes of data points are more linear then in Figure 19. Again the data overlap is almost complete for holes 13S/2W-32ccc, 18S/23E-18ddd and 31S/20E-22cac while hole 12S/17E-13bbd has a best fit line offset about 5°C/km below the other three lines.

Finally Figure 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-18ddd 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 gradient by 4-7°C/km. Hole 13S/2W-32ccc has the next lowest gradient by only 2-5°C/km and hole 18S/23E-18ddd has the highest gradient. Gradients from hole 31S/20E-22cac overlap the data from the last two holes, being closer to the results for 18S/23E-18ddd 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 PrePennsylvanian carbonate sections of each hole are shown in Table 7a. The relative heat flow values are in the same sense as the relative gradients for the whole holes shown in Figures 18-20. The fact that the relative relationships of all of the

TABLE 7a. Adopted values of heat flow

LOCATION	BEST HEAT FLOW VALUES mWm^{-2} (μcal/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 7b. Heat flow derived from temperature and transit time logs using the procedure described in the text.

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

holes (except 31S/20E-22cac) are so similar is evidence that the relative heat flow values shown in Table 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. Quantative heat flow values can be derived from the data shown in the figures.

The quantative analysis of the data shown in Figures 18-20 depends on the number of different lithologies involved. If only shale and limestone are involved then 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 then 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)

$$R_T = -140 + 4.83\ t$$

and the relationship

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

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 7b. The agreement with the heat flow values in Table 7a is within 10% so that the heat flow values using the data from the whole section in each hole are within 10% 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-18ddd and 31S/20E-22cac in that apparent thermal conductivities are higher for the first two holes then for the second two holes. Either there is a slight change in heat flow at the Pennsylvanian-Mississippian contact ($<$5-10 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 8. Except for the Cherokee Shale in holes 12S/17E-13bbd and 13S/2W-32ccc, all values are less then 1.3 $Wm^{-1}K^{-1}$ and the average value, excluding the Cherokee Shale in 13S/2W-32ccc is 1.18 $Wm^{-1}K^{-1}$. The discrepancy of the Pennsylvanian sections was discussed in the previous paragraph and the results in Table 8 emphasis 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 7a.

TABLE 8. Inferred values of thermal conductivity (K) and observed geothermal gradients (G) and thicknesses (t). The three quantities are shown for each shale unit in order, for each hole in which the shale occurs. Units are $Wm^{-1}K^{-1}$, °C/km and meters respectively. The mean shale thermal conductivity (excluding the Cherokee Shale in 13S/2W-32ccc) is 1.18 ± 0.03 $Wm^{-1}K^{-1}$ (2.82 ± 0.07 mcal/cm sec°C).

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						

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 ± 0.03 $Wm^{-1}K^{-1}$.

4) Heat flow values do not vary more then 10% between the Pennsylvanian and PrePennsylvanian 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 22 on a map which includes the simplified geology of the basement rocks in Kansas. If such things as aquifer motions are not effecting 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 particular 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 μWm^{-3} and 4.9 μWm^{-3} respectively. These data are shown in Figure 23 on a heat flow-heat production plot for data from the Central Stable Region of the United States (see 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 μWm^{-3}. A value of 3.2 μWm^{-2} was found by

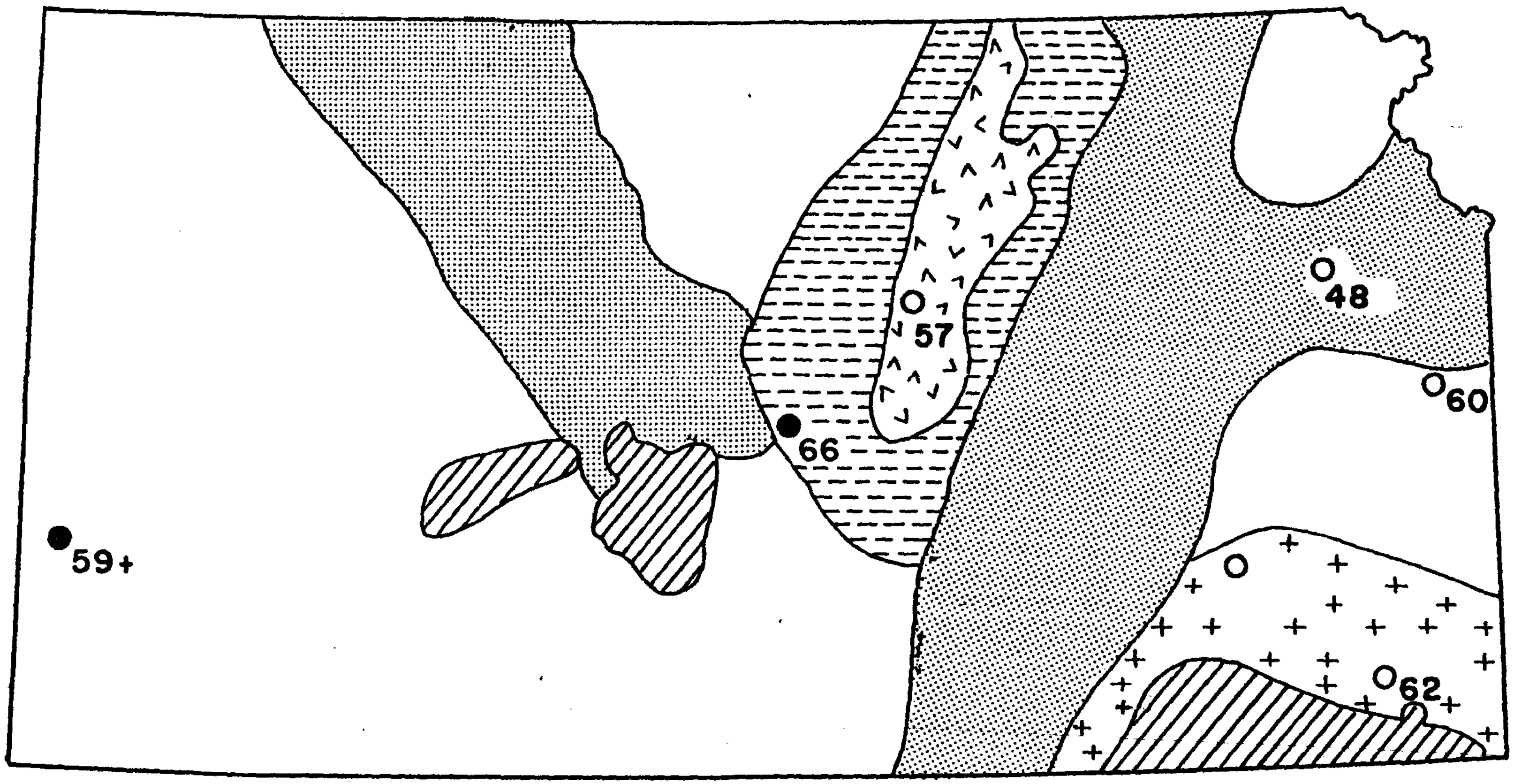


FIGURE 22. Generalized basement rock lithology map (from Bickford _et al_, 1979). Key: dot pattern-mesozonal granitic rocks; diagonal ruling-rhyolite; dashes-Precambrian sedimentary rocks; v's-mafic intrusive rocks; +'s-epizonal granitic rocks. Heat flow values shown in mWm^{-2}.

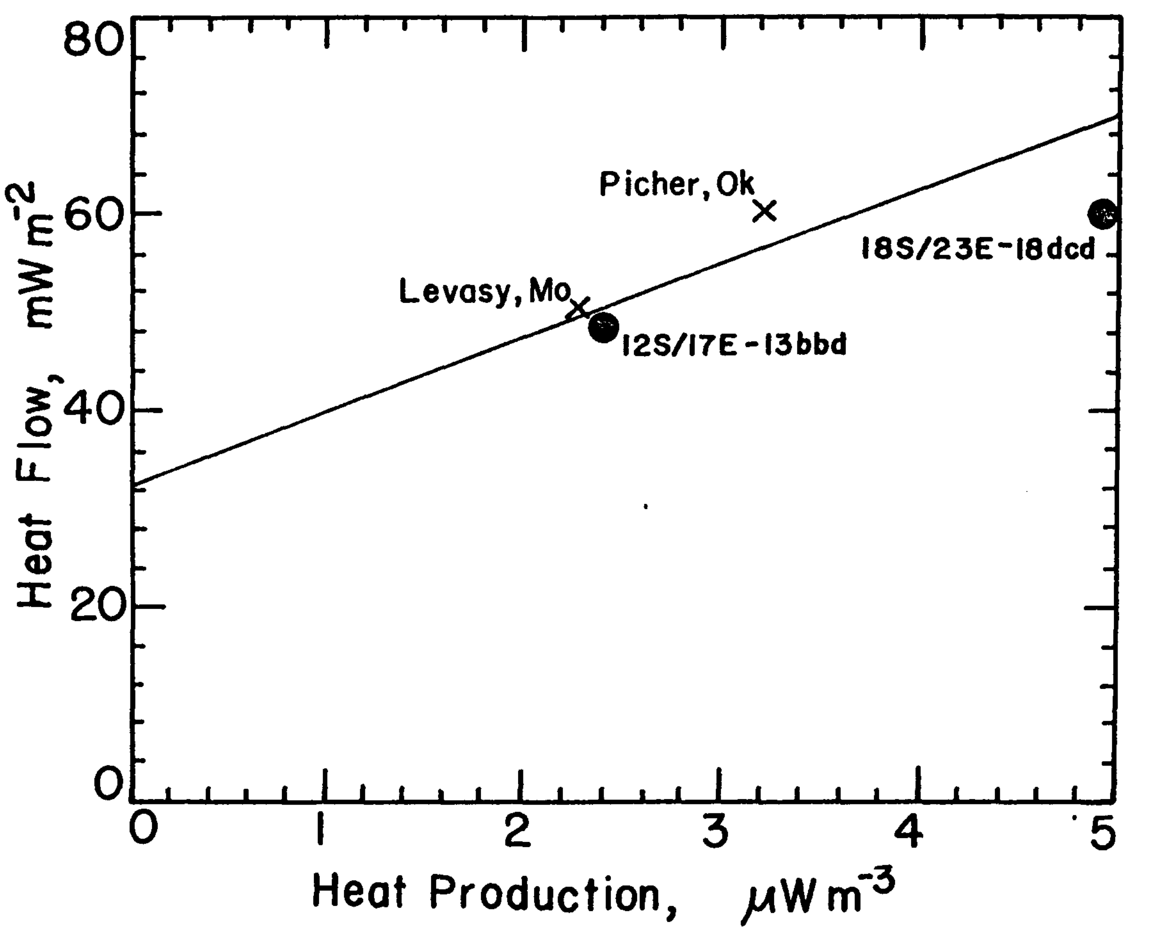


FIGURE 23. Plot of heat flow versus heat generation for the Midcontinent. Line, and data from Levasy, Missouri and Picher, Oklahoma are from Roy et al, (1968a).

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 those observed in the other drill holes. Additional studies could allow investigation of the nature of the Precambrian basement more directly then 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/or 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}.

Geothermal 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 12 shows an estimate of these temperature 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 heat flow and temperature variation seems to be 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. The analysis indicates that the heat flow values do not vary because the thermal conductivity offsets the variations 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% 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 excepted 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 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 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 then 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, 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 then 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 then have previously been expected. Furthermore in some of the deep basins in the Midcontinent, thicker sections of sedimentary rocks are available then 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 then those presently outlined in the eastern United States. For example, if a large region of the basement has a heat generation similar to the White Mountain Batholith of New England (6 μWm^{-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°C/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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APPENDIX A

APPENDIX B

Big Springs, Kansas   12S/17E-13bbd

Depth (feet)	Bulk Conductivity $Wm^{-1}K^{-1}$
300 - 310	2.71
400 - 410	2.76
500 - 510	3.49
550 - 560	2.47
570 - 580	2.53
600 - 610	2.69
700 - 710	2.39
750 - 760	2.86
800 - 810	2.33
840 - 850	2.77
890 - 900	2.69
900 - 910	2.81
910 - 920	3.19
920 - 930	3.16
930 - 940	2.68
940 - 950	2.80
960 - 970	3.16
1000 - 1010	3.03
1100 - 1110	2.63
1200 - 1210	2.26
1300 - 1310	2.41
1400 - 1410	2.39
1490 - 1500	2.67
1500 - 1510	3.28
1520 - 1530	3.61
1530 - 1540	3.10
1560 - 1570	3.12
1580 - 1590	2.66
1600 - 1610	4.76
1620 - 1630	3.86
1640 - 1650	3.28
1660 - 1670	2.94
1680 - 1690	2.92
1690 - 1700	2.62
1700 - 1710	3.14
1710 - 1720	3.21
1720 - 1730	3.26
1740 - 1750	3.23
1760 - 1770	3.11
1780 - 1790	3.11
1800 - 1810	3.05
1810 - 1820	3.48
1820 - 1830	3.48
1900 - 1910	2.79
1990 - 2000	2.93
2000 - 2010	3.04
2050 - 2060	2.51
2080 - 2090	2.45

Depth (feet)	Bulk Conductivity $Wm^{-1}K^{-1}$
2100 - 2110	2.48
2150 - 2160	4.82
2200 - 2210	4.11
2250 - 2260	5.02
2300 - 2310	4.66
2350 - 2360	5.46
2400 - 2410	4.06
2450 - 2460	5.07
2500 - 2510	3.93
2550 - 2560	5.67
2600 - 2610	5.03
2650 - 2660	5.48
2700 - 2710	4.36
2750 - 2760	5.09
2800 - 2810	4.66
2850 - 2860	6.10
2900 - 2910	4.69
2950 - 2960	3.94

	Core Conductivity $Wm^{-1}K^{-1}$
2968'8"-2968'9"	3.22
2970'5"-2970'6"	3.21
2974'1.5"-2974'2.5"	3.22
2977'3"-2977'4"	3.22

Smoky Hill, Kansas 13S/2W-32ccc

Depth (feet)	Bulk Conductivity $Wm^{-1}K^{-1}$
950 - 960	3.39
906 - 970	3.64
1700 - 1710	2.70
1750 - 1760	3.22
1860 - 1870	2.80
1940 - 1950	2.82
2010 - 2020	2.62
2100 - 2110	2.96
2150 - 2160	2.98
2260 - 2270	2.74
2350 - 2360	2.98
2440 - 2450	2.62
2560 - 2570	2.68
2650 - 2660	3.04
2700 - 2710	3.86
2760 - 2770	4.21
2860 - 2870	2.65
2950 - 2960	2.54
3020 - 3030	3.84
3070 - 3080	3.26
3130 - 3140	3.28
3150 - 3160	2.82
3210 - 3220	2.77
3250 - 3260	3.12
3345 - 3355	2.97
3400 - 3410	(2.31)
3446 - 3456	3.72
3500 - 3510	4.53
3550 - 3560	4.35
3600 - 3610	3.90
3650 - 3660	4.97

Watson-1, Kansas 18S/23E-18dcd

Depth (feet)	Bulk Conductivity $Wm^{-1}K^{-1}$
350 - 355	4.11
405 - 410	2.72
450 - 455	2.89
505 - 510	2.92
550 - 555	2.41
600 - 605	2.52
650 - 655	2.98
700 - 705	2.63
755 - 760	2.78
770 - 775	3.02
820 - 825	3.23
850 - 855	2.40
895 - 900	2.90
945 - 950	3.21
995 - 1000	4.46
1050 - 1055	3.12
1105 - 1110	3.69
1150 - 1155	3.95
1200 - 1205	2.28
1210 - 1215	2.96
1250 - 1255	3.85
1355 - 1360	4.82
1450 - 1455	4.50
1550 - 1555	4.85
1650 - 1655	4.38
1745 - 1750	5.13
1855 - 1860	5.29