TERRESTRIAL HEAT FLOW IN NORTH CENTRAL UNITED STATES

by

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Thesis Supervisor

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Chairman, Departmental Committee on Graduate Students

To my wife, Carol

ABSTRACT

Terrestrial Heat Flow in
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Submitted to the Department of Earth and Planetary Sciences
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The average of twenty-six new heat flow determinations in the North Central area of the United States is 1.36±0.34 HFU; the values range from 0.90 to 2.2 HFU. Except for two determinations in Indiana, all of the measurements were obtained from continuous temperature-depth curves that were recorded in existing boreholes. With continuous temperature logs, we obtained very precise values of the geothermal gradient over short intervals, measured the thermal conductivity on a few samples for these selected intervals, and obtained precise values for the heat flow.

Although all the stations are located in the stable continental interior, there are two distinct regions both on the basis of physiography and on the basis of heat flow. The Interior Lowlands is characterized by a regional value of 1.4 HFU, whereas the regional value for the Northern Great Plains is about 2.0 HFU. Local variations of heat flow in the Interior Lowlands are attributed to the differences in basement rock type and the attendant contrast in radiogenic elements as well as the thermal conductivity contrasts. In particular, the surface heat flow correlates well with basement lithology in the central stable interior of the United States. Since the basement lithology is similar in the Interior Lowlands and the Northern Great Plains and since seismic data indicate little difference in the crustal thickness beneath the two areas, the major part of the deviations in heat flow must be attributed to differences in temperature conditions in the upper mantle.

Heat flow correlates with P_n velocities and seismic travel time residuals. That is, the lower heat flow values, 1.5 HFU or less, are associated with negative travel time anomalies, whereas the high values 1.8 HFU

or more, are related to positive station residuals. In addition, the lower P_n velocities are associated with the high heat flux in the Northern Great Plains. Therefore, both the P_n velocities and the travel time anomalies support the conclusion that the difference in regional heat flux can be attributed to differences in the temperatures in the upper mantle.

Thesis Supervisor: Gene Simmons

Title: Professor of Geophysics

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NOTATION

CONDUCTIVITY - The average thermal conductivity in 10^{-3}cal/cm-sec-^{o}C. The number in parenthesis after the value is the number of samples used to obtain the average value.

DENSITY - Bulk density of the sample in gm/cm^3.

DEPTH - Depth below ground level in meters.

DIAMETER - The diameter of the specimen in centimeters.

ELEVATION - Elevation of local ground level above sea level in meters.

HEAT FLOW - The value of terrestrial heat flow in 10^{-6}cal/cm^2-sec.

HGU - Heat generation unit which is defined to be equal to 1.0×10^{-13} cal/cm^3-sec.

HFU - Heat flow unit which is defined to be equal to 1.0×10^{-6} cal/cm^2-sec.

TEMPERATURE - Temperature in ^{o}C.

THERMAL CONDUCTIVITY - The measured thermal conductivity in units of 10^{-3} cal/cm-sec-^{o}C.

THICKNESS - The thickness of the specimen in centimeters.

CHAPTER 1

INTRODUCTION

The geologic environment of the North Central United States consists of a thick sedimentary sequence overlying the Precambrian basement. The basement configuration reflects the basin and arch provinces recognized in the Paleozoic rocks of this region, and thus supports the usual premise that the basement forms a regional structural framework for the overlying sedimentary strata. Basement is defined here as the first igneous or metamorphic rocks found under the predominately sedimentary rocks.

Lithologic studies of a considerable number of well samples indicate that the basement in the midcontinental area is predominately granitic. Gravity and magnetic anomalies in Iowa, Indiana, and Michigan appear to be caused by Keweenawan-type basalts and sediments superimposed on the granite. Detailed investigations of these anomalies have been made by a number of scientists (Thiel, 1956; Henderson and Zietz, 1958; Zietz and Griscom, 1964; Rudman and Blakely, 1965; Rudman et al., 1965; Zietz et al., 1966; Cohen and Meyer, 1966). The differences in basement rock types will provide an extremely useful input for the interpretation of the heat flow field.

The fundamental equation of heat conduction for an isotropic media is that

$$Q = -K \frac{\partial T}{\partial z}$$

where Q is the amount of heat that flows across a unit area of surface normal to the z direction in unit time, K is the thermal conductivity of the solid, and $\frac{\partial T}{\partial z}$ is the temperature gradient in the z direction (Carslaw and Jaeger, 1959 or Ingersoll et al., 1954). Q is considered positive in the direction of decreasing z. Thus, the determination of the terrestrial heat flow, Q, requires the measurement of two separate quantities: the geothermal gradient, $\frac{\partial T}{\partial z}$, existing at a location and the thermal conductivity, K, of the rocks in which the temperature gradient has been measured. In the present investigation, the geothermal gradients have been obtained from both continuous and discrete temperature measurements in vertical boreholes. Thermal conductivities have been obtained from measurements on rock samples either from the same boreholes or from adjacent ones. The data pertinent to the calculation of the heat flow are presented and discussed in chapters 4 thru 8.

An important point that will be demonstrated in this investigation is that with the excellent control on gradients afforded by continuous temperature logs, one can obtain very precise values of the geothermal gradient over short intervals, measure the thermal conductivity for these selected intervals, and obtain precise values for the heat flow. The advantage of measuring thermal conductivity on 10 discs rather than 100 is obvious. Throughout this thesis, the heat flow is obtained by calculating the product of the thermal gradient for a finite interval and the average conductivity for the same interval.

Although approximately 400 measurements of heat flow on land are published or are in various stages of completion, a comprehensive picture of both the local and regional variation of heat flow has been presented for only one continental area, in particular, Lake Superior (Hart et al., 1968). The closely spaced data presented in the present investigation affords an opportunity to relate the heat flow values determined with the local and regional geological, geochemical, and geophysical data.

CHAPTER 2

TEMPERATURE MEASUREMENTS

2.1 INTRODUCTION AND EQUIPMENT

Most of the published values of heat flow obtained to date in continental areas have been derived from temperatures measured at discrete points in boreholes, mines or tunnels. At first mercury maximum thermometers were used to obtain geothermal gradients, but these have been replaced by thermistors in combination with Wheatstone-type bridges and electronic null detectors. The thermistor, which is placed in a probe, is lowered in the borehole on an electrical cable and temperatures are measured at discrete intervals, usually every 10 or 15 meters, after waiting 5 to 10 minutes for the thermistor to come to equilibrium. Although the technique of measuring temperatures at discrete intervals is quite adequate for heat flow determinations, all of the temperature measurements discussed in this thesis were obtained as a continuous function of depth, except for the Linkville and Monroeville fields in Indiana. These particular fields will be discussed in a later section. The continuous temperature logging equipment used during this work has been described earlier by Simmons (1965).

2.2 TEMPERATURES AND CORRECTIONS

It is well known that high precision in the temperature measurements is required for heat flow determinations, but high accuracy is not required. The repeatability of the measured temperatures-- that is, the precision of the system-- was about 0.01°C whereas the absolute accuracy of the system was probably no better than 0.1°C. In order to present the data in a useful form, the temperature as a function of depth at five meter intervals for each of the boreholes has been tabulated in Appendix I. These data were obtained from the continuous temperature logs. The temperature data have also been presented in graphical form in the appropriate sections.

Heat flow determinations made in various parts of the world have shown variations from one area to another. In order to establish the reliability of a particular heat flow determination, one must consider whether the temperatures and therefore the thermal gradients have been affected by local conditions. The chief causes of variations may be classified as follows:

(a) movement of water in the strata, either natural or caused by drilling;

(b) disturbances due to uplift and erosion;

(c) diurnal and annual temperature variation; and

(d) effect of glaciation and climatic changes in the past.

Bullard (1947), Jaeger (1961), and Lachenbruch and Brewer (1959) have discussed the effect of drilling on the temperature distribution along a borehole. Since all of the boreholes except S-44, Royal Center and S-55, Royal Center, had been quiescent for a period of at least several months, there were no disturbances in the geothermal gradient which might have been caused by water circulation of some other drilling fluid.

The circulation of underground water is another cause of disturbance in subsurface temperature distributions. Whether the temperature is constant with depth in the case of movement of water in the borehole depends on the rate of flow. Although the slow movement of ground water through the entire lithologic section is a difficult condition to recognize, the points of entry and exit are readily recognized from the continuous temperature logs. This phenomenon was not observed in any of the boreholes which were measured.

Temperatures in some boreholes less than about 100 meters below ground level were somewhat irregular. These temperatures were presumably influenced by surface effects.

Therefore, only temperatures below 100 meters were used to determine heat flow in the present study.

Another problem incurred in obtaining geothermal gradients arises because of the fluid in the borehole. When there was a column of air in the borehole, the temperature-depth relationship was somewhat erratic and consequently these portions of the logs were not used in the geothermal gradient calculations. The erratic temperatures logged in air-filled boreholes is due to two causes:

1. convection, and
2. lack of equilibrium between the thermistor and the air produced by the longer time constant of the temperature probe in air and self heating of the probe produced by low thermal transfer rates.

However, with a column of water in the borehole there was no erratic behavior, and the geothermal gradient was easily determined. For example, consider the temperature log for the Carrie Hovland #1 borehole which appears on pages 160-167. The upper section of the borehole was logged with air in the column whereas below 750 meters the well was filled with water.

It is known that any change in the surface environment affects the subsurface temperature distribution. A number of effects, including climatic changes, glaciation, uplift, and erosion, on the subsurface temperature distribution have been investigated in detail by earlier heat flow workers (For example, Birch (1948), Birch (1950), Clark (1957), Crain (1968), and Horai (1969)).

In rugged or mountainous terrain the general tendency for more heat to flow out through the valleys than through the mountains disturbs the normal geothermal gradient. Methods of correcting for this effect, and also methods of correcting for the disturbances due to uplift and erosion, have been developed by Birch (1950) and Clark (1957). Since the maximum relief within a kilometer radius of any of the boreholes is only a few hundred meters, the hills and valleys tend to compensate. Therefore, in this investigation, no topographic corrections were deemed necessary. Finally, no corrections to the geothermal gradient for climatic changes, uplift, or erosion have been made in the present investigation.

2.3 THERMAL GRADIENTS

Since the temperatures in almost all of the boreholes were measured as a continuous function of depth, the thermal gradients were obtained by drawing a tangent to the temperature curve at the depth or over the particular intervals where the thermal conductivity was determined. The thermal gradients which were used in the final determination of heat flow appear in tables throughout the text.

Since the boreholes considered in this thesis all penetrated sedimentary sequences, there is a considerable range of thermal gradients. The gradients in some sandstone sections were as low as 6.0°C/km while those in some of the shale sections were as high as 70.0°C/km. But since the thermal conductivities have a minimum of 2.5×10^{-3} cal/cm sec °C for shales and a maximum of 15.0×10^{-3} cal/cm sec °C for the quartzose sandstones, all of the variation in gradient appears to be due to variation in conductivity and the heat flow is uniform.

The depth measurements in the present study are accurate to at least 0.1 percent and the temperatures were measured to within 0.01°C (Simmons, 1965). If the errors in the depth and temperature measurements are random, they amount to a one percent error in a geothermal gradient of 20°C/km obtained over a hundred meter interval.

CHAPTER 3

THERMAL CONDUCTIVITY

3.1 METHOD OF MEASUREMENT

Both transient and steady-state methods have been used in the laboratory for determination of thermal conductivities reported in this thesis. All of the rocks were measured using a steady-state method, while the conductivity substandards, plate glass and pyrex, were measured using both a steady-state and a transient method. All of the conductivities in this thesis are relative to that of fused silica.

Four sets of apparatus, similar to the one described by Birch (1950), were used for the steady-state measurements. In principal, the apparatus is a modification of the method of the "divided-bar" with samples of copper and Lexan, of the same size as the samples of rock, serving as the fixed parts of the bar. Throughout the remainder of this thesis the steady-state conductivity apparatus will be referred to as a divided-bar apparatus. A complete description of the apparatus is presented in Appendix III.

A single measurement consisted of observing the potential across the four thermocouples. These thermocouples were measured with a Honeywell model 2784 potentiometer and a Keithley model 148 nanovoltmeter. Readings were made to 0.5 microvolts, and the ratios of temperatures on the flat and parallel ground specimens were reproducible to ± 2 percent or better. Most of the specimens were ground to a ±0.002 inch tolerance.

3.2 CONDUCTIVITY SUBSTANDARDS

One of the main differences between the apparatuses in this investigation and those used by most other heat flow workers is a consequence of the size of the cores used in the thermal conductivity measurements. The size of core from diamond drill holes usually does not exceed 1 or 1½ inches, but most of the samples used for thermal conductivity determination in the present investigation were either 3½ of 4 inches in diameter.

Because of the size of the fused silica reference discs needed and therefore the cost, two substandards were used in the apparatuses. The substandards were a clear plate glass (soda-lime glass with approximately 72 weight % silica) and a pyrex glass (Dow Corning glass 7740). Discs of varying diameter and thickness were made from the plate glass and the pyrex and their conductivities were determined in the divided-bar apparatus.

The thermal conductivities measured in the present study are compared with literature values in Figure 3.1 and Figure 3.2. Chemical compositions are compared in Table 3.1.

Table 3.1

Chemical Composition of Glasses

Glass	Weight Percentage of Oxide				
	SiO_2	Na_2O	CaO_2	Al_2O_3	B_2O_3
Pyrex 1 (Corning 7740)	80	4	-	2	14
Pyrex 2*	80-81	4	-	2	12-13
Soda-Lime 1*	75	17	8	-	-
Soda-Lime 2*	72	15	11	-	-
Soda-Lime 3*	75	12	13	-	-
Soda-Lime of Present Study	71-73	?	?	?	?

* Ratcliffe, E.H., A survey of most probable values for the thermal conductivities of glasses between about -150 and 100 ^{o}C, including new data on twenty-two glasses and a working formula for the calculation of conductivity from composition, Glass Technology, 4(4), 113-128, 1963.

Figure 3.1 Thermal conductivity of soda-lime glasses as a function of temperature. The chemical composition of the glasses is presented in Table 3.1. The dashed line is for soda-lime 1. The dash-dot line is for soda-lime 2 and the solid line is for soda-lime 3. The dotted circles are thermal conductivities of soda-lime glass measured in the divided-bar apparatus while the dotted squares are conductivities determined with a needle probe.

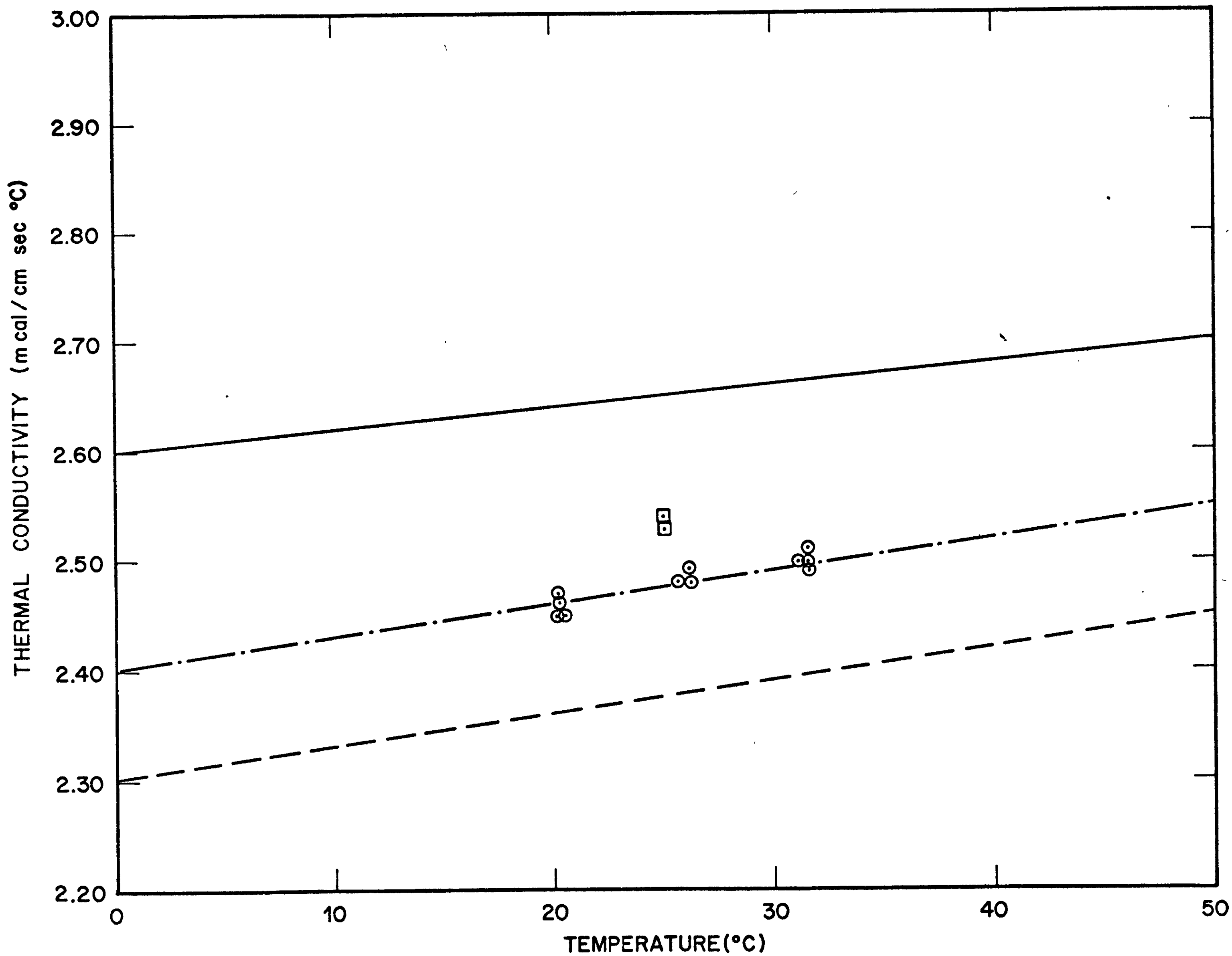
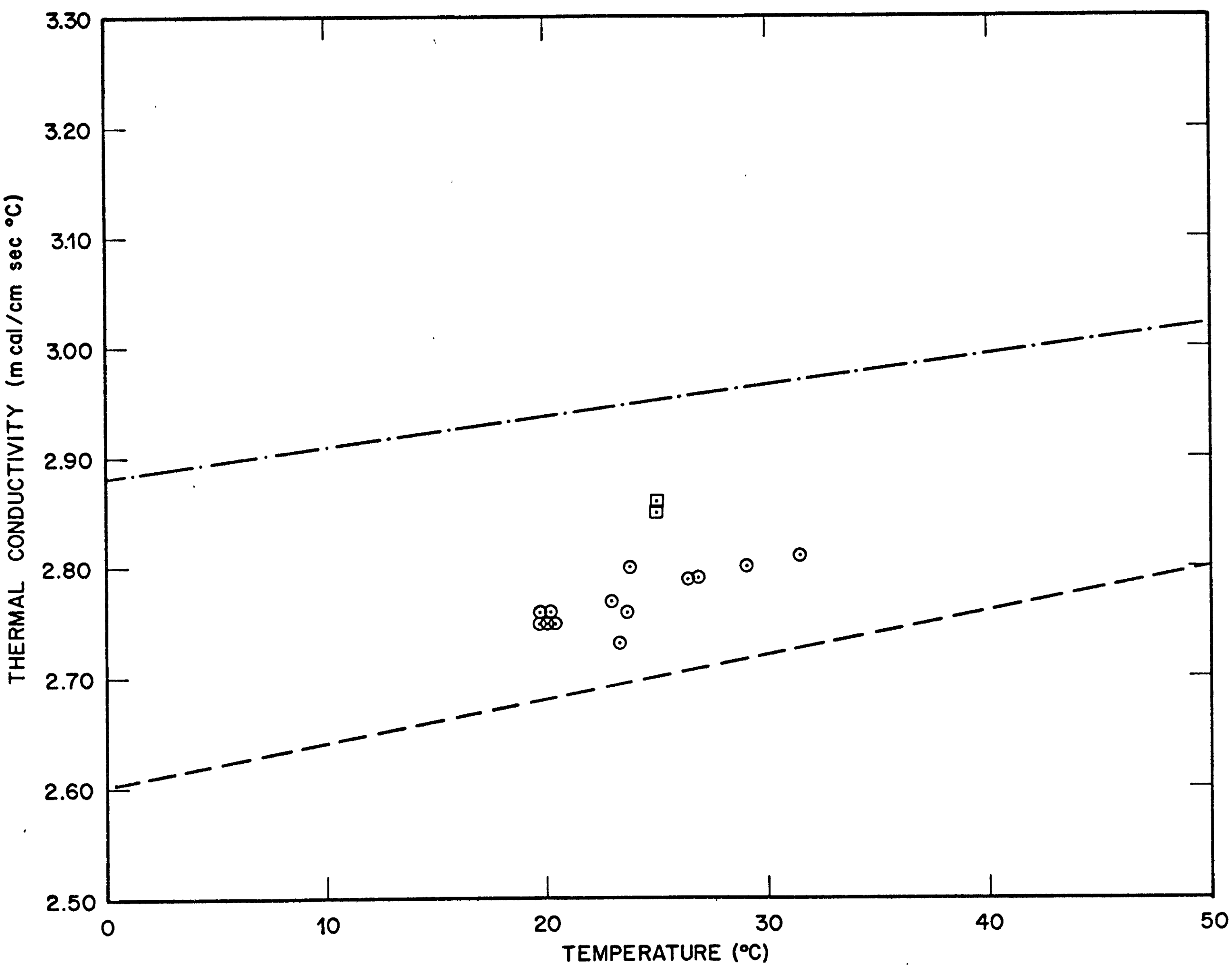

THERMAL CONDUCTIVITY (m cal / cm sec °C)
3.00
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
0
10
20
30
40
50
TEMPERATURE (°C)

Figure 3.2 Thermal conductivity of pyrex (chemically-resistant borosilicate glass) as a function of temperature. The dashed line is for Pyrex 2 of Table 3.1. The dash-dot line is for the pyrex studied by Birch and Clark (1940). The dotted circles are thermal conductivities of pyrex glass measured in the divided-bar apparatus while the dotted squares are conductivities determined with a needle probe.



3.30
3.20
3.10
3.00
2.90
2.80
2.70
2.60
2.50
THERMAL CONDUCTIVITY (m cal/cm sec °C)
0
10
20
30
40
50
TEMPERATURE (°C)

The thermal conductivity of the substandards was checked with the transient technique of K. Horai. Several pieces of pyrex and the soda-lime glasses were crushed to sizes less than 0.2 mm., mixed with distilled water and their conductivities were determined with a needle probe similar to that of von Herzen and Maxwell (1959). The results of the two methods are shown in Table 3.2.

Table 3.2

Thermal Conductivity of Substandards

Sample	Diameter	Thickness	Density	Thermal Conductivity divided-bar apparatus	needle probe technique
Glass 1	10.16	1.849	2.521	2.48	-
Glass 2	10.16	1.848	2.524	2.49	-
Glass 3	10.16	1.854	2.522	2.48	-
Glass 4	10.16	1.862	2.519	2.49	-
Glass 5	8.89	1.855	2.520	2.47	-
Glass 6	8.89	1.852	2.523	2.48	-
Glass 7	-	-	2.522	-	2.53
Glass 8	-	-	2.522	-	2.54
Pyrex 1	10.16	2.553	2.227	2.78	-
Pyrex 2	10.16	2.553	2.230	2.79	-
Pyrex 3	10.16	2.553	2.226	2.79	-
Pyrex 4	4.74	1.407	2.228	2.79	-
Pyrex 5	8.87	2.563	2.226	2.81	-
Pyrex 6	8.85	2.562	2.226	2.78	-
Pyrex 7	-	-	2.226	-	2.86
Pyrex 8	-	-	2.226	-	2.85

3.3 SATURATION, PRESSURE, AND TEMPERATURE EFFECTS

In porous rocks, the thermal conductivity depends on pressure, temperature, and the interstitial fluids. Several investigators (Birch and Clark, 1940; Clark, 1941; Bullard and Niblett, 1951; Beck and Beck, 1958; Horai and Uyeda, 1960; Woodside and Messmer, 1961) have demonstrated the marked effects that saturation, temperature, and pressure have on the thermal conductivities of very porous (> 1%) rocks.

All of the samples used in this investigation were from depths below the local water tables; therefore, all of the samples were saturated with water before their thermal conductivities were measured.

In order to saturate completely the specimens, the technique described by Brace, et. al., (1965) was used. A set of ten samples was placed in a vacuum oven for at least twenty-four hours. The vacuum was held at 25 mm of mercury. So that no new cracks or pores would be introduced by thermal expansion of the constituent minerals, the temperature was kept at 30 °C. After the samples were thoroughly dry and evacuated of air and water, they were suspended over a container of tap water inside the vacuum chamber. When the pressure in the chamber was sufficiently low for the water to boil (about 25mm Hg), the sample was tipped into the water. The rock cores were left in water and then placed in a gas pressure vessel and held overnight at 10 bars to force more water into the pores. The cores remained in the water until they were placed in the divided-bar apparatus for the conductivity determinations.

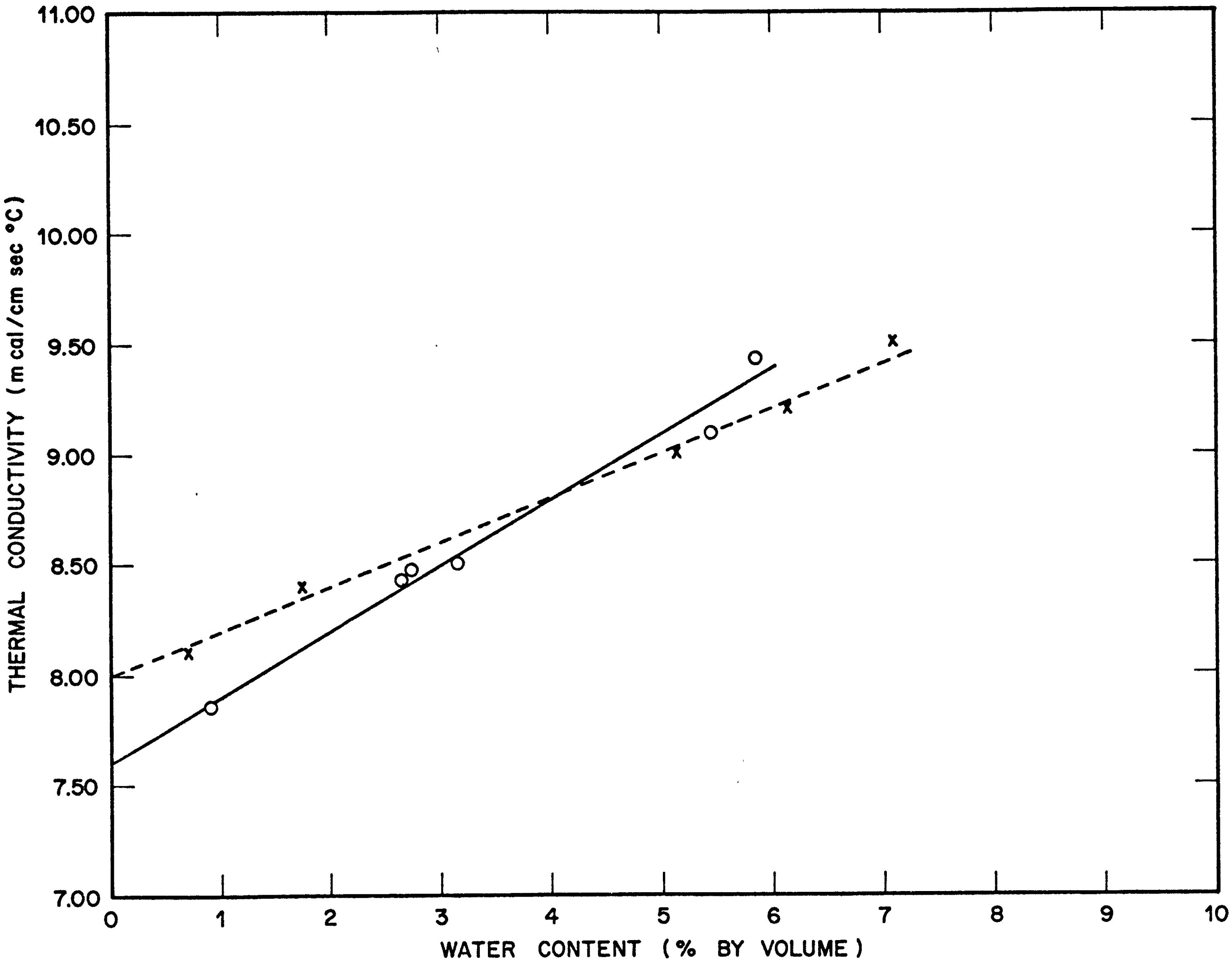
The effect of saturation was studied on a number of discs of varying porosity and it was found that the difference in thermal conductivity of a shelf-dried rock and a saturated rock could be as much as 40 per cent.

Each shelf-dried disc was weighed and the thermal conductivity was measured in the divided-bar apparatus with dry contacts between the faces of the rock disc and the bars. The discs were then saturated as was described above and their conductivity measured. The intermediate unsaturated states were obtained by letting the disc dry very slowly. Each disc was weighed before and after measurement and showed less than 0.1 per cent change in weight. The effect of saturation is emphasized in Figure 3.3, which is a plot of thermal conductivity as a function of water content (per cent by volume) for two sedimentary rocks of porosity between five and ten per cent.

Most of the samples were measured with an axial stress $\geq$ 50 bars. Several discs were run at stresses of 25 and 75 bars in order to determine the average correction for pressure. The pressure effects were small, less than 1% per 500 bars and consequently are neglected in the present study.

The temperature coefficients for the rock discs ranged from -1%/10 ^{o}C to -5%/10 ^{o}C and were important in most cases. In order to estimate the conductivity of the rocks at the in situ temperature, each sample was measured at several (2-6) different temperatures.

Figure 3.3 Thermal conductivity as a function of water content for two porous sedimentary rocks. The crosses and broken line are for a rock of 7.1% porosity. The circles and solid line are for a rock of 5.9% porosity.


THERMAL CONDUCTIVITY (m cal / cm sec °C)
11.00
10.50
10.00
9.50
9.00
8.50
8.00
7.50
7.00
0
1
2
3
4
5
6
7
8
9
10
WATER CONTENT (% BY VOLUME)

3.4 CONCLUSIONS

All of the thermal conductivities in this thesis are relative to that for fused silica (General Electric Company type G/P 125). The thermal conductivity of fused silica obtained by Ratcliffe (1959) was used. The combined systematic and random errors in the measurement of a single disc is less than 5 per cent, which is much less than the variation from specimen in most rocks.

Conductivites for all of the rock discs are tabulated as a function of in situ temperature and depth in Appendix II. The conductivities are arranged by state in which the well is located.

CHAPTER 4

HEAT FLOW IN ILLINOIS

4.1 INTRODUCTION

Four determinations of heat flow which have been made in northeastern Illinois are shown in Figure 4.1. All of them are located north of the Illinois basin in two gas storage fields which are operated by the Northern Illinois Gas Company. The Musser #1 borehole is located in Livingston County in the Ancona field while the other three are located in Iroquois County in the Crescent City field. The sedimentary section in this region has been temperature logged and sampled for thermal conductivity determinations to a total depth of 1100 meters.

4.2 RESULTS

Table 4.1 contains the geographic location, elevation, and best heat flow value calculated for the four boreholes. All elevations in this thesis pertain to the elevation of local ground level above sea level.

Figure 4.1 Terrestrial heat flow in Illinois. All values are in units of HFU.

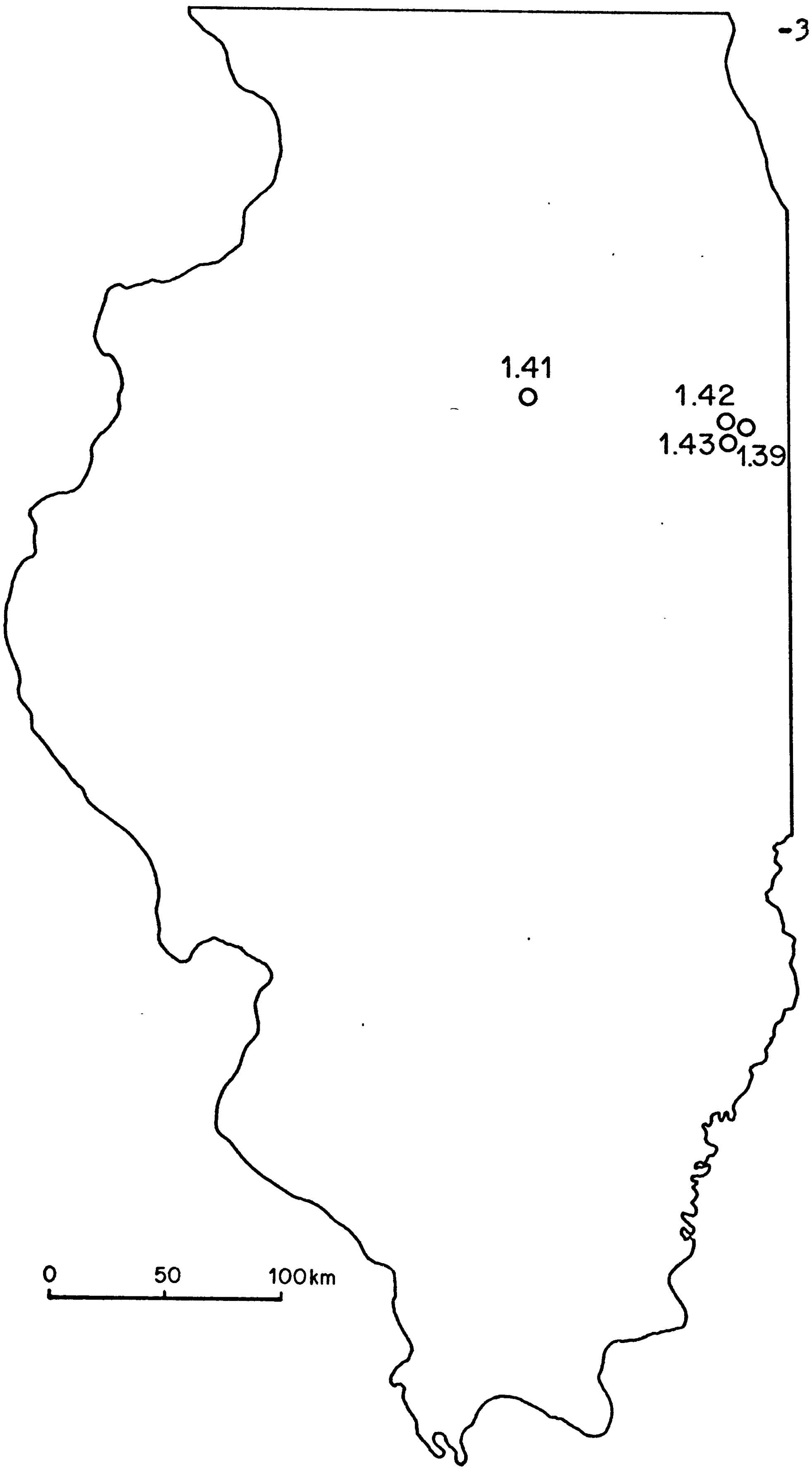

1.41
1.42
1.43
1.39
0
50
100km

TABLE 4.1 HEAT FLOW DETERMINATIONS IN ILLINOIS

WELL NAME	NORTH LATITUDE	WEST LONGITUDE	ELEVATION	HEAT FLOW
MUSSER #1, Ancona	41° 01.2'	88° 53.7'	194	1.41±0.04
CONDIT #1, Crescent City	40° 48.6'	87° 53.6'	194	1.42±0.03
TADEN #1, Crescent City	40° 45.3'	87° 47.3'	198	1.43±0.03
F. WESSELS #1, Crescent City	40° 45.7'	87° 48.4'	197	1.39±0.02

By comparing the temperature-depth graphs for the four wells, (Figures 4.2 thru 4.8), it is seen that the sedimentary sequence is essentially the same in these two fields. This observation is substantiated by comparing the lithologic logs. Since core samples were intermittently recovered from a depth of approximately 200 to 1100 meters, a number of different rock types were sampled. All of the thermal conductivity values are tabulated in Appendix II while Appendix I contains temperature measurements at five meter intervals that were obtained from the continuous temperature logs.

Tables 4.2 - 4.5 give the data pertinent to the calculation of the best value for the heat flow that was indicated in Table 4.1. From these tables, it can be seen that the value for the heat flow remained essentially unchanged over the total depths of the boreholes. This is the

Figure 4.2 Temperature-depth plot for the Condit #1, Crescent City, Illinois. Drilling completed: 6-3-60.

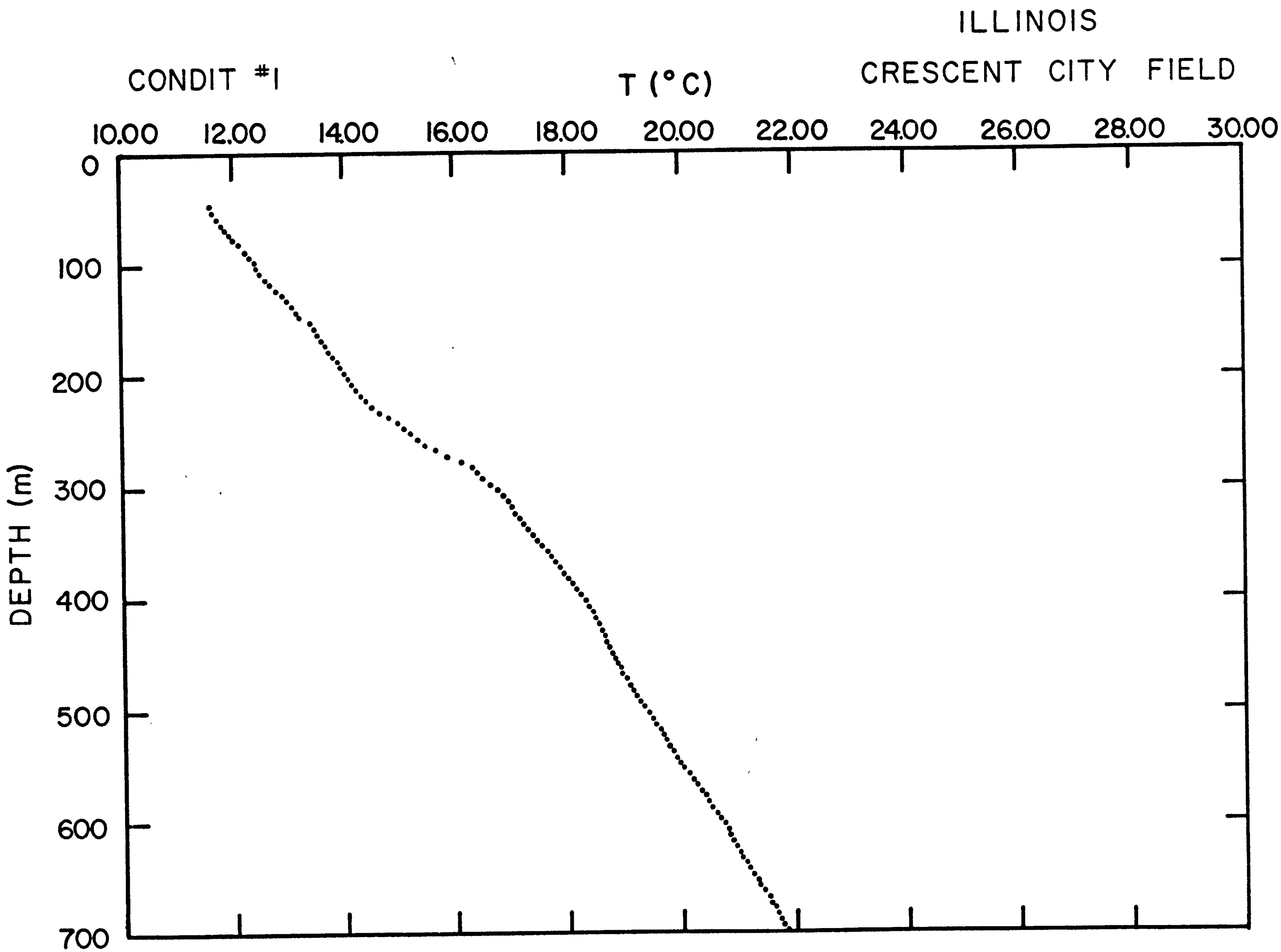

ILLINOIS
CRESCENT CITY FIELD
CONDIT #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 4.3 Continuation of the temperature-depth plot for the Condit #1.

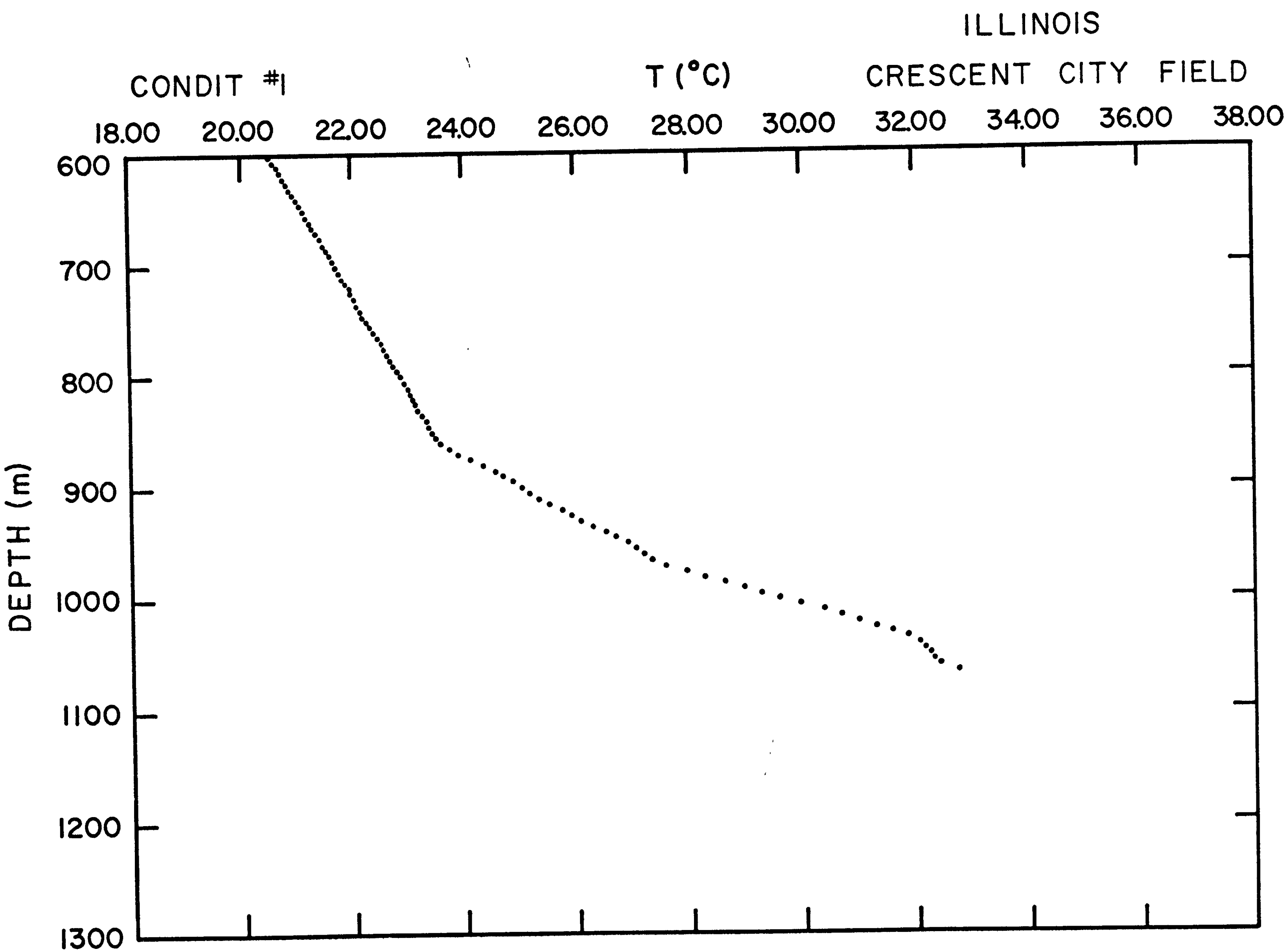

ILLINOIS
CRESCENT CITY FIELD
CONDIT #1
T (°C)
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
34.00
36.00
38.00
DEPTH (m)
600
700
800
900
1000
1100
1200
1300

Figure 4.4 Temperature-depth plot for the Musser #1, Ancona, Illinois. Drilling completed: 10-8-62.

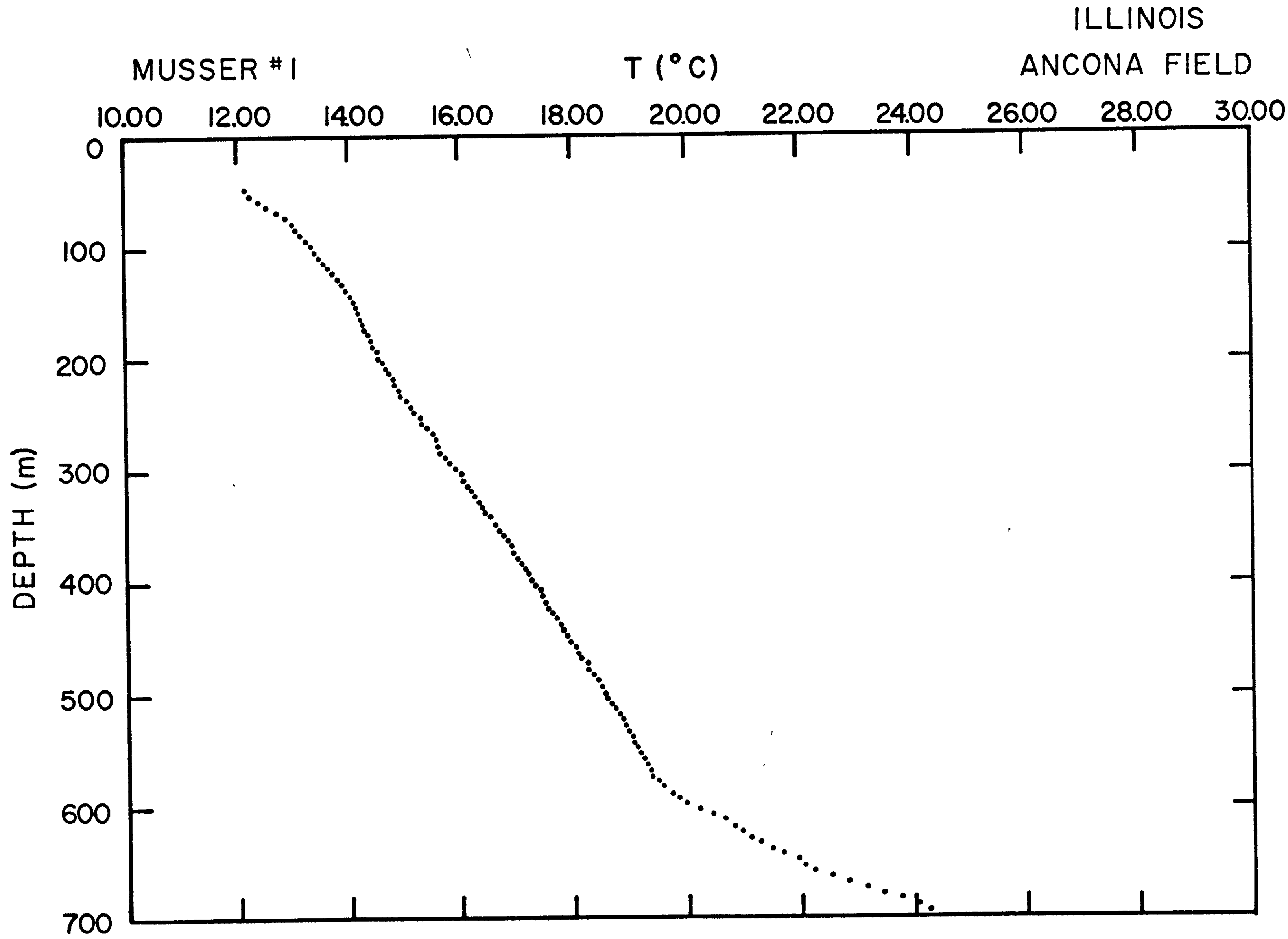
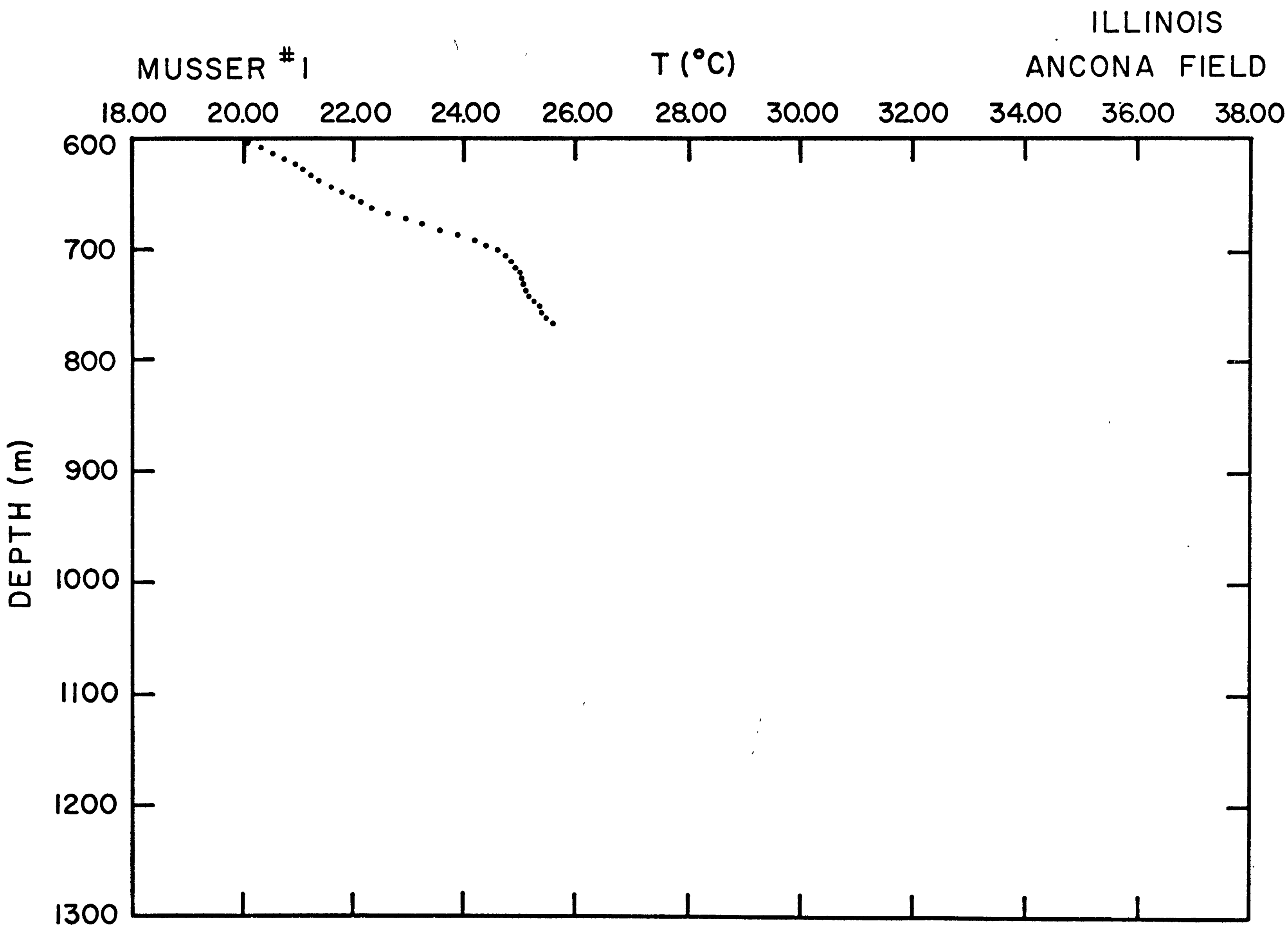

ILLINOIS
ANCONA FIELD
MUSSER #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 4.5 Continuation of the temperature-depth plot for the Musser #1.



ILLINOIS
ANCONA FIELD
MUSSER #1
T (°C)
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
34.00
36.00
38.00
DEPTH (m)
600
700
800
900
1000
1100
1200
1300

Figure 4.6 Temperature-depth plot for the Taden #1, Crescent City, Illinois. Drilling completed: 5-14-60.

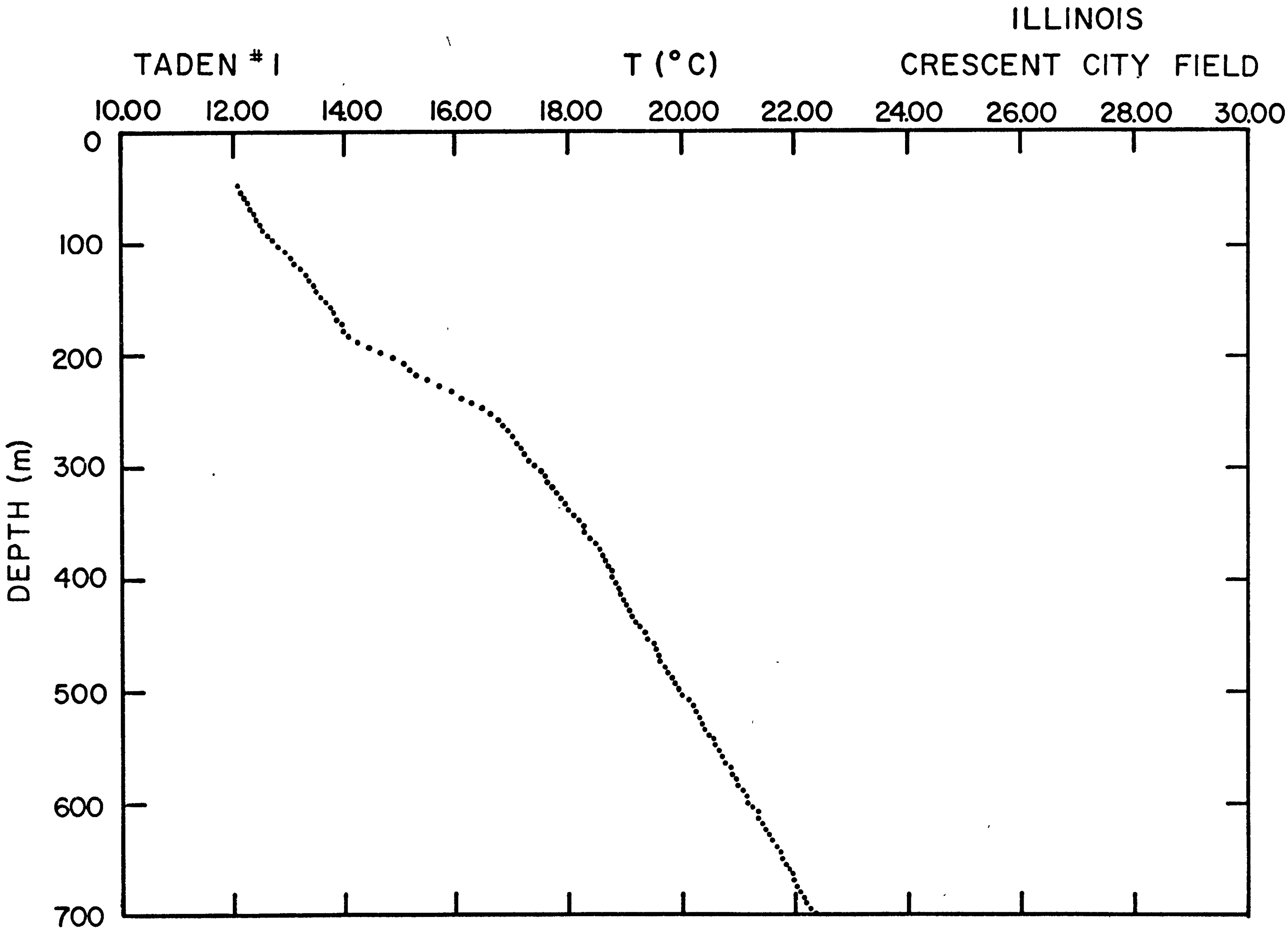

ILLINOIS
TADEN # 1
T (°C)
CRESCENT CITY FIELD
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 4.7 Continuation of the temperature-depth plot for the Taden #1.

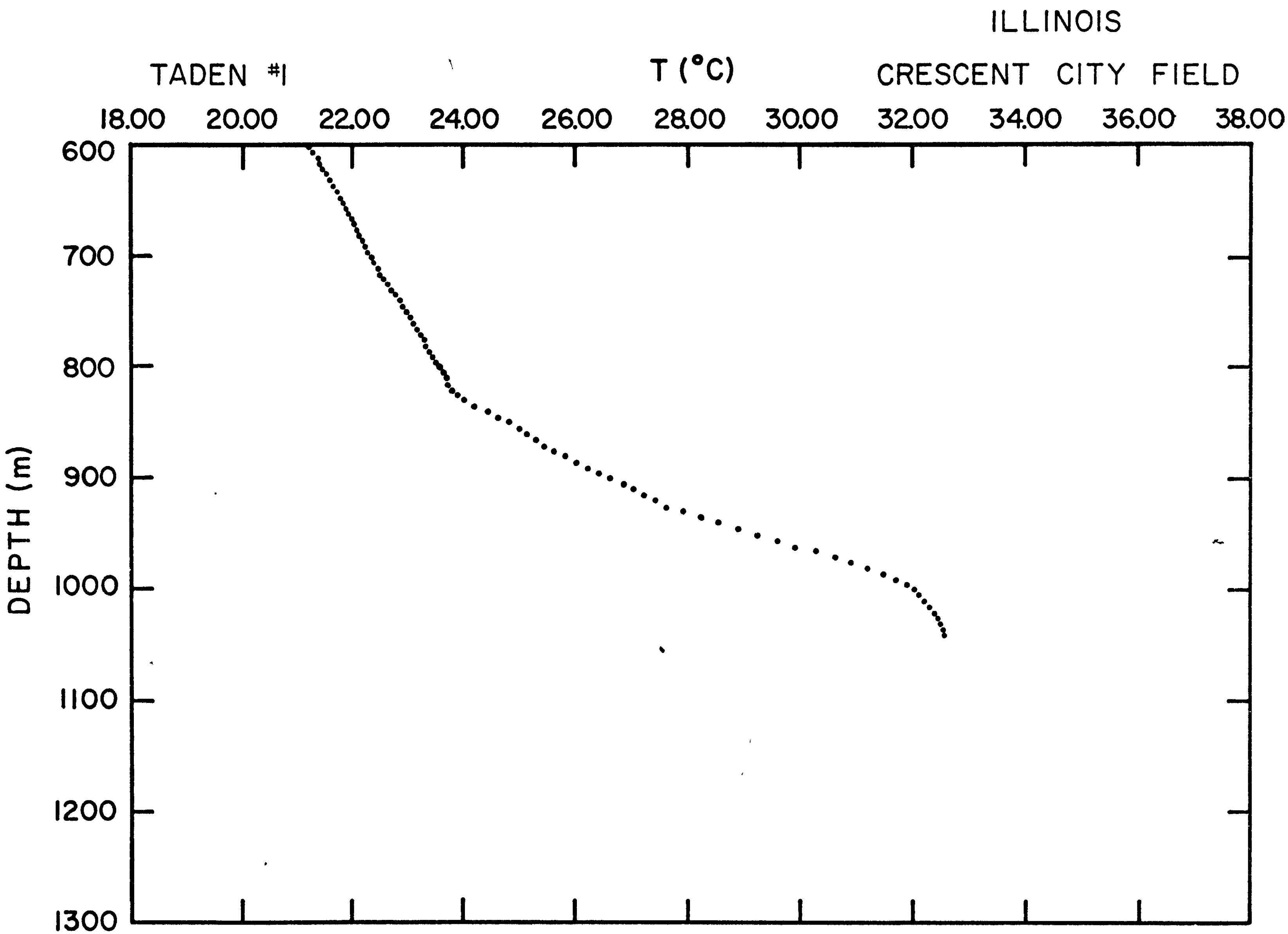
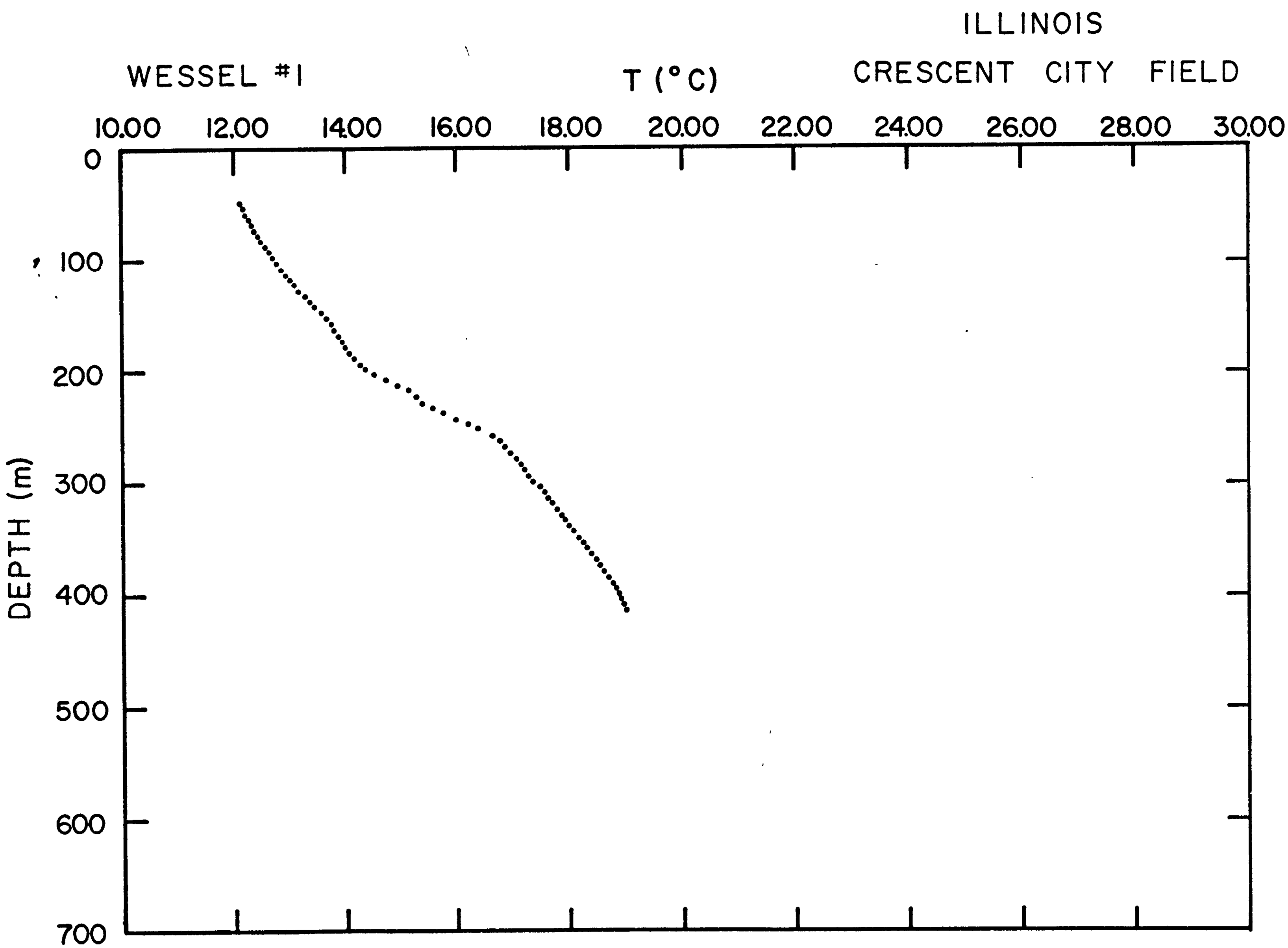

ILLINOIS
TADEN #1
T (°C)
CRESCENT CITY FIELD
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
34.00
36.00
38.00
DEPTH (m)
600
700
800
900
1000
1100
1200
1300

Figure 4.8 Temperature-depth plot for the Wessel #1, Crescent City, Illinois. Drilling completed: 6-25-60.


ILLINOIS
CRESCENT CITY FIELD
WESSEL #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

result that one would expect to encounter when making a steady-state heat flow determination in an undisturbed borehole.

TABLE 4.2 MUSSER #1, ANCONA

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
696	21.2	6.79 (1)	1.44
707	10.3	13.25 (1)	1.37
724-729	10.7	13.27 (3)	1.42
733-736	10.7	13.01 (2)	1.39
750	12.4	11.41 (1)	1.41

TABLE 4.3 CONDIT #1, CRESCENT CITY

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
386-391	12.7	11.15 (2)	1.42
428	11.0	12.95 (1)	1.42
431-441	9.65	14.40 (2)	1.39
781-804	11.7	12.22 (6)	1.43
853	14.1	9.96 (1)	1.40
1049	10.5	13.77 (1)	1.45
1062	11.4	12.36 (1)	1.41

TABLE 4.4 TADEN #1, CRESCENT CITY

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
205	19.7	7.25 (1)	1.43
250-254	19.5	7.27 (2)	1.42
262-269	18.4	7.89 (2)	1.45
308-328	17.4	8.10 (3)	1.41
337-344	19.6	7.34 (2)	1.44
413-416	10.8	13.38 (2)	1.45
778-789	11.2	13.00 (3)	1.46

TABLE 4.5 F. WESSELS #1, CRESCENT CITY

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
353-381	16.3	8.55 (6)	1.39
388-393	11.0	12.77 (2)	1.41
404-407	9.97	13.84 (2)	1.38

The Crescent City field as well as a number of fields in Indiana and Iowa offer a unique opportunity to determine the heat flow from several boreholes located in a limited area, and consequently, obtain some estimate of the validity of the separate heat flow values.

4.3 DISCUSSION AND CONCLUSIONS

The boreholes in Illinois are located on the low Kankakee arch which structurally separates the Michigan basin from the Illinois basin. The local stratigraphic section consists of essentially flat-lying Paleozoic sediments overlying the crystalline basement (King, 1959). Bradbury and Atherton (1965), Aldrich et al. (1960), and Muehlberger et al. (1964), using basement rock samples from deep boreholes, have shown that the Illinois basement rocks are characterized chiefly by igneous rocks of granitic or closely related composition. No Precambrian mafic igneous rocks or metasediments have been encountered in the fifteen basement samples that have been recovered in Illinois. Furthermore, this knowledge of the Precambrian crystalline rocks conbined with available gravity and magnetic data (McGinnis and Heigold, 1961; Beck, 1965; and McGinnis, 1966) indicate that the local basement consists of a large, homogeneous body of granitic rock.

From the heat flow values presented in Table 4.1 combined with the geological and geophysical data discussed above, one can conclude that the source of the measured heat flow can not be a near surface effect. This conclusion is further supported by the fact that radiogenic elements (chiefly U, Th, K) which could conceivably be sources of local heating are rare in the Paleozoic sedimentary section in northern Illinois. In addition, there are no local large scale thermal conductivity contrasts. Therefore, a value of 1.41 HFU is proposed as the best value for the regional heat flow in northeastern Illinois.

CHAPTER 5

HEAT FLOW IN INDIANA

5.1 INTRODUCTION

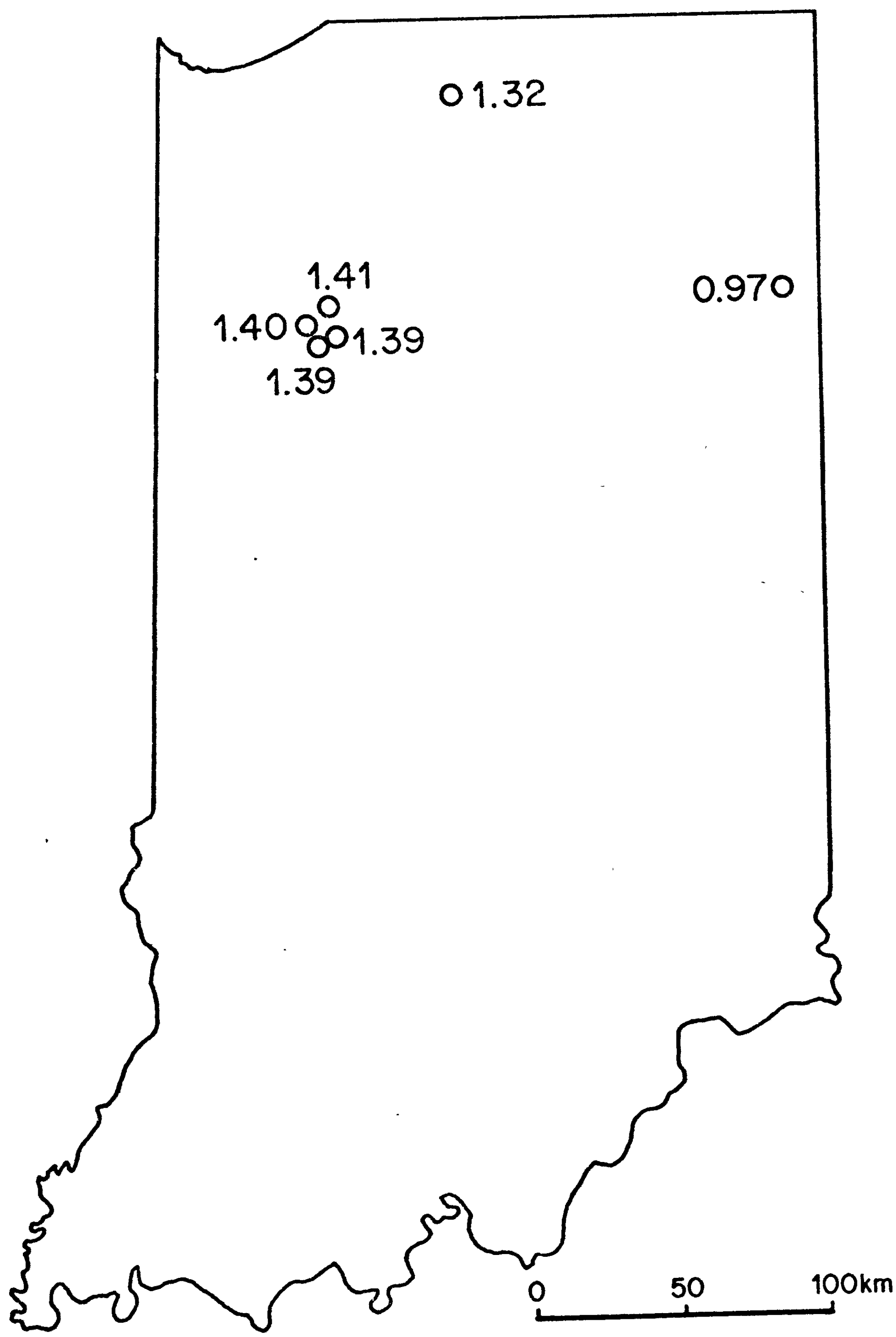
Three separate fields operated by the Northern Indiana Public Service Company were investigated in Indiana. Two of the fields, Linkville and Royal Center, are associated with an anticlinal structure that has been faulted. The third field, Monroeville, is located on an anticlinal structure that does not appear to have been faulted. In general, the Precambrian basement surface slopes from the east to the western edge of the state, in particular, the depth to basement at Monroeville is approximately 600 meters while the sedimentary cover at Linkville and Royal Center is greater than 1200 meters (Henderson and Zietz, 1958).

Continuous temperature - depth curves were recorded for the five boreholes logged in the Royal Center field, but discrete temperature - depth curves were obtained for the eight wells at Linkville and the Leuenberger well in the Monroeville field. Measurements were made by P. Spencer at every three meters in order to construct the discrete curves.

5.2 RESULTS

Table 5.1 contains the location, elevation, and best

Figure 5.1 Terrestrial heat flow in Indiana. All values are in units of HFU.


1.32
1.41
0.97
1.40
1.39
1.39
0
50
100km

value for the heat flow obtained for the boreholes in Indiana and the heat flow station are shown in Figure 5.1.

TABLE 5.1 HEAT FLOW DETERMINATIONS IN INDIANA

WELL NAME	NORTH LATITUDE	WEST LONGITUDE	ELEVATION	HEAT FLOW
LEUENBERGER WELL, Monroeville	40° 58.5'	84° 52.1'	243	0.97±0.03
LINKVILLE FIELD	41° 23.0'	86° 14.0'	247	1.33±0.20
S-36, Royal Center	40° 53.4'	86° 28.3'	226	1.41±0.02
S-38, Royal Center	40° 53.4'	86° 28.0'	226	1.39±0.06
S-46, Royal Center	40° 54.5'	86° 27.8'	226	1.40±0.02
S-55, Royal Center	40° 55.1'	86° 27.1'	227	1.39±0.02

Data used for the determination of the heat flow value for the Leuenberger well located in Allen County is tabulated in Table 5.2 and the individual values of temperatures and thermal conductivities are presented in Appendix I and II. The temperature - depth data for the Leuenberger well is plotted in Figure 5.2.

Figure 5.2 Temperature-depth plot for Leuenberger well, Monroeville, Indiana. Well completed: 6-30-62.

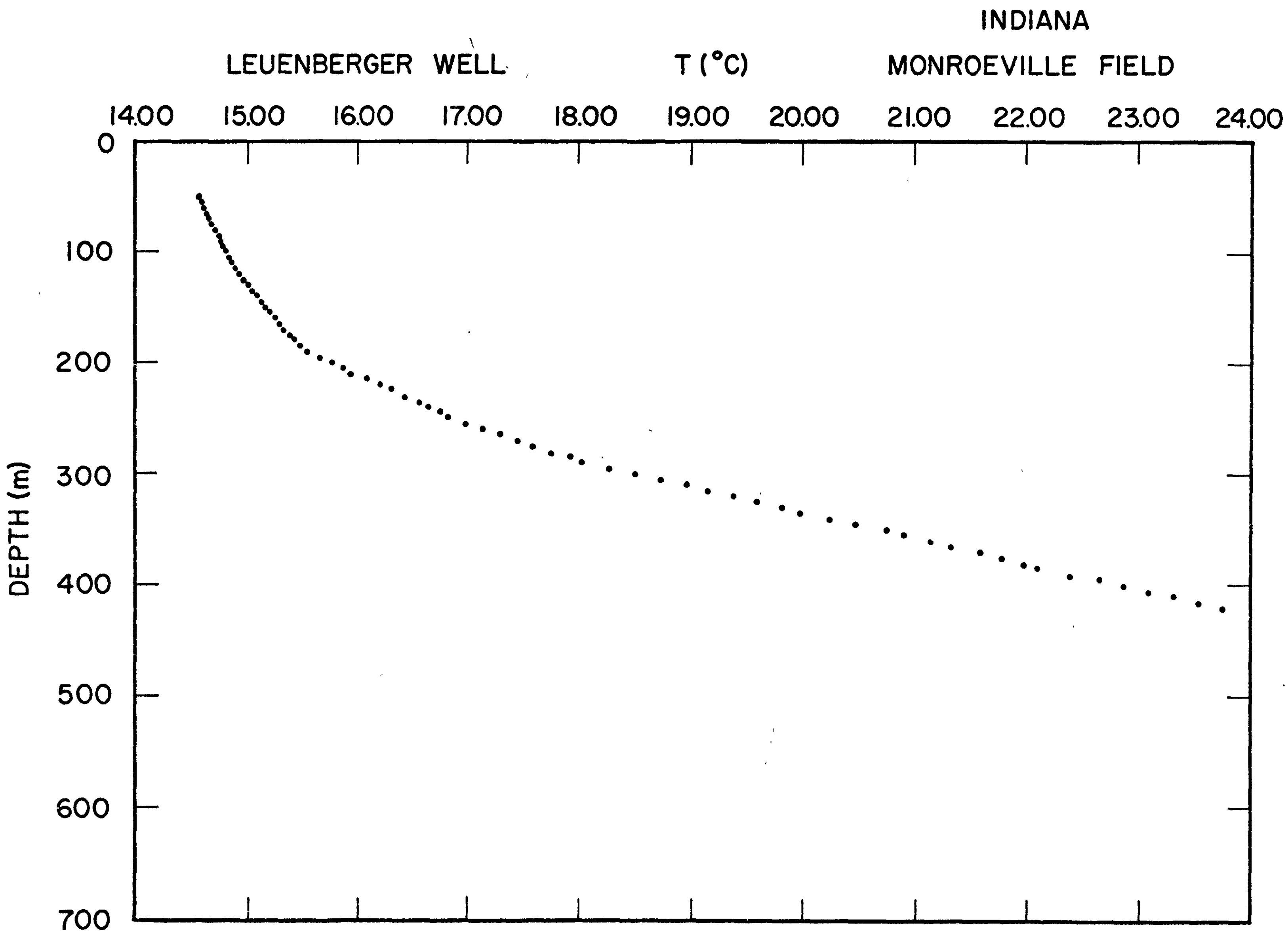

INDIANA
LEUENBERGER WELL
T (°C)
MONROEVILLE FIELD
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
24.00
DEPTH (m)
0
100
200
300
400
500
600
700

TABLE 5.2 LEUENBERGER WELL, MONROEVILLE

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
111-117	9.02	11.09 (3)	1.00
133	9.48	10.23 (1)	0.97
143-152	8.50	11.53 (3)	0.98
155-162	7.87	12.20 (2)	0.96
167	10.0	9.87 (1)	0.99
172-176	8.39	11.21 (2)	0.94

The Linkville field, located in Marshall County, is approximately 5 by 6 km. The existence of a large number of boreholes in this limited area allowed us to examine the spatial variation of heat flow. Because the boreholes were all less than 150 meters deep, eight different holes scattered uniformly throughout the field were logged. Three of the wells were logged at two different times in order to determine whether a steady-state temperature response was being measured. The resultant temperature-depth curves are presented in Figures 5.3 to 5.10.

Since only one set of rock cores was available for thermal conductivity determinations, the conductivities over two intervals, in particular, 100-120 meters and 120-150 meters were averaged. This somewhat arbitrary division was made because of the differences in lithology between the

Figure 5.3 Temperature-depth plot for borehole LW-25, Linkville, Indiana. Drilling completed: 11-29-60. The X's indicate temperatures measured on 8-29-64 and the dots indicate those measured on 9-1-64.

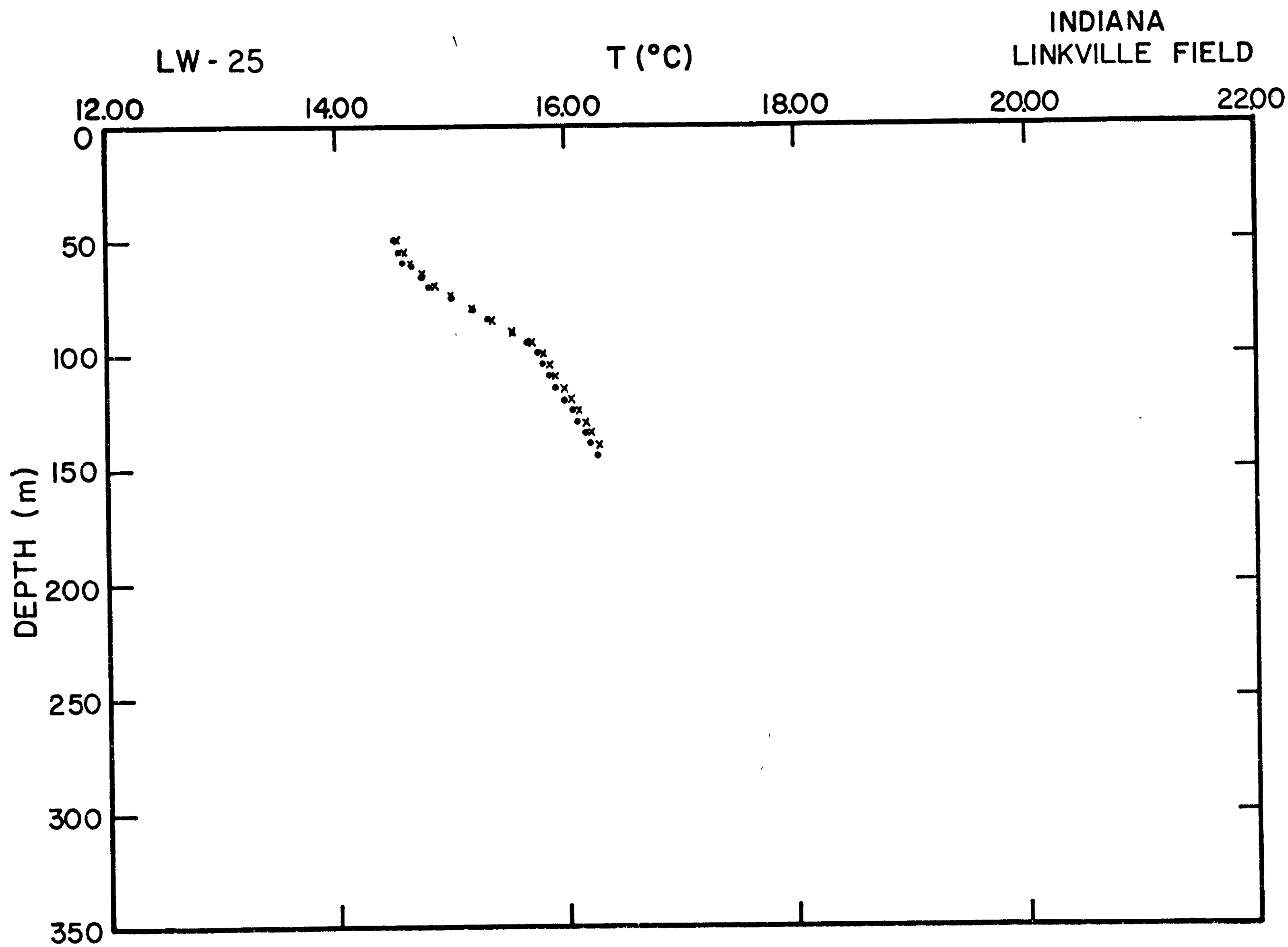

LW - 25
T (°C)
INDIANA
LINKVILLE FIELD
12.00
14.00
16.00
18.00
20.00
22.00
DEPTH (m)
0
50
100
150
200
250
300
350

Figure 5.4 Temperature-depth plot for borehole LW-41, Linkville, Indiana. Drilling completed: 5-10-62.

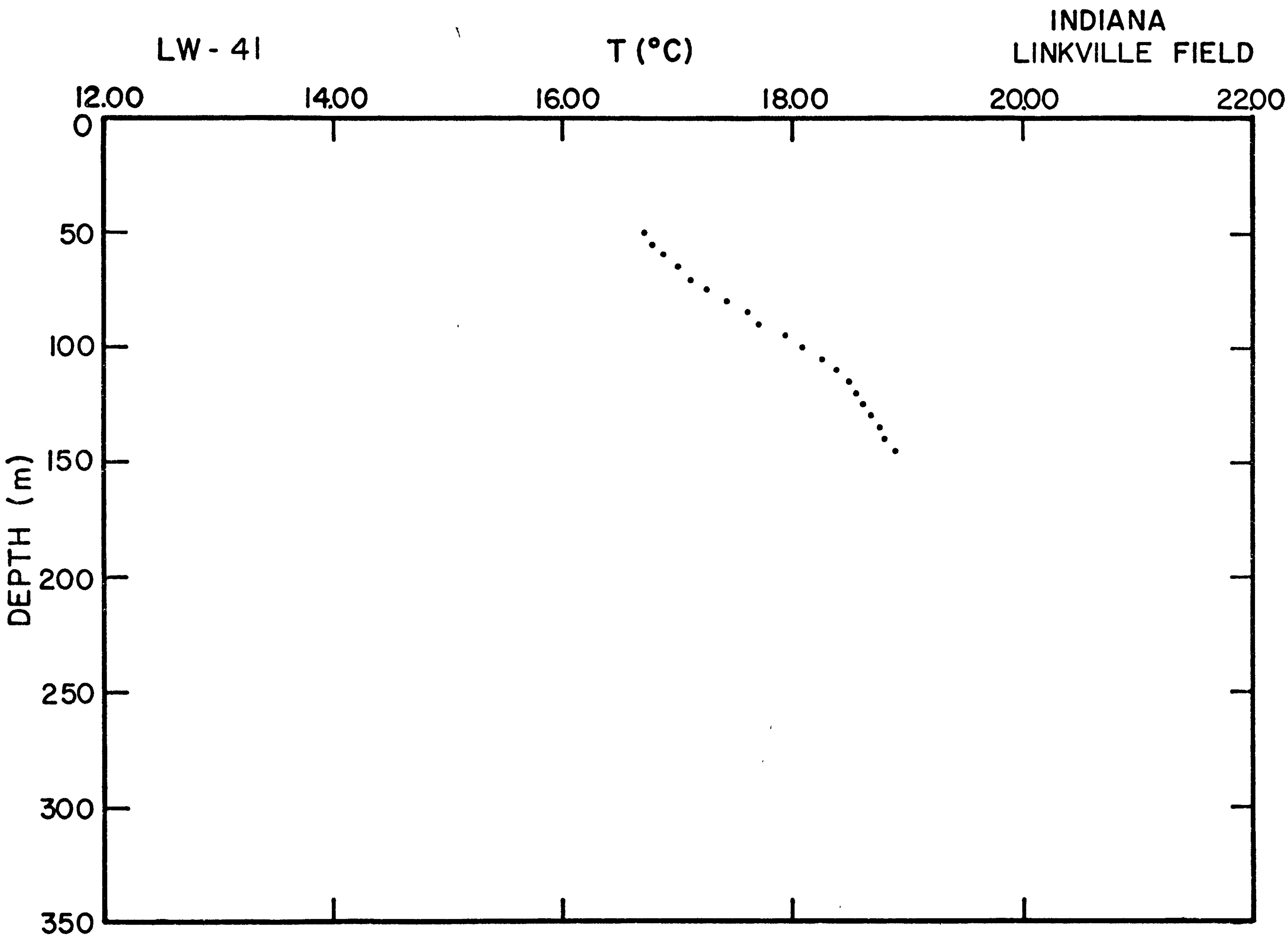

LW - 41
T (°C)
INDIANA
LINKVILLE FIELD
12.00
14.00
16.00
18.00
20.00
22.00
DEPTH (m)
0
50
100
150
200
250
300
350

Figure 5.5 Temperature-depth plot for borehole LW-57, Linkville, Indiana. Drilling completed: 4-22-62. The X's indicate temperatures measured on 8-30-64 and the dots indicate those measured on 9-2-64.

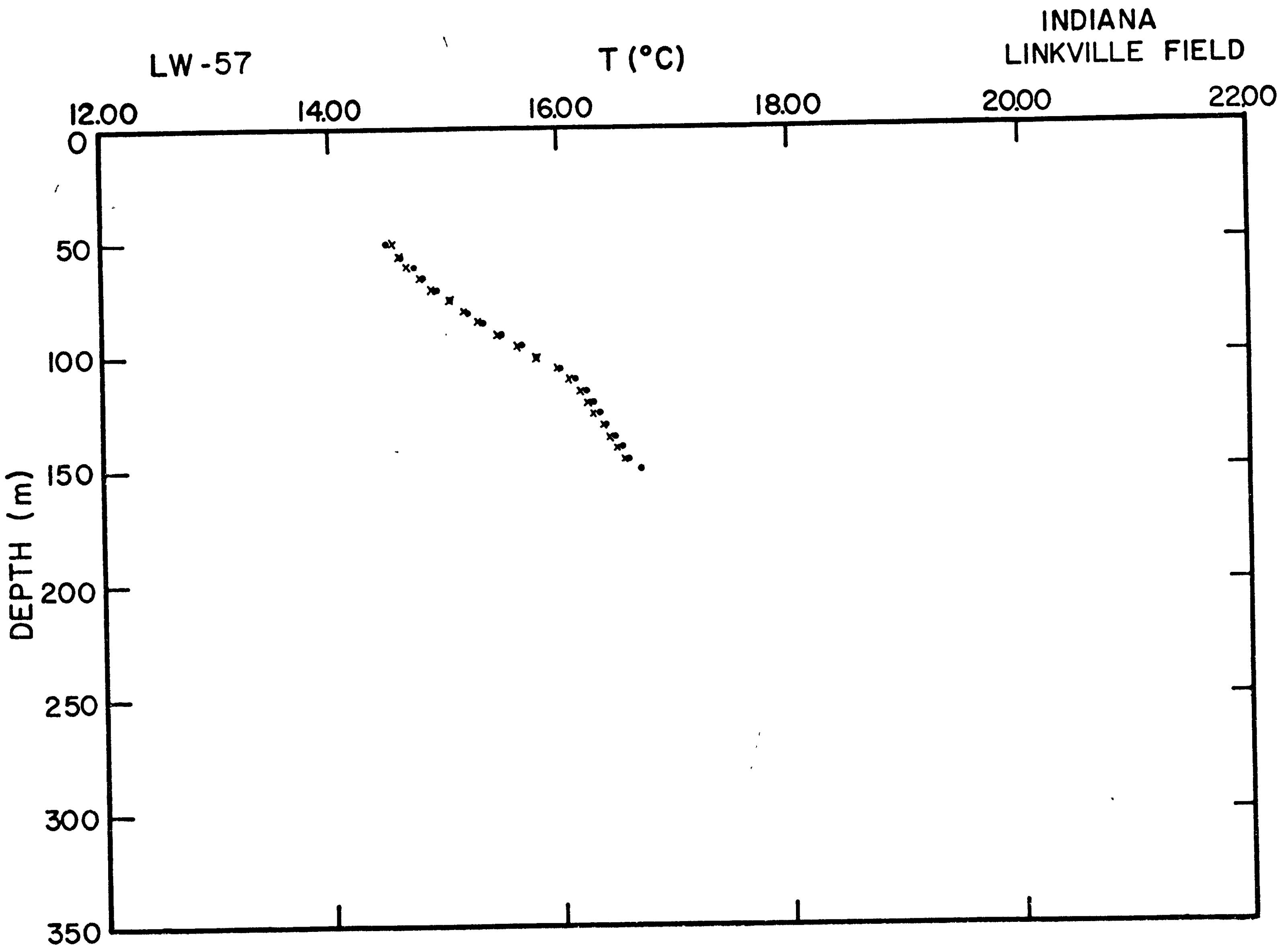

INDIANA
LINKVILLE FIELD
LW-57
T (°C)
12.00
14.00
16.00
18.00
20.00
22.00
DEPTH (m)
0
50
100
150
200
250
300
350

Figure 5.6 Temperature-depth plot for borehole LW-62, Linkville, Indiana. Drilling completed: 3-5-62.

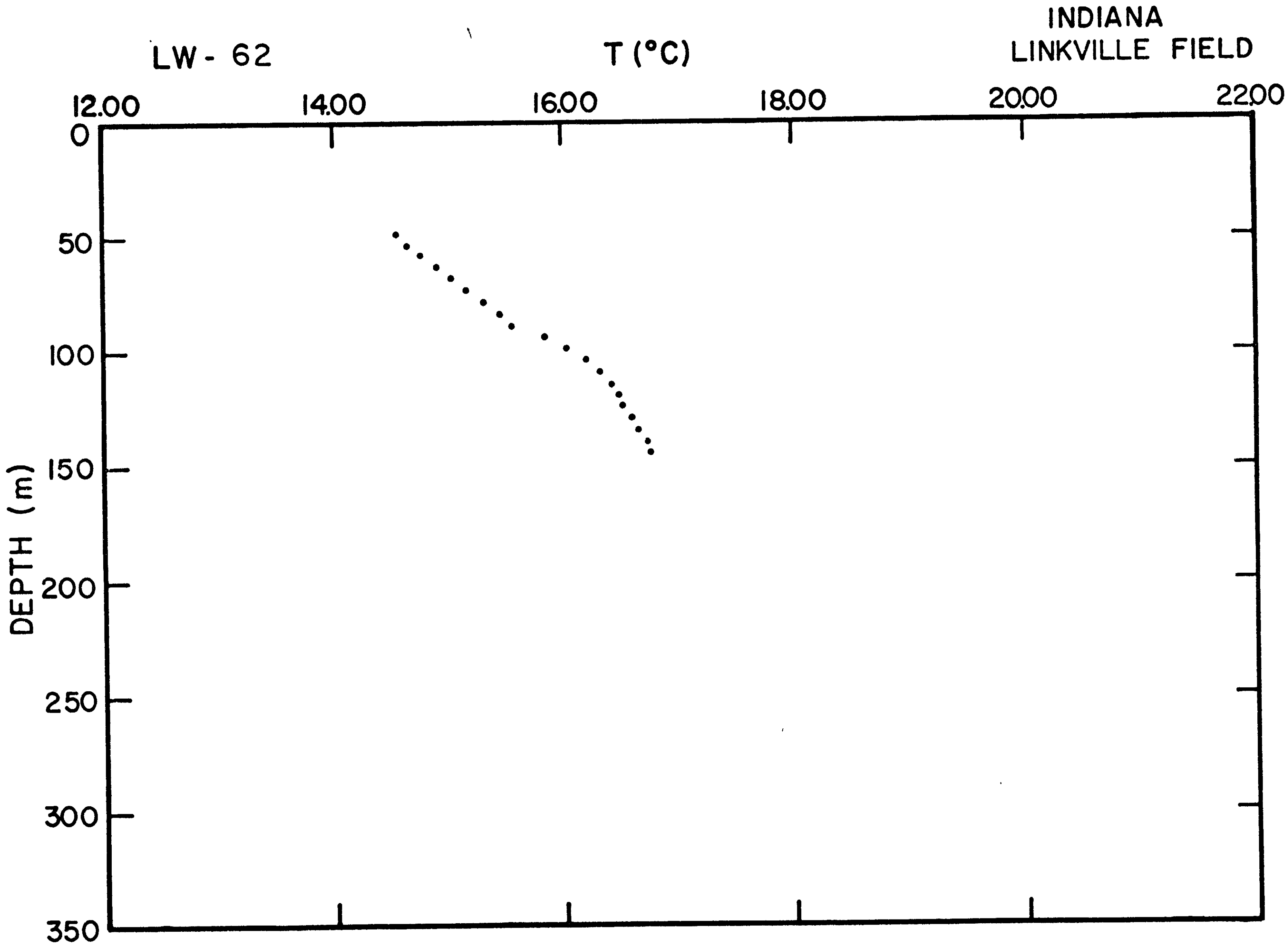

LW - 62
T (°C)
INDIANA
LINKVILLE FIELD
12.00
14.00
16.00
18.00
20.00
22.00
0
50
100
150
200
250
300
350
DEPTH (m)

Figure 5.7 Temperature-depth plot for borehole LW-65, Linkville, Indiana. Drilling completed: 3-18-62. The X's indicate temperatures measured on 8-28-64 and the dots indicate those measured on 9-1-64.

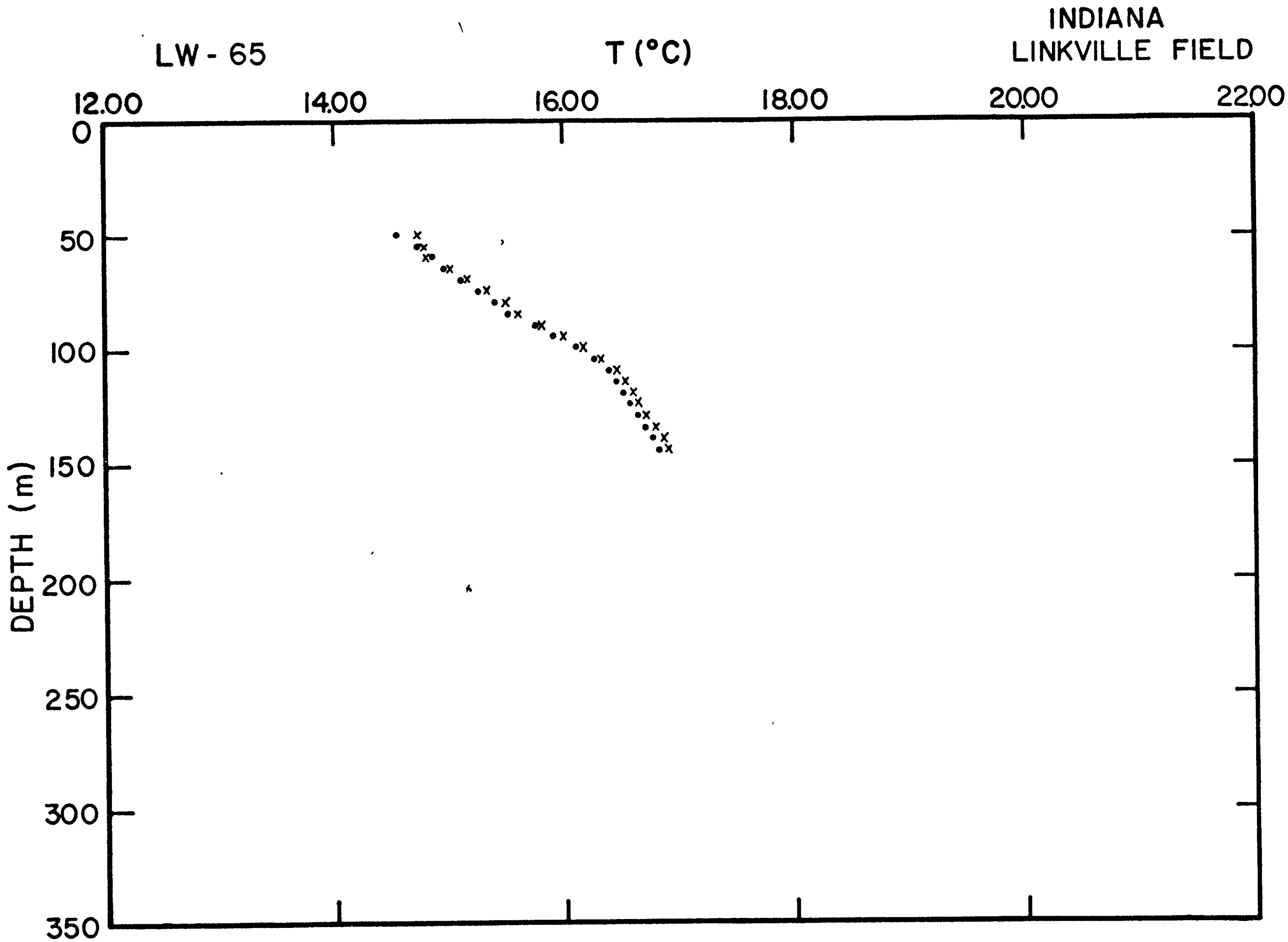
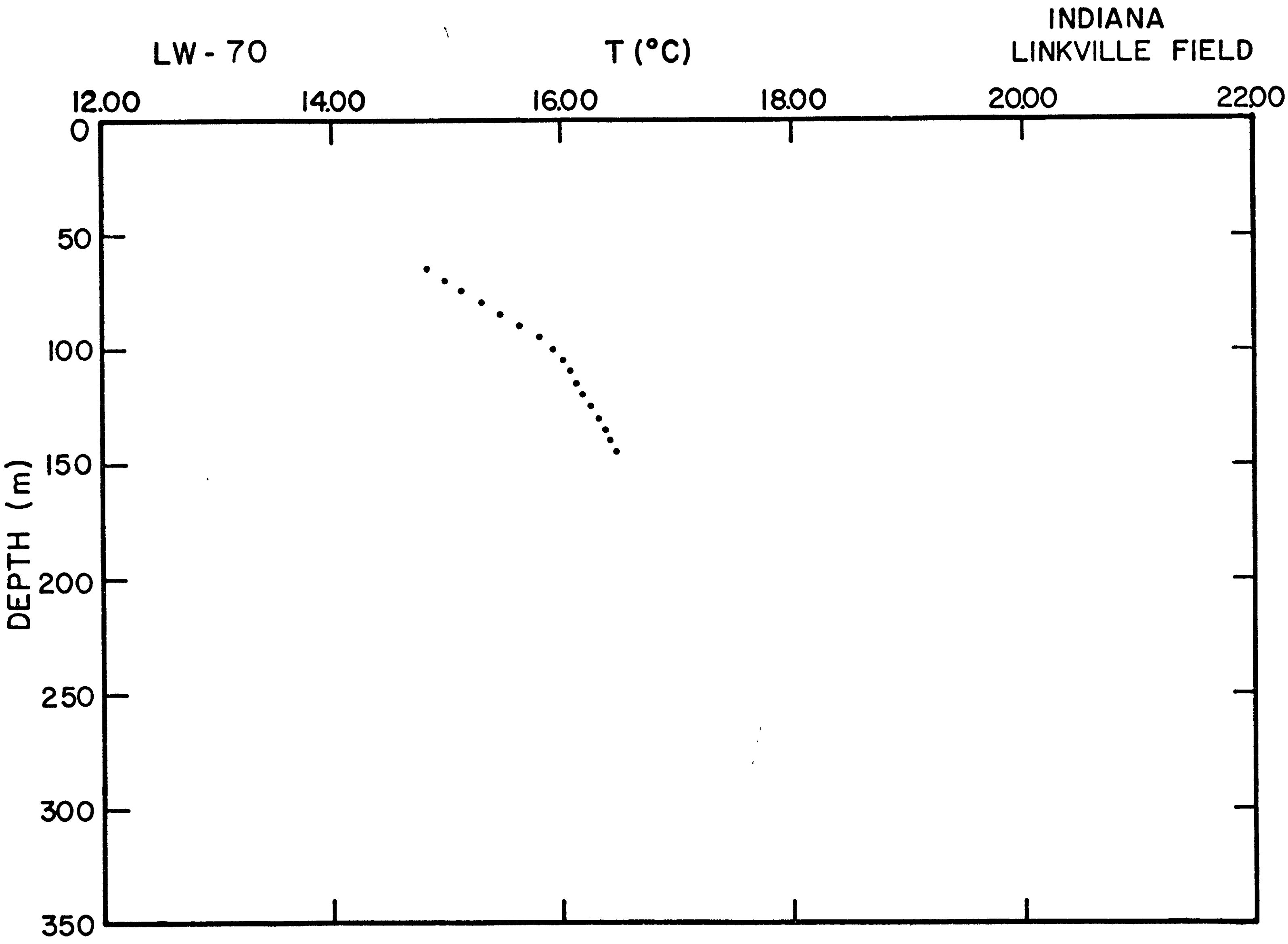

LW - 65
T (°C)
INDIANA
LINKVILLE FIELD
12.00
14.00
16.00
18.00
20.00
22.00
0
50
100
150
200
250
300
350
DEPTH (m)

Figure 5.8 Temperature-depth plot for borehole LW-70, Linkville, Indiana. Drilling completed: 4-25-62.



INDIANA
LINKVILLE FIELD
LW - 70
T (°C)
12.00
14.00
16.00
18.00
20.00
22.00
DEPTH (m)
0
50
100
150
200
250
300
350

Figure 5.9 Temperature-depth plot for borehole LW-77, Linkville, Indiana. Drilling completed: 6-10-63.

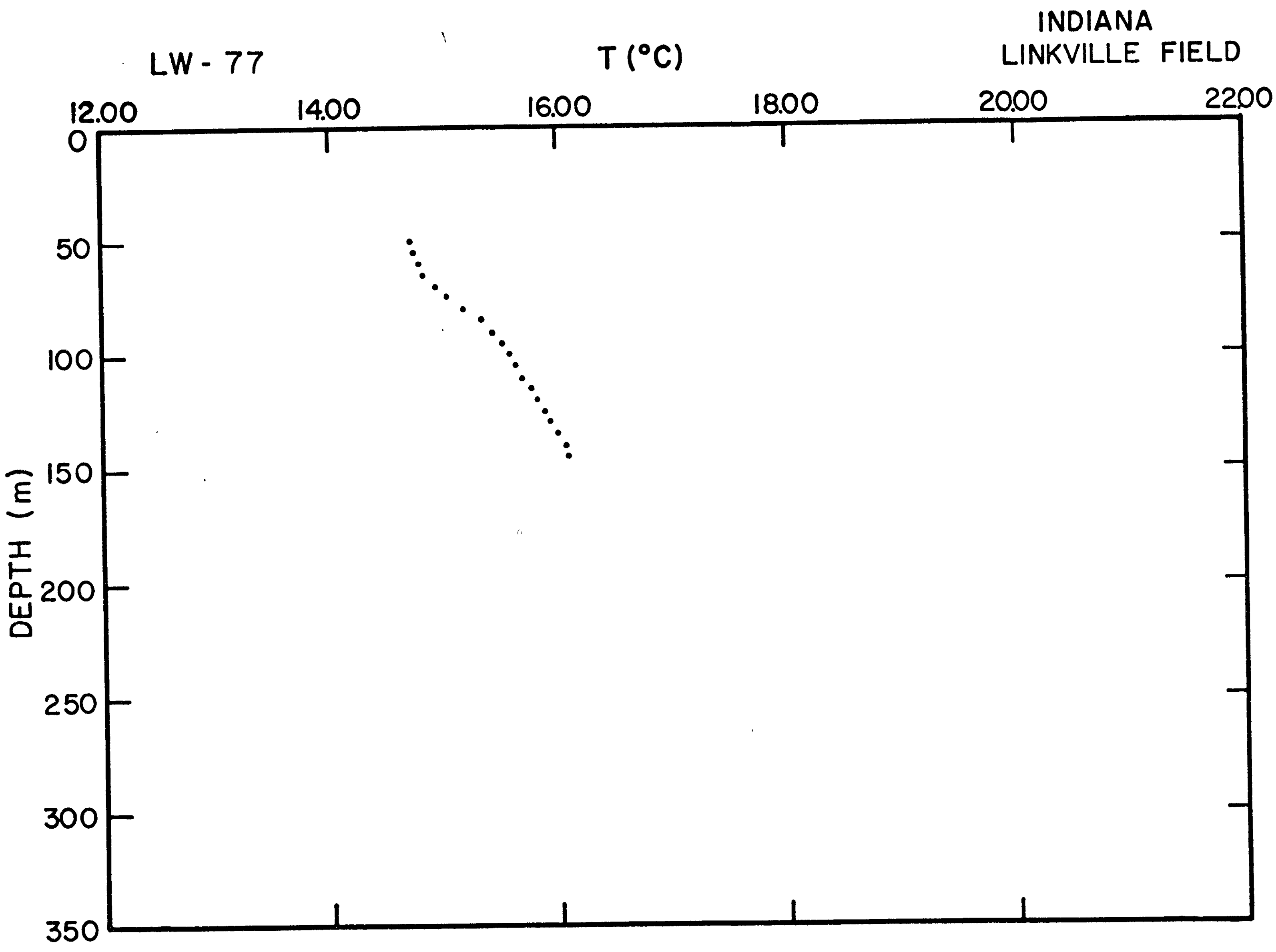
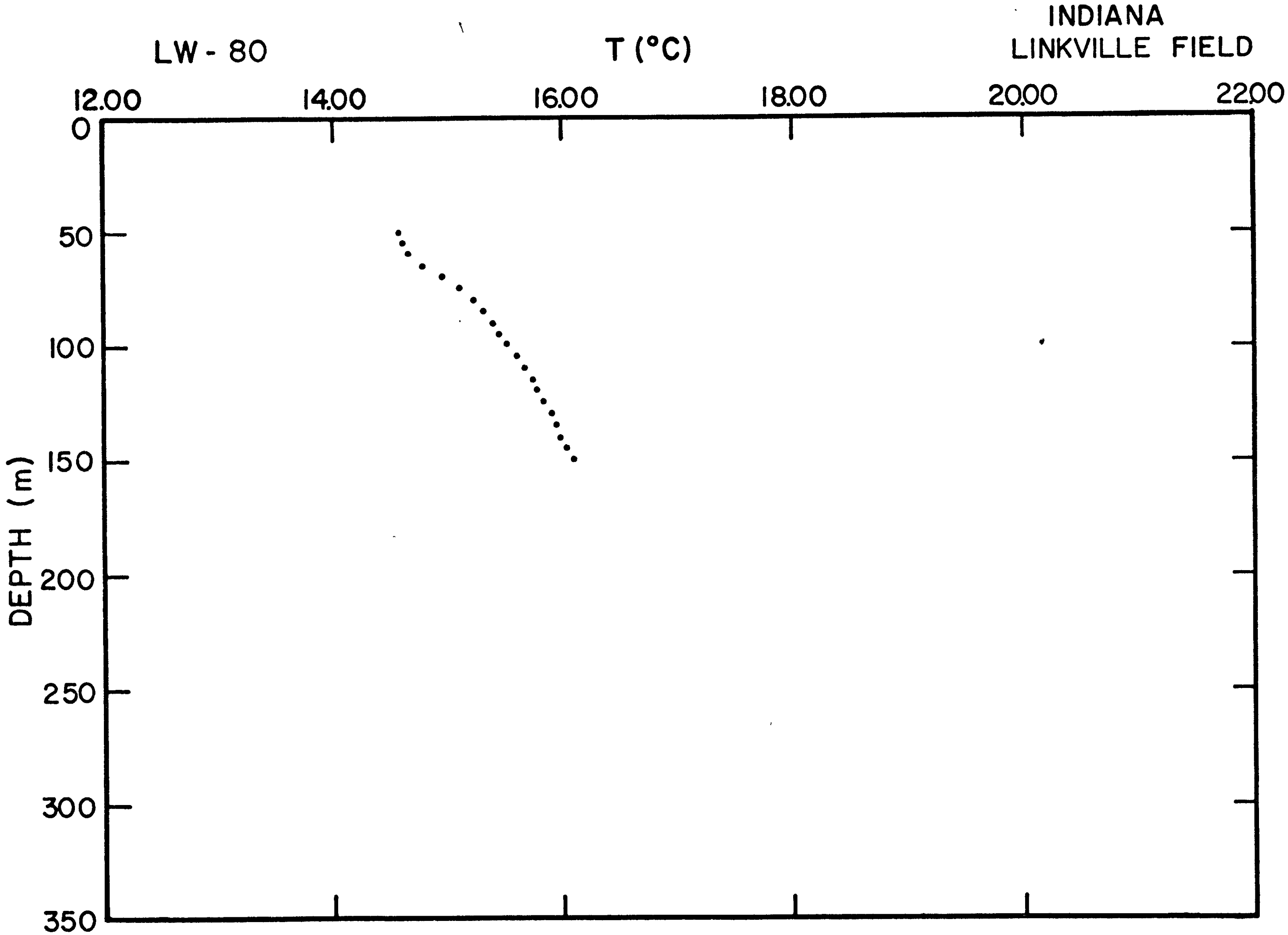

INDIANA
LINKVILLE FIELD
LW - 77
T (°C)
12.00
14.00
16.00
18.00
20.00
22.00
0
50
100
150
200
250
300
350
DEPTH (m)

Figure 5.10 Temperature-depth plot for borehole LW-80, Linkville, Indiana. Drilling completed: 3-18-64.


LW - 80
T (°C)
INDIANA
LINKVILLE FIELD
12.00
14.00
16.00
18.00
20.00
22.00
0
50
100
150
200
250
300
350
DEPTH (m)

upper and lower sections of the core. Table 5.3 contains the average thermal gradients over the two intervals for all of the wells, and Table 5.4 gives the data pertinent to the calculation of the best heat flow value.

TABLE 5.3 THERMAL GRADIENTS FOR THE BOREHOLES IN THE LINKVILLE FIELD

WELL NAME	GRADIENT (°C/km)	
	100-120 meters	120-150 meters
LW-25, LINKVILLE	17.8	12.8
LW-41, LINKVILLE	17.5	12.9
LW-57, LINKVILLE	17.9	12.5
LW-62, LINKVILLE	18.3	12.9
LW-65, LINKVILLE	18.0	12.8
LW-70, LINKVILLE	17.7	12.3
LW-77, LINKVILLE	18.5	12.4
LW-80, LINKVILLE	18.1	12.0

The errors in Table 5.4 indicate the total range of values for the gradients, conductivities, and heat flow determinations.

If one considers the average gradient and average conductivity which are indicated in Table 5.4, and determines the worst possible limits, i.e., the smallest gradient times the smallest conductivity and the largest gradient times the largest conductivity, the best value for the Linkville field is 1.33 HFU with a total range of 0.20 HFU.

TABLE 5.4 HEAT FLOW DETERMINATION IN LINKVILLE FIELD

DEPTH INTERVAL	AVERAGE GRADIENT	AVERAGE CONDUCTIVITY	AVERAGE HEAT FLOW
100-120	18.0±0.5	7.33±0.71	1.32±0.18
120-150	12.6±0.6	10.57±1.78	1.33±0.20

The Royal Center field, located in Cass and Fulton Counties, is approximately 6.5 by 8.0 km. Continuous temperature-depth curves were obtained in five wells in this field. One of the wells, S-46, was logged at two different times on the same day and the temperature-depth curves are plotted on separate graphs. Only four of the five wells had core samples available for thermal conductivity determinations.

Temperature-depth curves for the Royal Center boreholes are plotted in Figures 5.11 to 5.17. Comparison of these curves with those for the Ancona and Crescent City fields in Illinois indicates that the sedimentary sequences in all three fields are quite similar. This observation can be substantiated by considering the lithologies that are present in the different core samples. The data that are pertinent to the calculation of the best heat flow values for the Royal Center wells are presented in Tables 5.5 - 5.8.

TABLE 5.5 S-36, ROYAL CENTER

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
301-302	13.4	10.63 (2)	1.42
306	16.0	8.77 (1)	1.40
312-330	12.4	11.30 (5)	1.40
333-335	14.7	9.57 (2)	1.41
340-343	18.8	7.60 (2)	1.43

Both S-44, Royal Center and S-55, Royal Center had been drilled only a short time before the temperature logs were run and therefore they show a somewhat erratic behavior.

TABLE 5.6 S-38, ROYAL CENTER

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
366-371	19.2	7.25 (3)	1.39

TABLE 5.7 S-46, ROYAL CENTER

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
158-166	17.1	8.24 (3)	1.41
183	13.9	9.95 (1)	1.38
186	24.5	5.72 (1)	1.40

Figure 5.11 Temperature-depth plot for borehole S-36, Royal Center, Indiana. Drilling completed: 7-1-63.

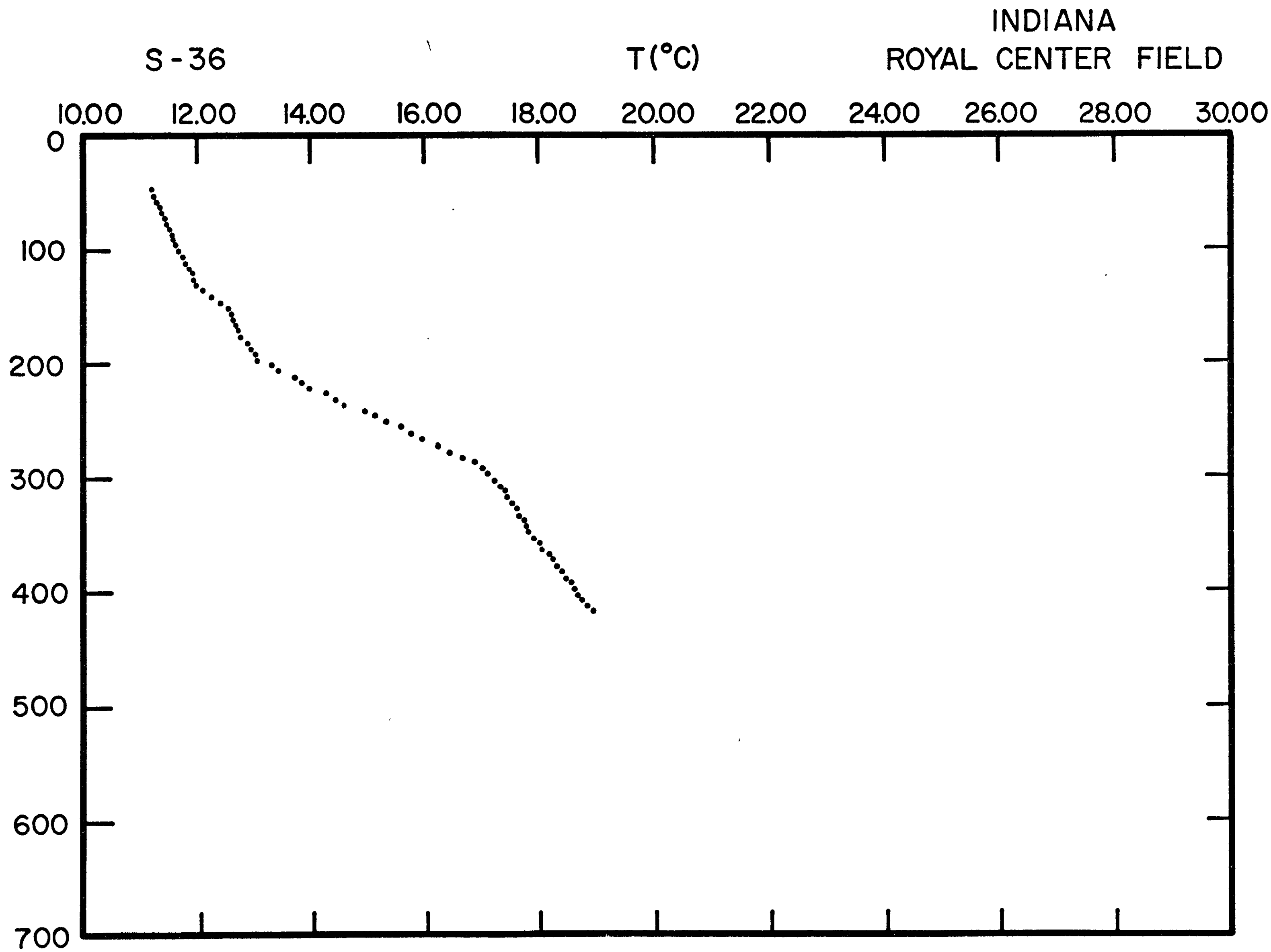
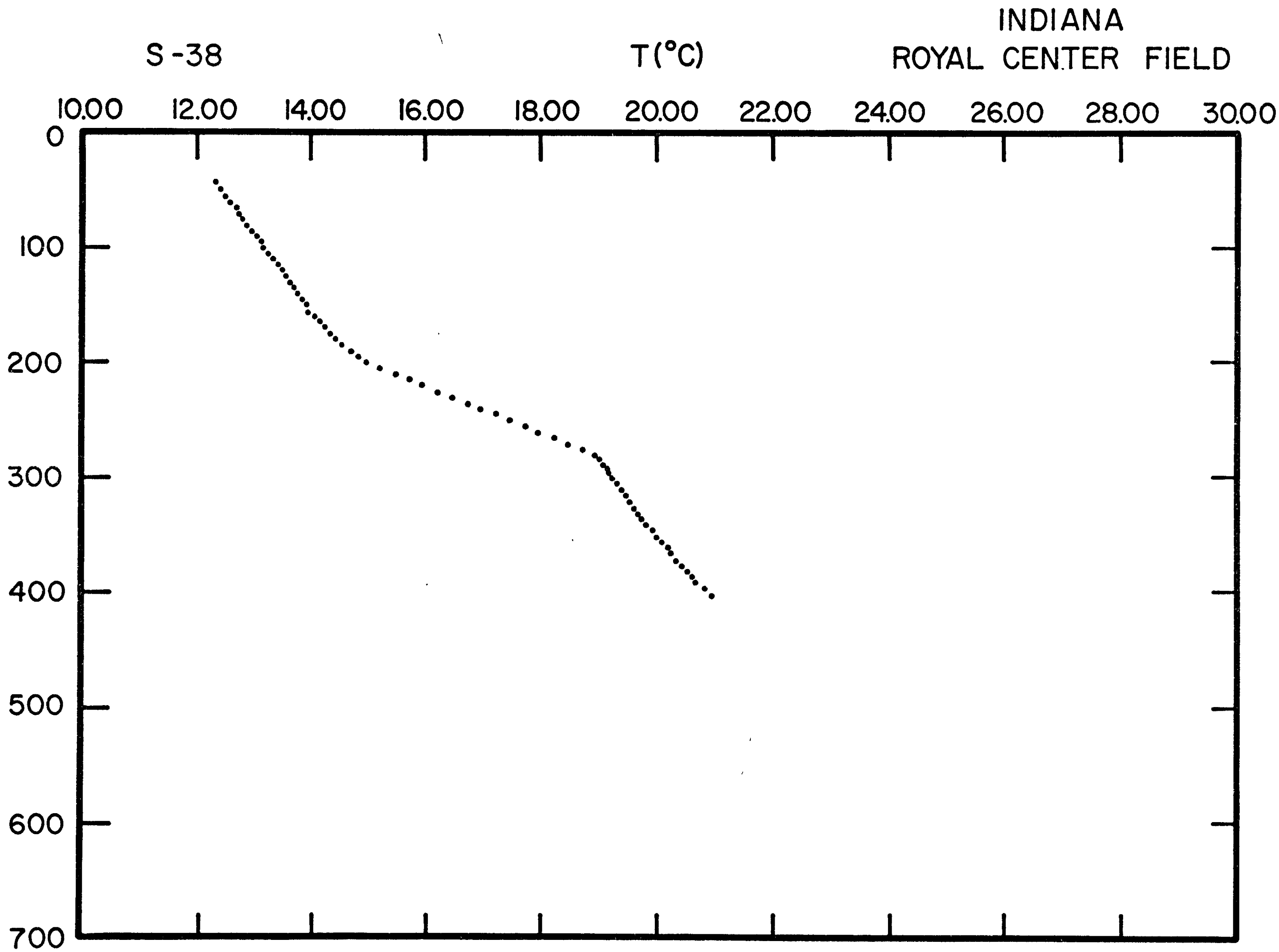

INDIANA
ROYAL CENTER FIELD
S-36
T(°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700

Figure 5.12 Temperature-depth plot for borehole S-38, Royal Center, Indiana. Drilling completed: 7-24-63.



INDIANA
ROYAL CENTER FIELD
S-38
T(°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700

Figure 5.13 Temperature-depth plot for borehole S-44, Royal Center, Indiana. Drilling completed: 9-24-63.

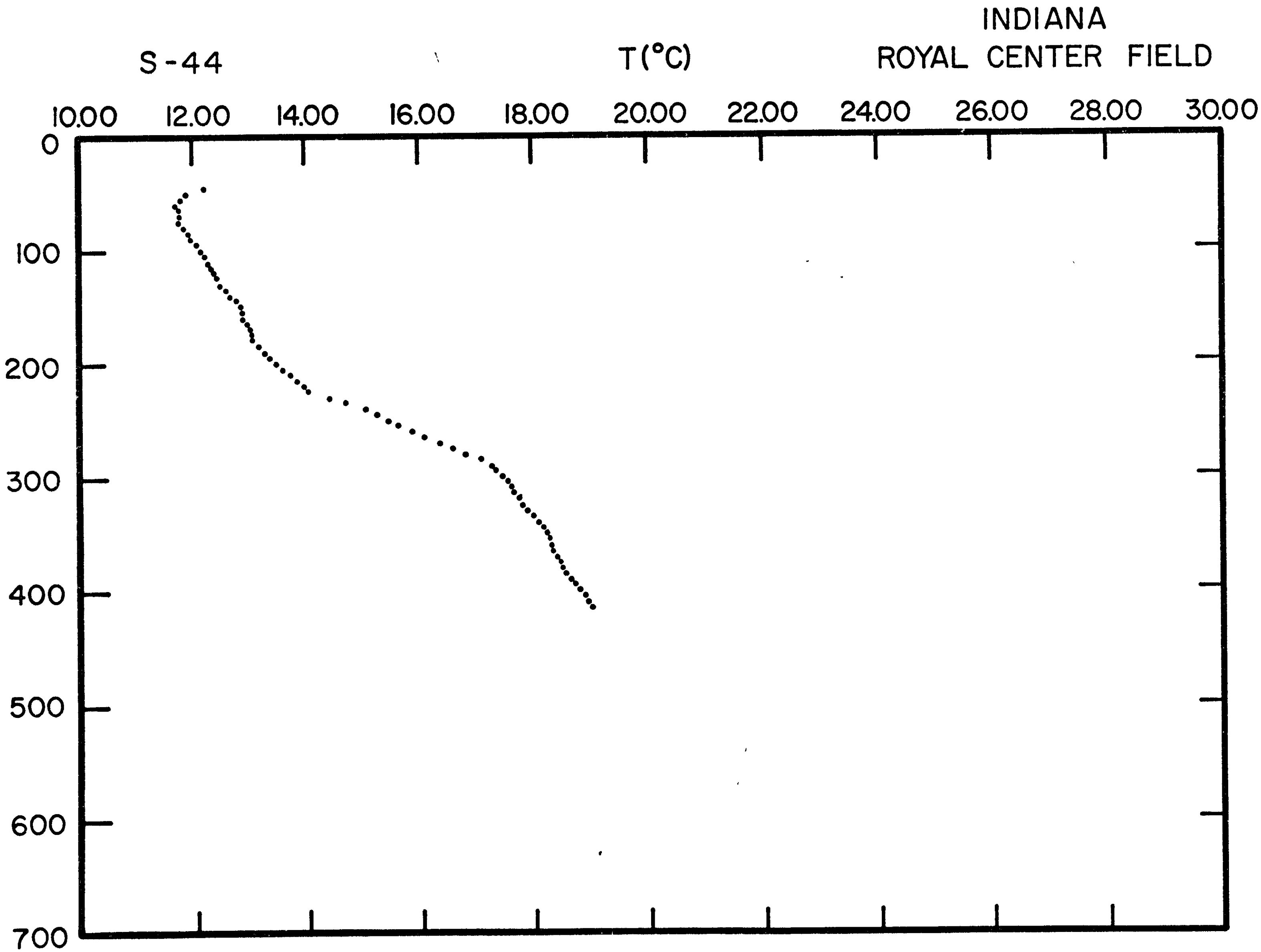

INDIANA
ROYAL CENTER FIELD
S-44
T(°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700

Figure 5.14 Temperature-depth plot for borehole S-46, Royal Center, Indiana. Drilling completed: 7-19-63.

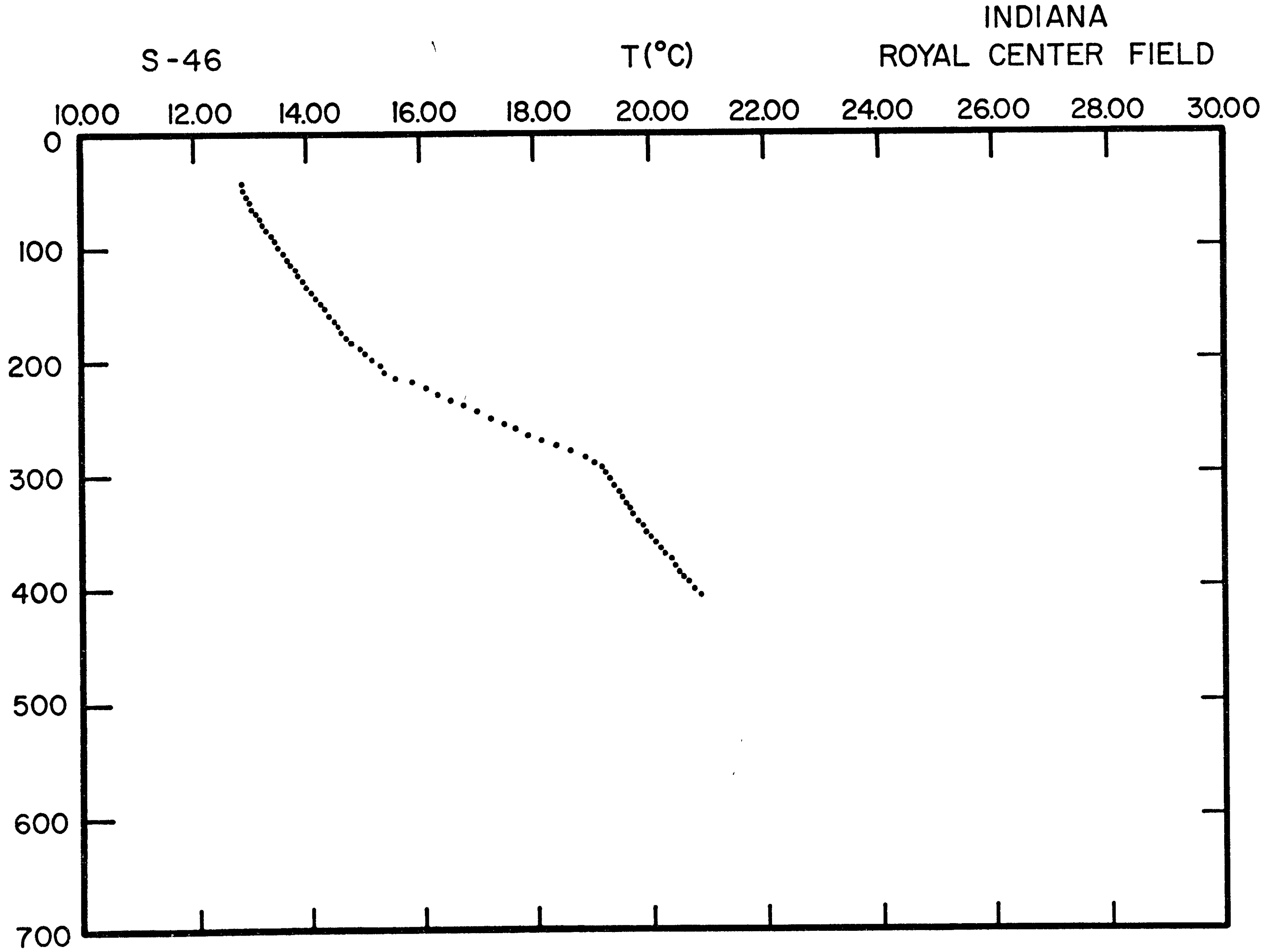

S-46
T(°C)
INDIANA
ROYAL CENTER FIELD
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700

Figure 5.15 Temperature-depth plot for borehole S-46, Royal Center, Indiana. Drilling completed: 7-19-63. This is the second temperature log for the S-46 borehole.

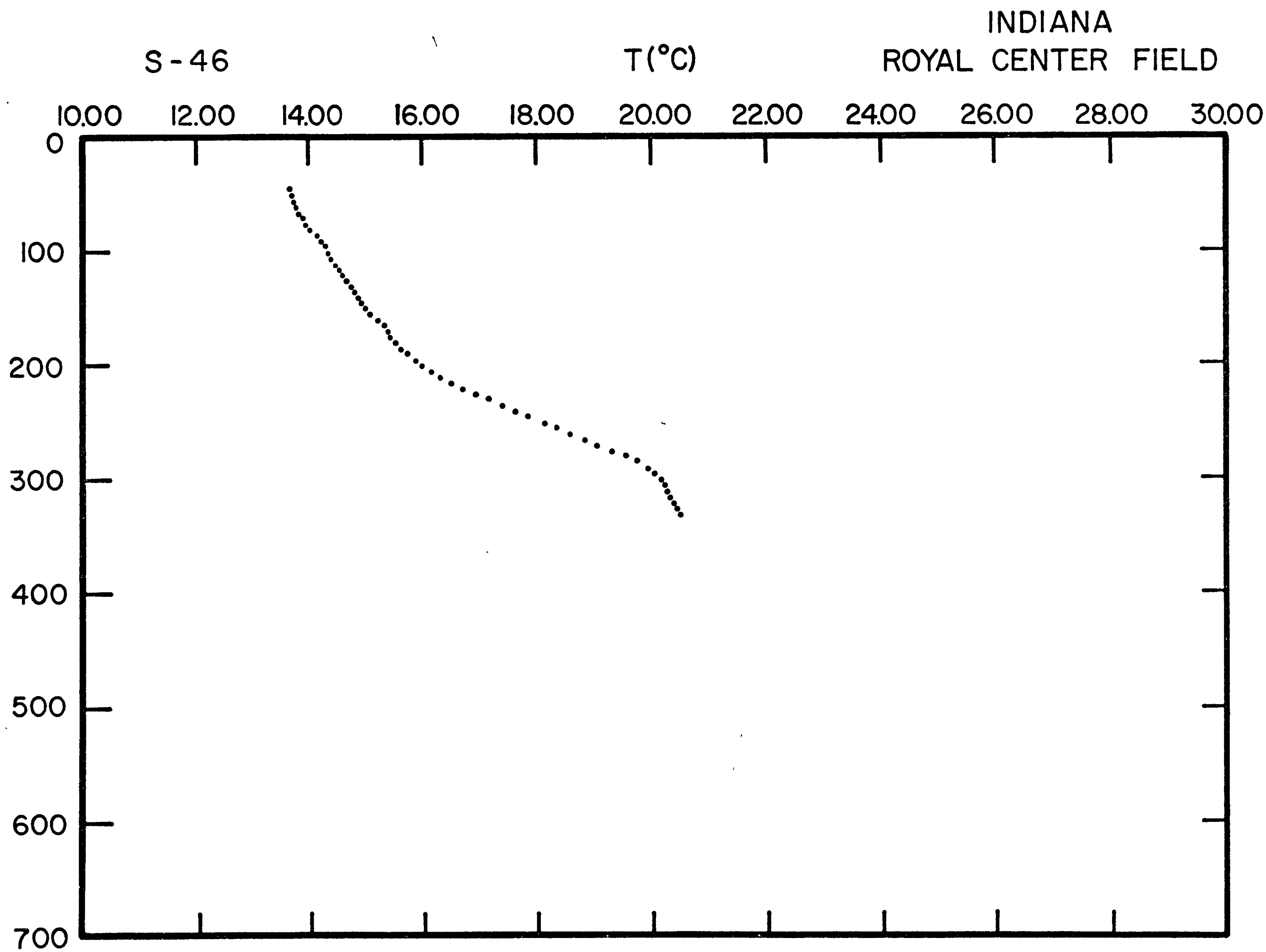

INDIANA
S-46
T(°C)
ROYAL CENTER FIELD
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700

Figure 5.16 Temperature-depth plot for borehole S-55, Royal Center, Indiana. Drilling completed: 6-29-62.

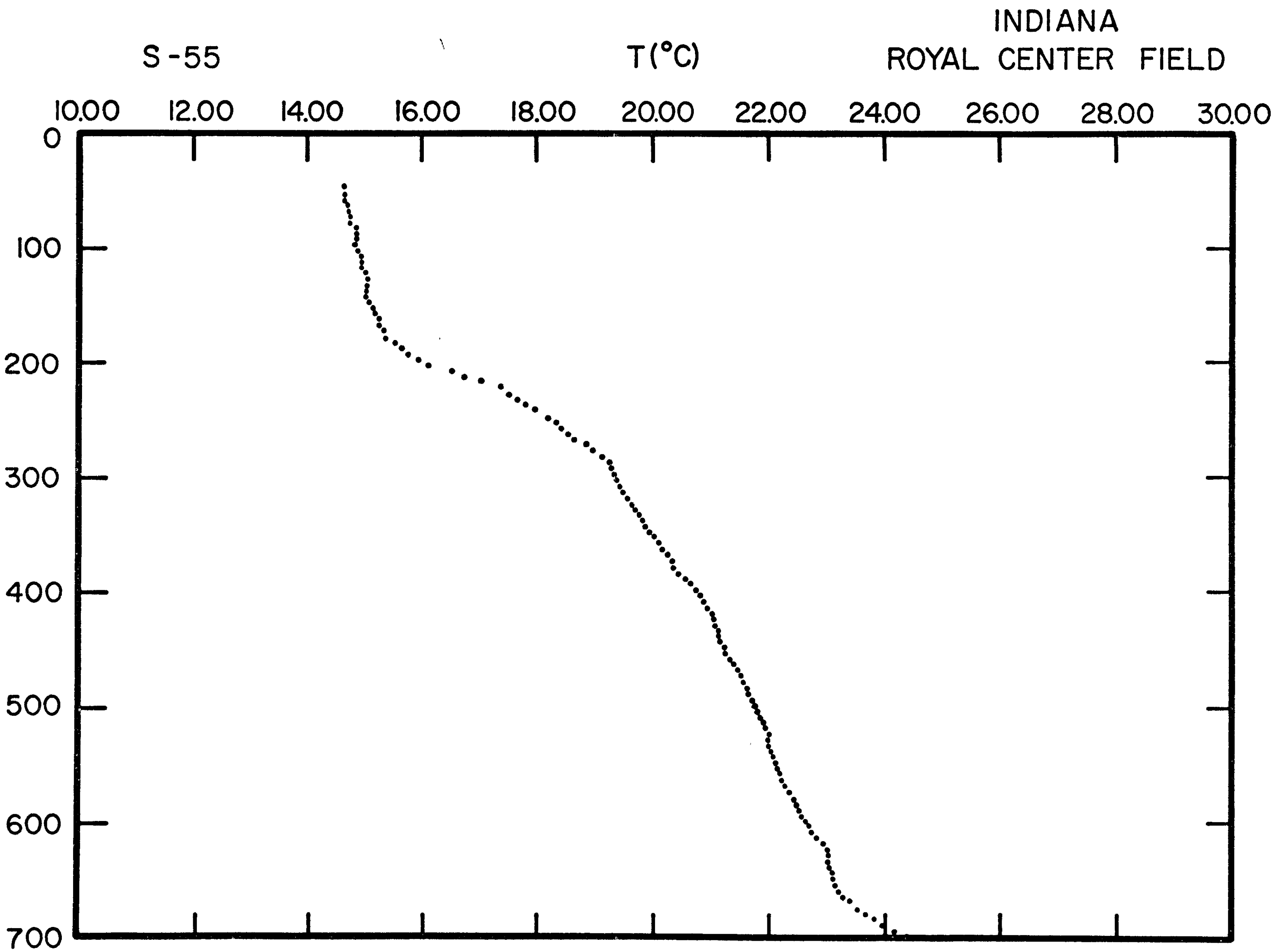
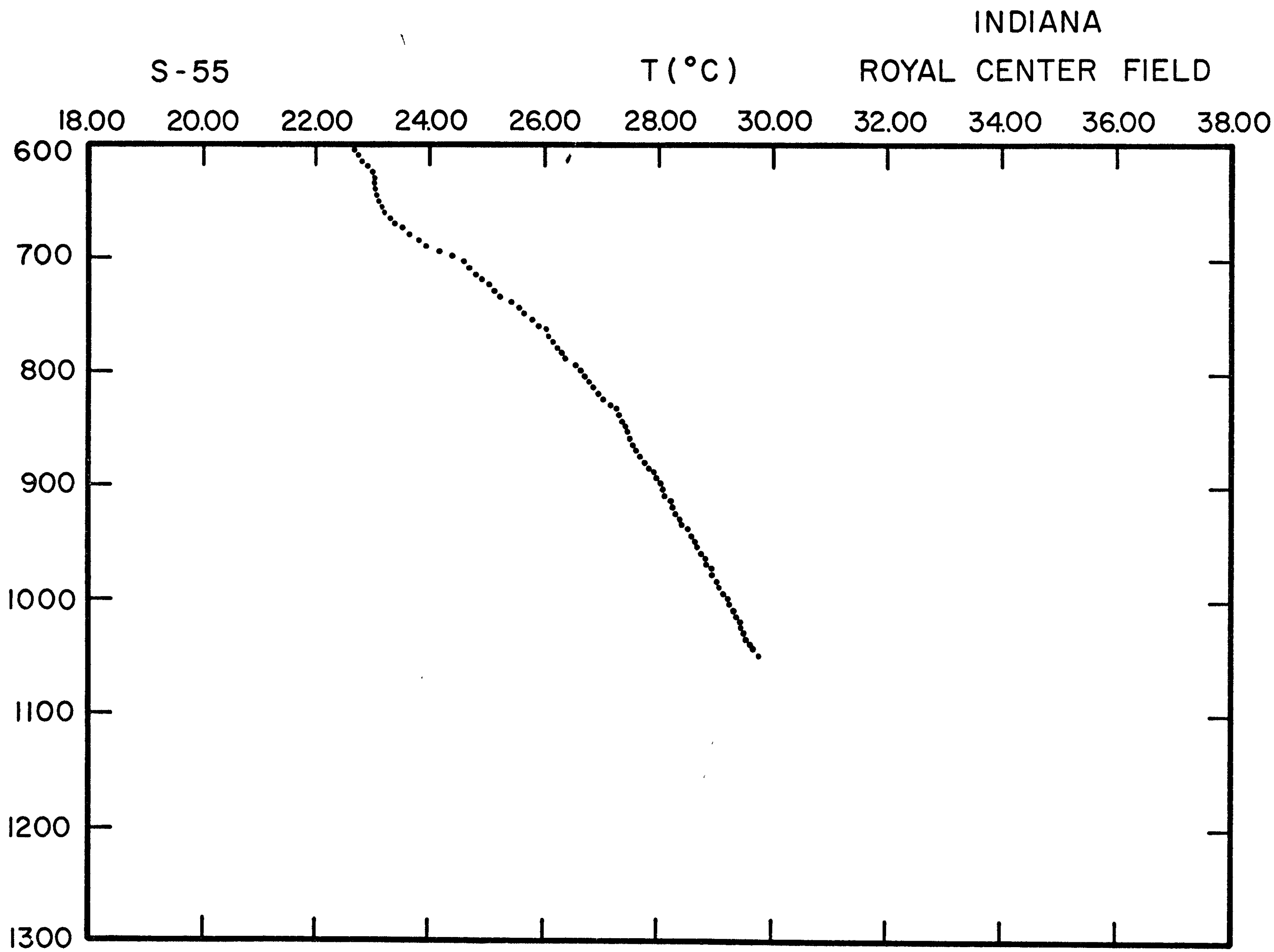

INDIANA
ROYAL CENTER FIELD
S-55
T(°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700

Figure 5.17 Continuation of temperature-depth plot for the S-55 borehole.


INDIANA
S-55
T(°C)
ROYAL CENTER FIELD
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
34.00
36.00
38.00
600
700
800
900
1000
1100
1200
1300

However, from Table 5.9, one can see that even though the individual temperature measurements were erratic, the geothermal gradient over the two depth intervals tabulated are similar. From the similarity of the gradients in these closely spaced boreholes, one can also assert that a heat flow determination that has been obtained from the thermal conductivity in one well and the geothermal gradient from an adjacent well is reliable if the rock type remains essentially the same throughout the different boreholes.

TABLE 5.8 S-55, ROYAL CENTER

DEPTH	GRADIENT	CONDUCTIVITY	HEAT FLOW
308-328	12.0	11.43 (3)	1.38
343-348	18.7	7.38 (2)	1.38
698-712	24.3	5.80 (2)	1.41
736	16.4	8.43 (1)	1.38
782	15.6	8.95 (1)	1.40
801-808	15.6	8.80 (2)	1.37
860	9.32	14.91 (1)	1.39
991-1011	10.7	13.09 (2)	1.40

Finally, it should be noted that slight disturbances in the temperature profile do not necessarily indicate that the geothermal gradient will be useless for a heat flow determination.

TABLE 5.9 GEOTHERMAL GRADIENTS IN THE ROYAL CENTER FIELD

WELL NAME	GRADIENT (°C/km) 200-300 meters	300-350 meters
S-36, ROYAL CENTER	46.5	13.9
S-38, ROYAL CENTER	48.8	13.6
S-44, ROYAL CENTER	47.1	14.0
S-46-1, ROYAL CENTER	46.6	13.6
S-46-2, ROYAL CENTER	46.4	13.6
S-55, ROYAL CENTER	47.3	14.0

5.3 DISCUSSION AND CONCLUSIONS

Indiana is part of the central stable region of North America which has undergone only mild deformation since the beginning of Paleozoic time (King, 1951). Upper Cambrian sedimentary rocks rest directly on the Precambrian basement complex throughout the state. While the sedimentary sequence throughout the state is essentially the same, there is a general trend of thickening toward the west and southwest into the region of the Illinois basin. The basement complex, however, varies from granitic to basaltic.

The major portion of Indiana lies within the mid-continental granitic province, but studies of basement lithologies and the interpretation of aeromagnetic and gravity anomalies by Rudman and Blakely (1965) indicate the existence of a number of patches of basalt that closely resemble the Keweenawan flows of the midcontinental region.

Basement sample studies and geophysical data of previous workers (Rudman, et al., 1965; Rudman and Blakely, 1965; Muehlberger, et al., 1964; Henderson and Zietz, 1958), indicate that the basement underlying the Linkville and Royal Center fields is granitic, while the Monroeville field is underlain by basalt. Furthermore, the Monroeville field is located on a pronounced magnetic high which has been interpreted as a large basaltic plug intruded into the granitic basement. While the Royal Center field is on a local magnetic low, the Linkville field is not associated with any magnetic anomaly. Finally, both the Monroeville and Royal Center fields are located on gravity highs, but the Linkville field is associated with a gravity low.

There does not appear to be any direct correlation between the heat flow determinations and the available gravity and magnetic data. However, if one examines the contrast in content of radiogenic elements (U, Th and K) between granitic and basaltic rocks (Birch, 1951), he must conclude that there is a relationship between the heat flow values and the associated basement complex. In particular, the low value, 0.97 HFU is associated with a basaltic basement whereas the normal values, 1.32 to 1.41, are associated with the granitic basement. Furthermore, Horai and Nur (1970) have suggested that by consideration of the geometrical relationship and the thermal conductivity contrast one can account for this difference in heat flow. Since both of the effects would produce the low heat flow value, one can not separate them. If, however, one combines the corrections for the thermal conductivity contrast and heat source difference, the low heat flow value at Monroeville can be made to coincide with the regional heat flow value of 1.4 HFU.

CHAPTER 6

HEAT FLOW IN IOWA

6.1 INTRODUCTION

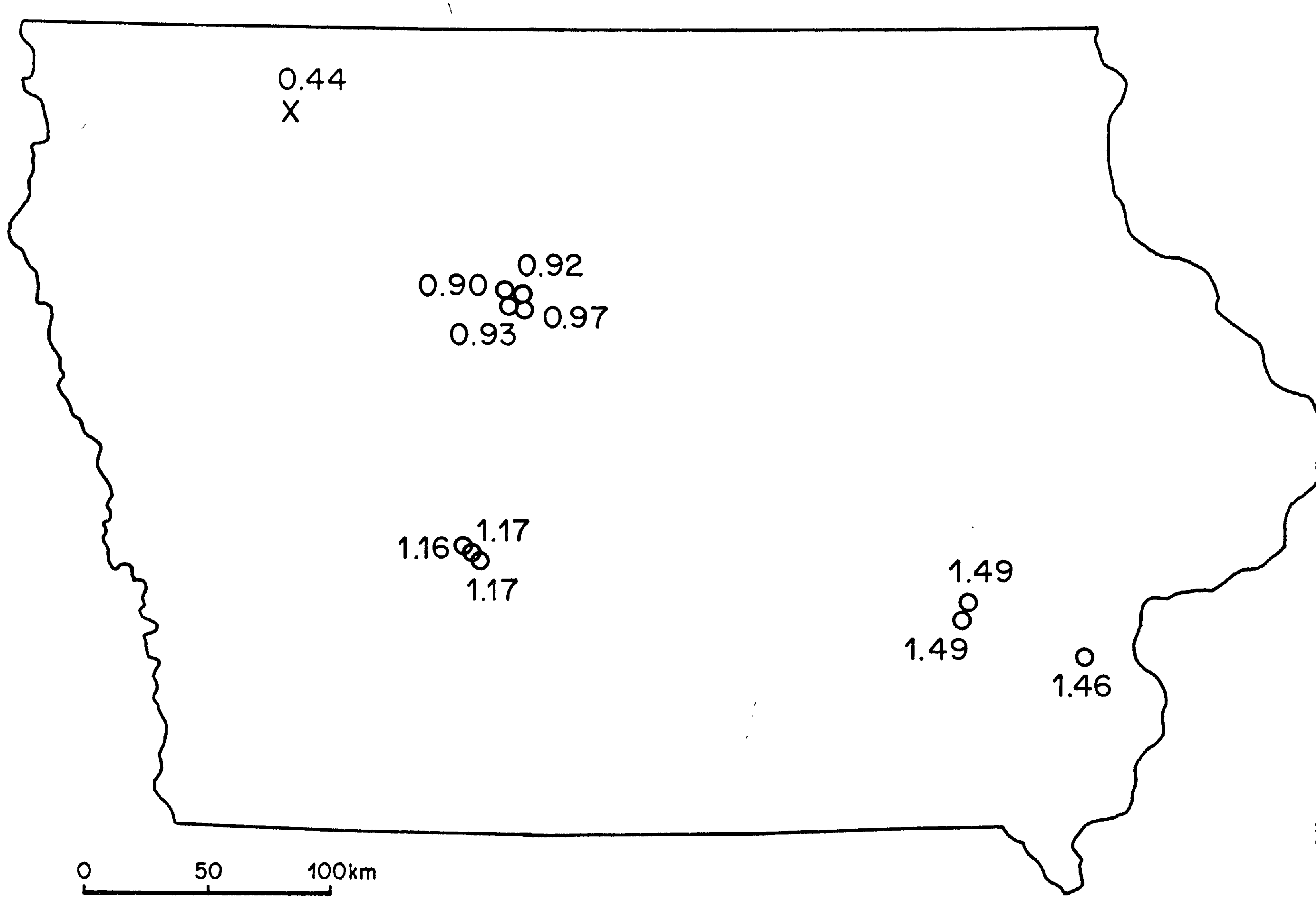
The ten heat flow stations investigated in Iowa are located in a band that extends southeast-northwest (see Figure 6.1). An eleventh value at the northwest end of this band has been reported by Roy, et al., (1968). The heat flow values for the ten new stations range from 0.90 to 1.49 HFU while the published value of Roy, et al., (1968) is only 0.44 HFU.

The ten boreholes that were investigated are located in four different fields. Two of the fields, Cairo and Keota, are operated by the Natural Gas Pipeline Company of America. The other two fields, Redfield and Vincent, are operated by the Northern Natural Gas Company. The maximum depth of these boreholes is approximately 700 meters.

6.2 RESULTS

In the Vincent field, four boreholes were measured using the continuous temperature-logging equipment. The author logged the Hofmann #1 and the Olson #1 "G" while the Anderson #1 and Anderson #3 wells were measured by A. England.

Figure 6.1 Terrestrial heat flow in Iowa. Circles indicate data from this investigation while the X indicates a published value of Roy et al. (1968). All values in units of HFU.


0.44
X
0.92
0.90
0.97
0.93
1.17
1.16
1.17
1.49
1.49
1.46
0
50
100km

As can be seen in Figures 6.2 to 6.5, the temperature-depth curves are quite similar. One particular change in gradient is noticeable. There is a high geothermal gradient between 350 and 400 meters in all of the boreholes. From the lithologic logs for this field, it is known that this high gradient corresponds to a thin shale sequence located between two thick dolomite sections. In other words, the difference in thermal conductivity produces a change in the geothermal gradient. From the above-mentioned correlation between the lithologic logs and the temperature logs for this field as well as similar evidence from other fields in the midcontinent, it can be argued that continuous temperature-depth curves provide a useful tool for determining the distribution of different rock types in the subsurface.

Core samples were not available for any of the wells that were logged, but three other wells located in the Vincent field had been cored. Since there were no significant lateral changes in rock type in order to obtain thermal conductivities, the available cores were measured and correction to the _in situ_ temperatures was made for each of the wells. The data pertinent to the heat flow calculations is presented in Tables 6.1 to 6.4.

Figure 6.2 Temperature-depth plot of the Anderson #1, Vincent, Iowa. Well completed: 9-3-64.

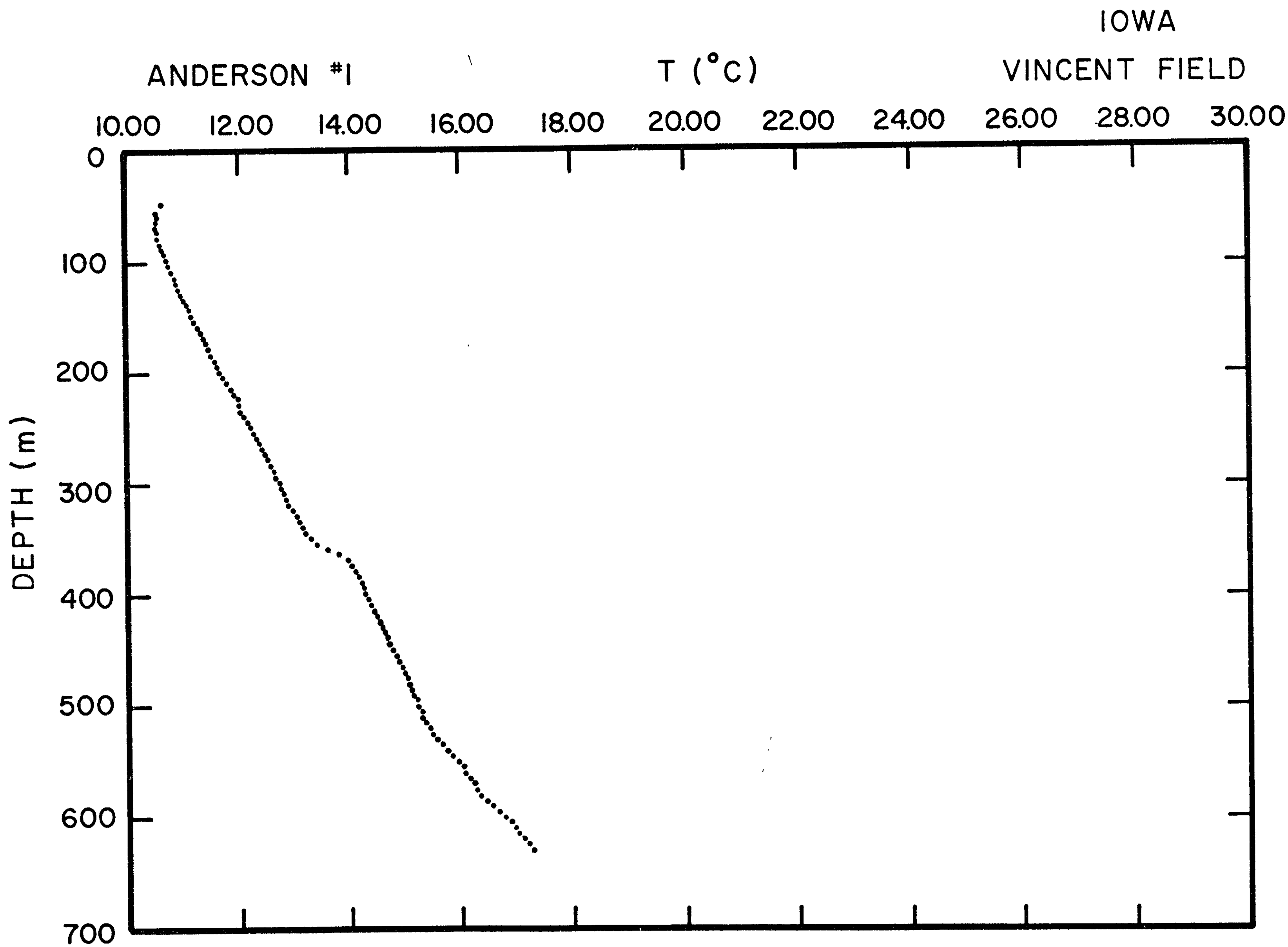

IOWA
VINCENT FIELD
ANDERSON #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 6.3 Temperature-depth plot for the Anderson #3, Vincent, Iowa. Well completed: 3-28-66.

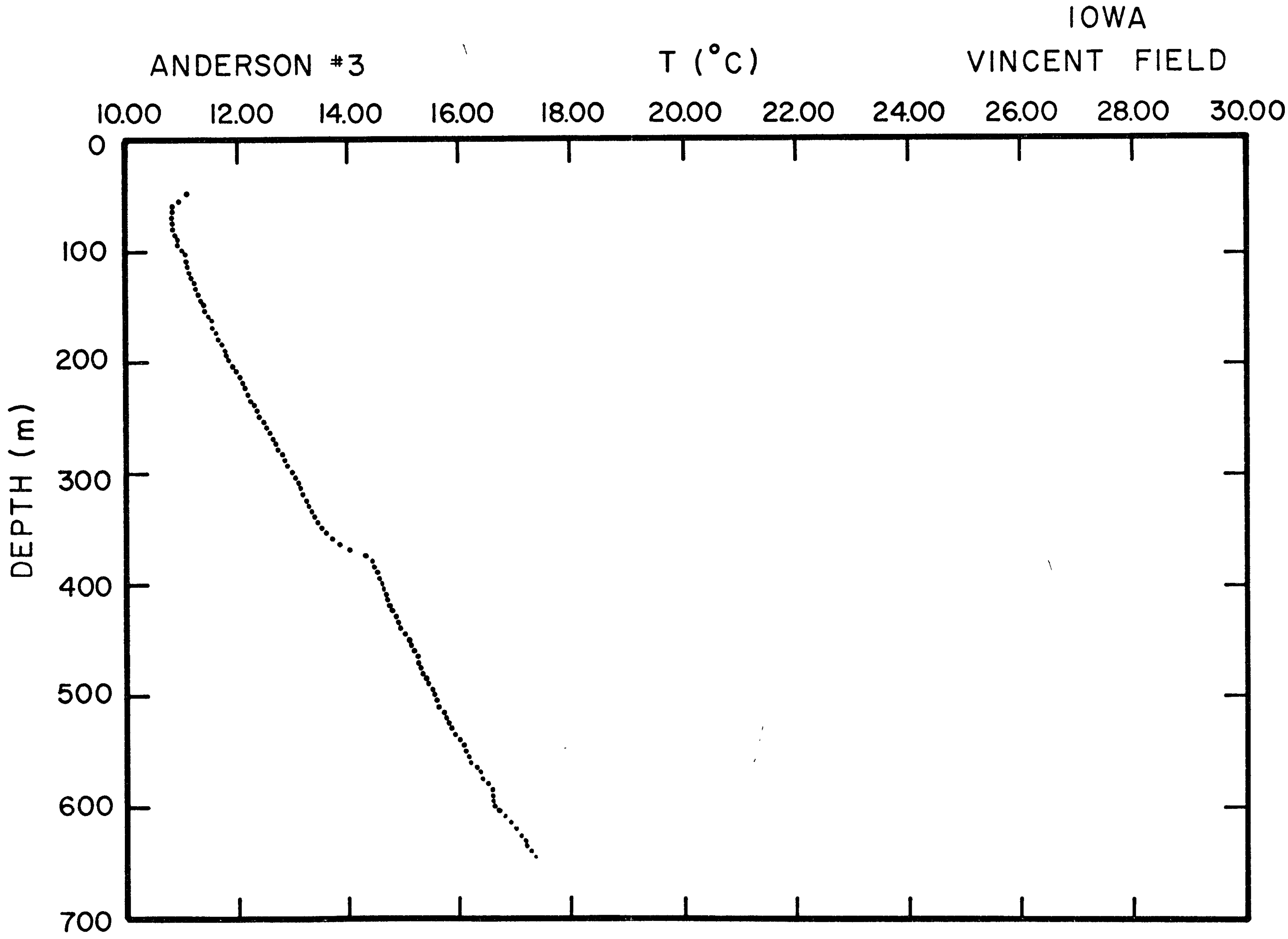

IOWA
ANDERSON #3
T (°C)
VINCENT FIELD
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 6.5 Temperature-depth plot for the Olson #1 "G", Vincent, Iowa. Well completed: 3-7-64.

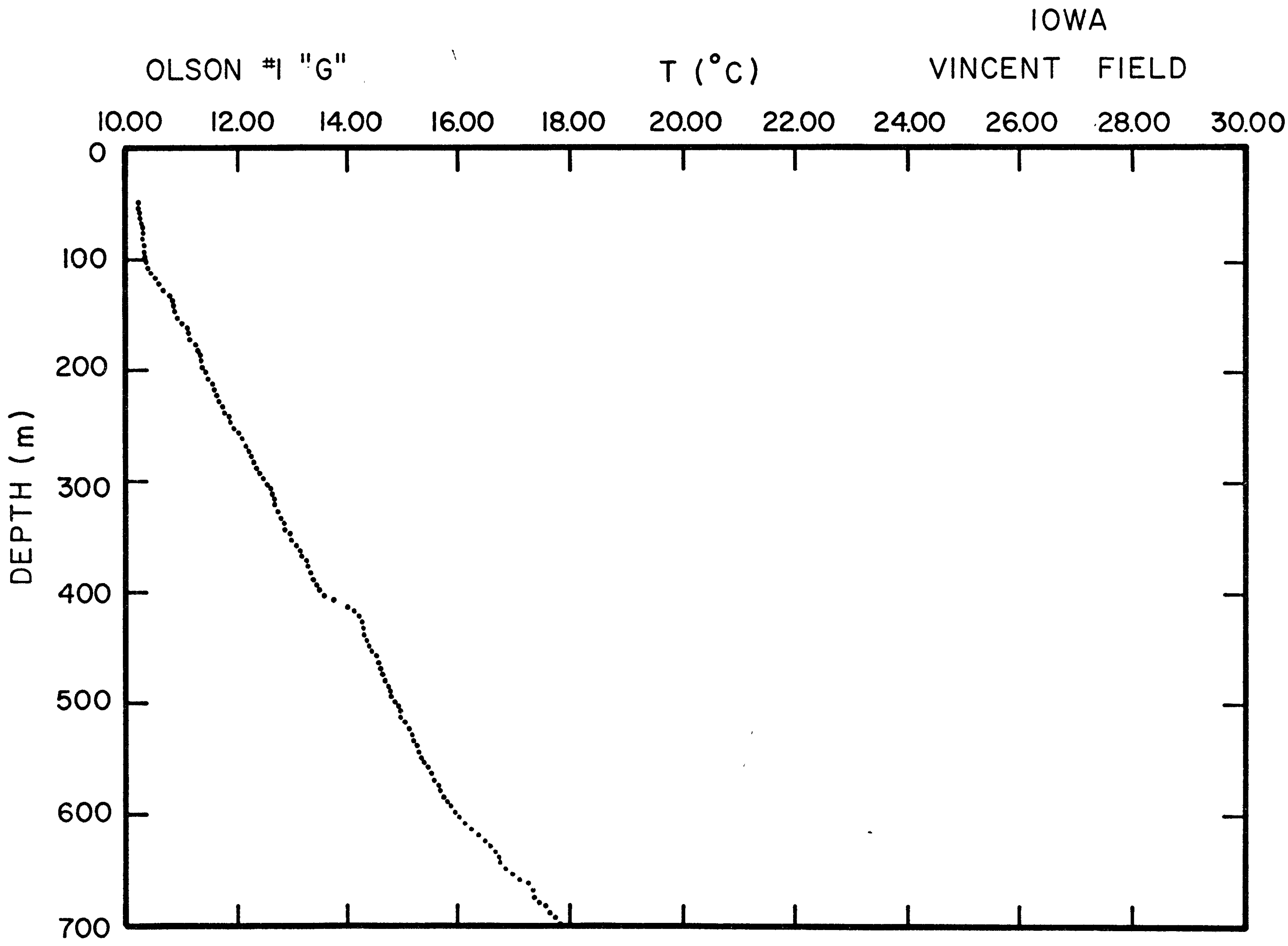

IOWA
OLSON #1 "G"
T (°C)
VINCENT FIELD
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700
DEPTH (m)

Figure 6.4 Temperature-depth plot for the Hoffman #1, Vincent, Iowa. Well completed: 8-7-64.

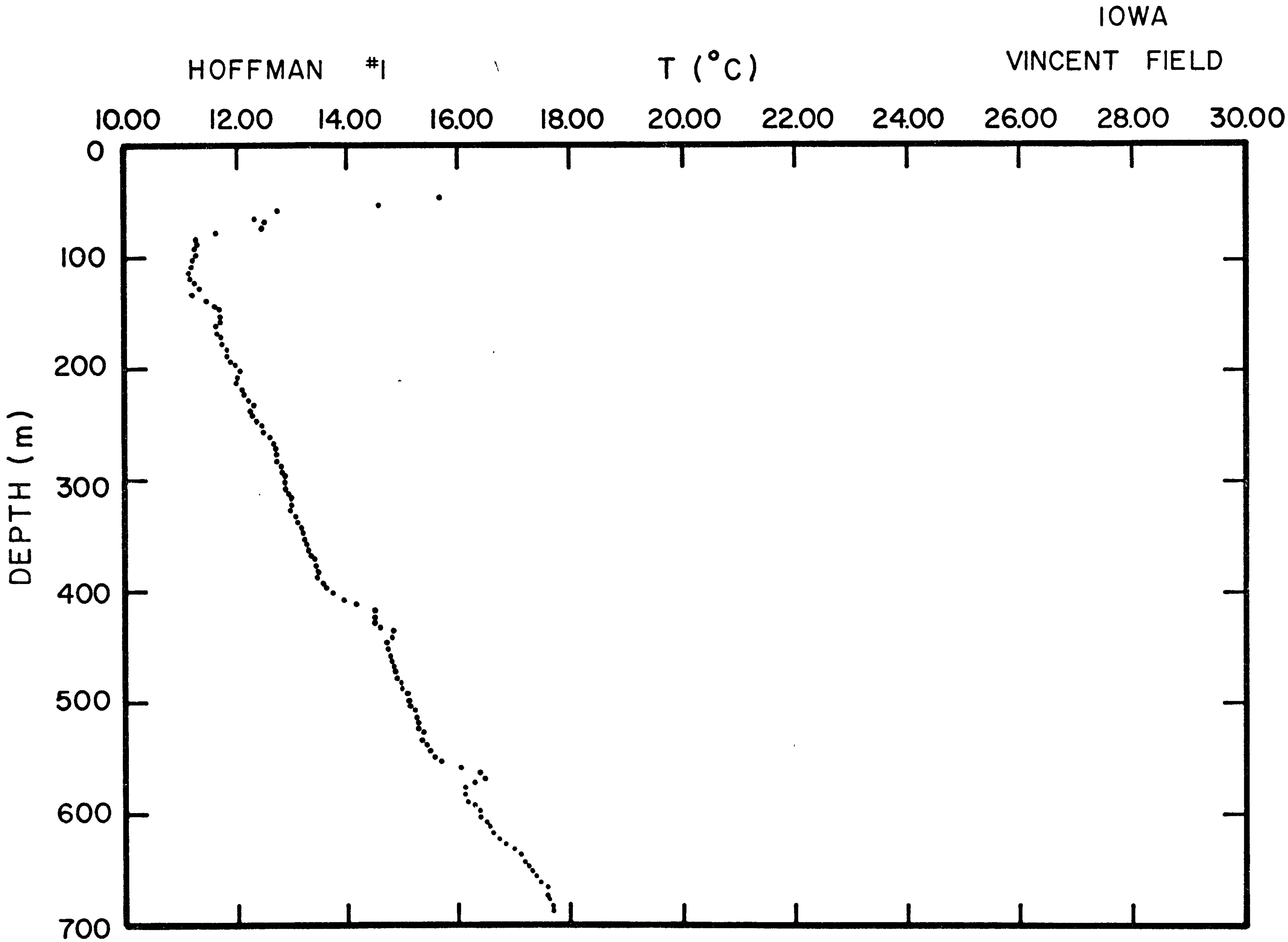

IOWA
VINCENT FIELD
HOFFMAN #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

TABLE 6.1 ANDERSON #1, VINCENT

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
217-228	7.66 (3)	11.8	0.90
290-325	9.37 (6)	9.60	0.90
446	13.07 (1)	7.04	0.92
576-587	8.85 (3)	10.3	0.91
617-622	6.87 (3)	12.9	0.89

TABLE 6.2 ANDERSON #3, VINCENT

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
217-228	7.66 (3)	11.8	0.90
290-325	9.36 (6)	10.0	0.94
446	13.06 (1)	6.98	0.91
576-587	8.85 (3)	10.6	0.94
617-622	6.87 (3)	13.3	0.91

TABLE 6.3 OLSON #1 "G", VINCENT

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
217-228	7.67 (3)	11.7	0.90
290-325	9.38 (6)	9.80	0.92
446	13.08 (1)	7.29	0.95
576-587	8.87 (3)	10.6	0.94
617-622	6.88 (3)	13.7	0.94

TABLE 6.4 HOFFMAN #1, VINCENT

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
217-228	7.66 (3)	12.9	0.99
290-325	9.38 (6)	9.40	0.88
617-622	6.87 (3)	15.1	1.04

Since drilling in the Hoffman #1 had been completed only a few days before the temperatures were measured, the values are somewhat erratic, and therefore only three of five intervals for which core was available could be used in the heat flow determination. However, comparison of the data in Tables 6.1 to 6.4 indicate that it is possible to obtain heat flow valid to perhaps 5% from a borehole shortly after drilling.

Samples for thermal conductivity determinations were available for all three wells logged in the Redfield field. The temperature-depth curves are presented in Figures 6.6 to 6.8. Data used to obtain the heat flow values are given in Tables 6.5 to 6.7.

TABLE 6.5 BOOK #1, REDFIELD

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
648	7.40 (1)	16.1	1.19
651	10.86 (1)	10.5	1.14

Figure 6.6 Temperature-depth plot for the Book #1, Redfield, Iowa. Well completed: 2-25-55.

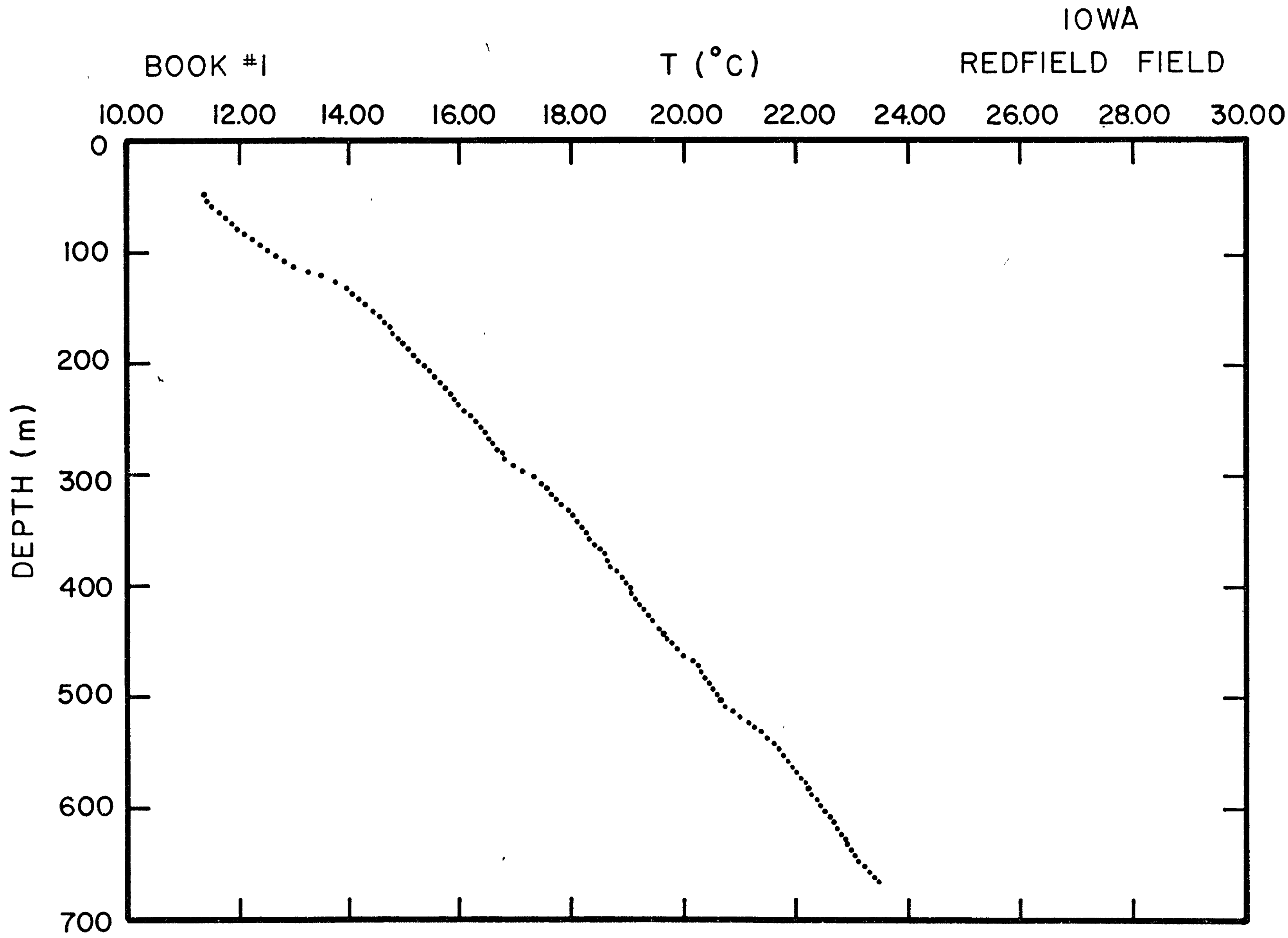

IOWA
REDFIELD FIELD
BOOK #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 6.7 Temperature-depth plot for the Broderick #1, Redfield, Iowa. Well completed: 6-1-55.

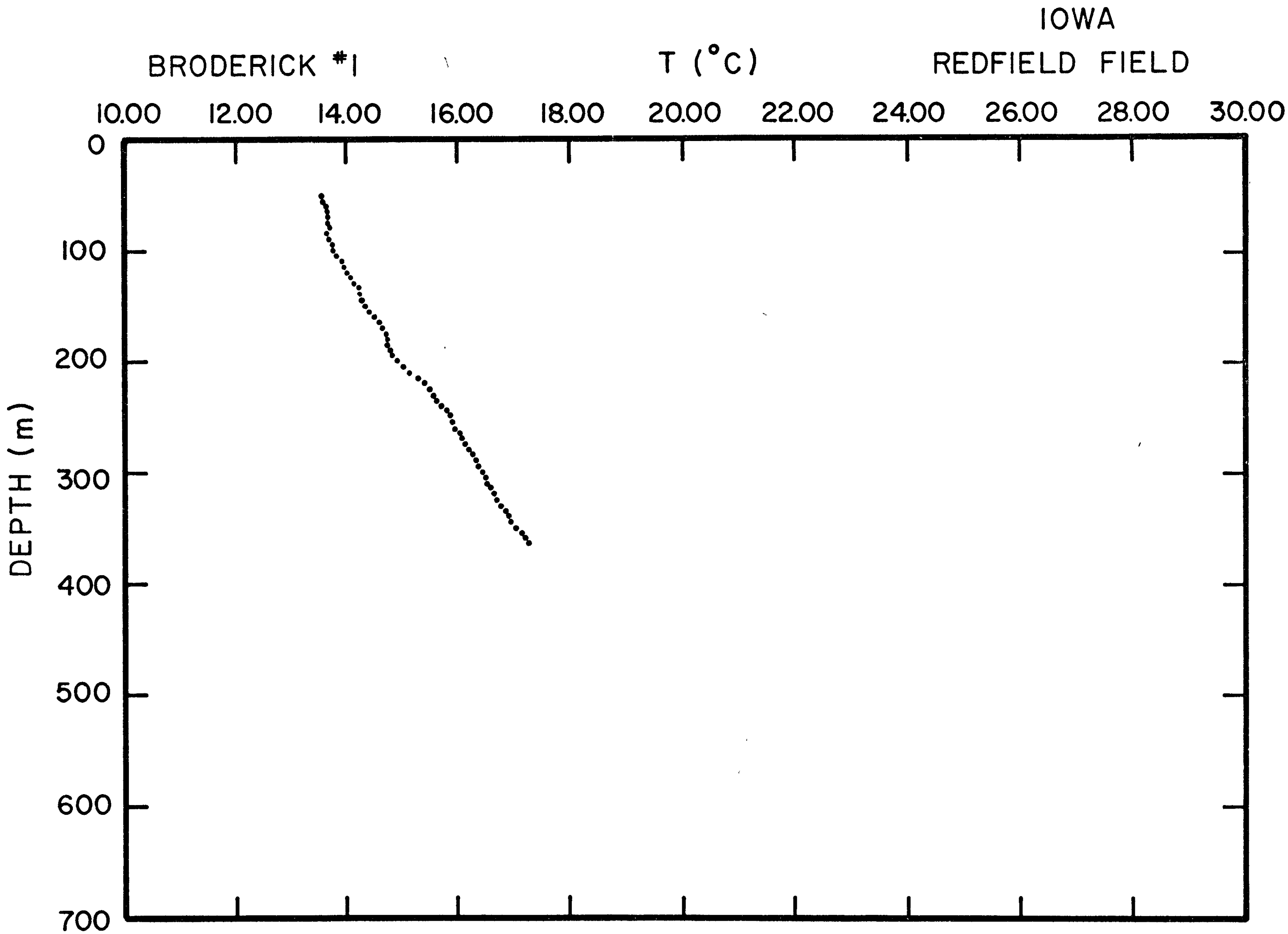

IOWA
BRODERICK #1
T (°C)
REDFIELD FIELD
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
0
100
200
300
400
500
600
700
DEPTH (m)

Figure 6.8 Temperature-depth plot for the Price #1, Redfield, Iowa. Well completed: 9-27-54.

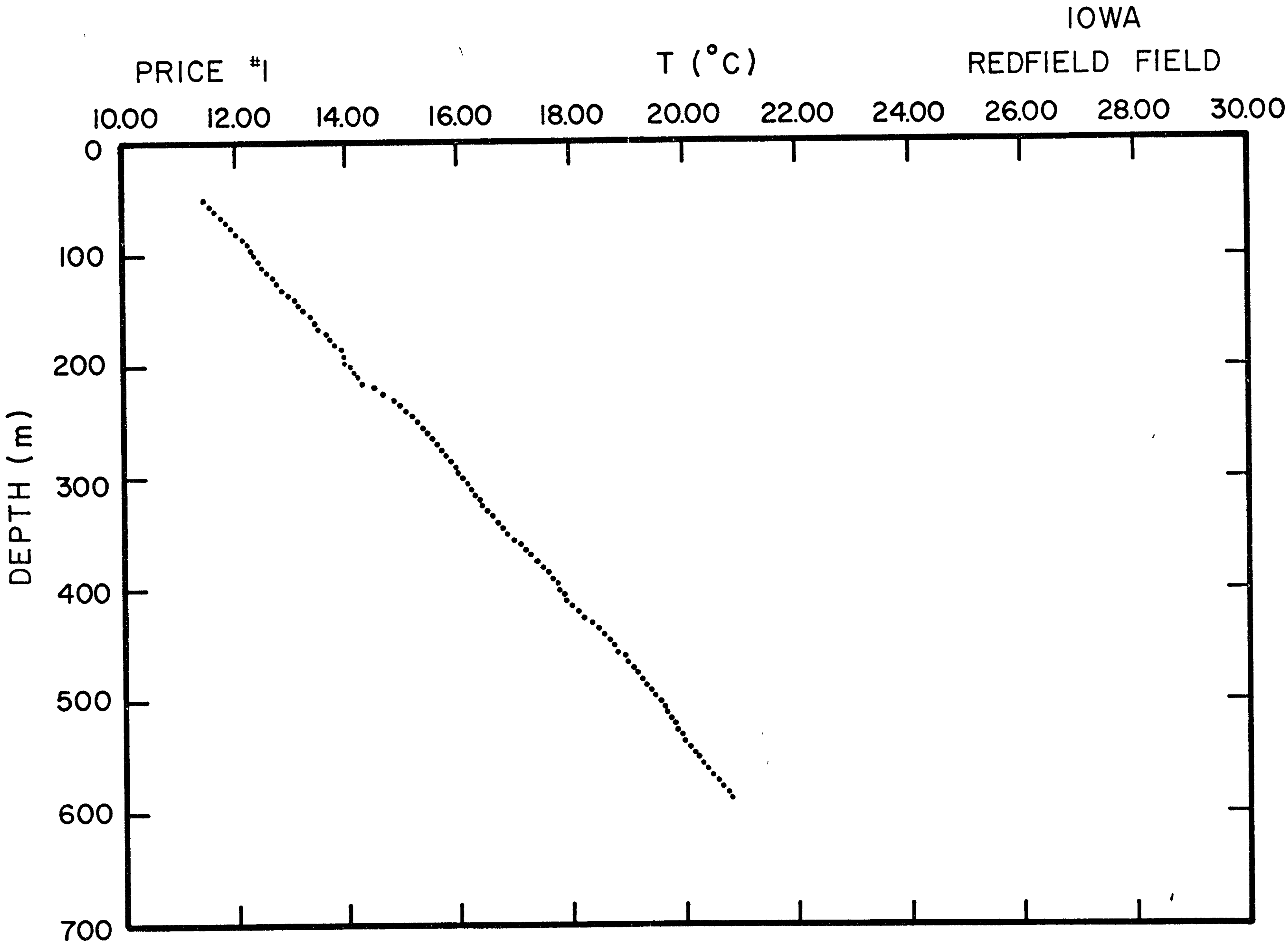

IOWA
REDFIELD FIELD
PRICE #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

TABLE 6.5 BOOK #1, REDFIELD (con't.)

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
653-658	7.78 (2)	15.0	1.17
664	11.49 (1)	10.2	1.16

TABLE 6.6 BRODERICK #1, REDFIELD

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
155-160	7.70 (2)	15.5	1.19
166	9.53 (1)	12.0	1.14

TABLE 6.7 PRICE #1, REDFIELD

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
415-430	5.40 (3)	21.8	1.18
452-457	4.88 (1)	23.4	1.14

Two boreholes were available in the Keota field. Comparison of Figure 6.9 with Figure 6.10 again illustrates the similarity of the temperature-depth curves for closely spaced boreholes located in a uniform lithologic sequence. Core samples were obtained from another well in the field which was not available to be logged. These measured thermal conductivities were used for both boreholes. The data are presented in Tables 6.8 and 6.9.

Figure 6.9 Temperature-depth plot for the J. Anderson #1, Keota, Iowa. Well completed: 6-22-63.

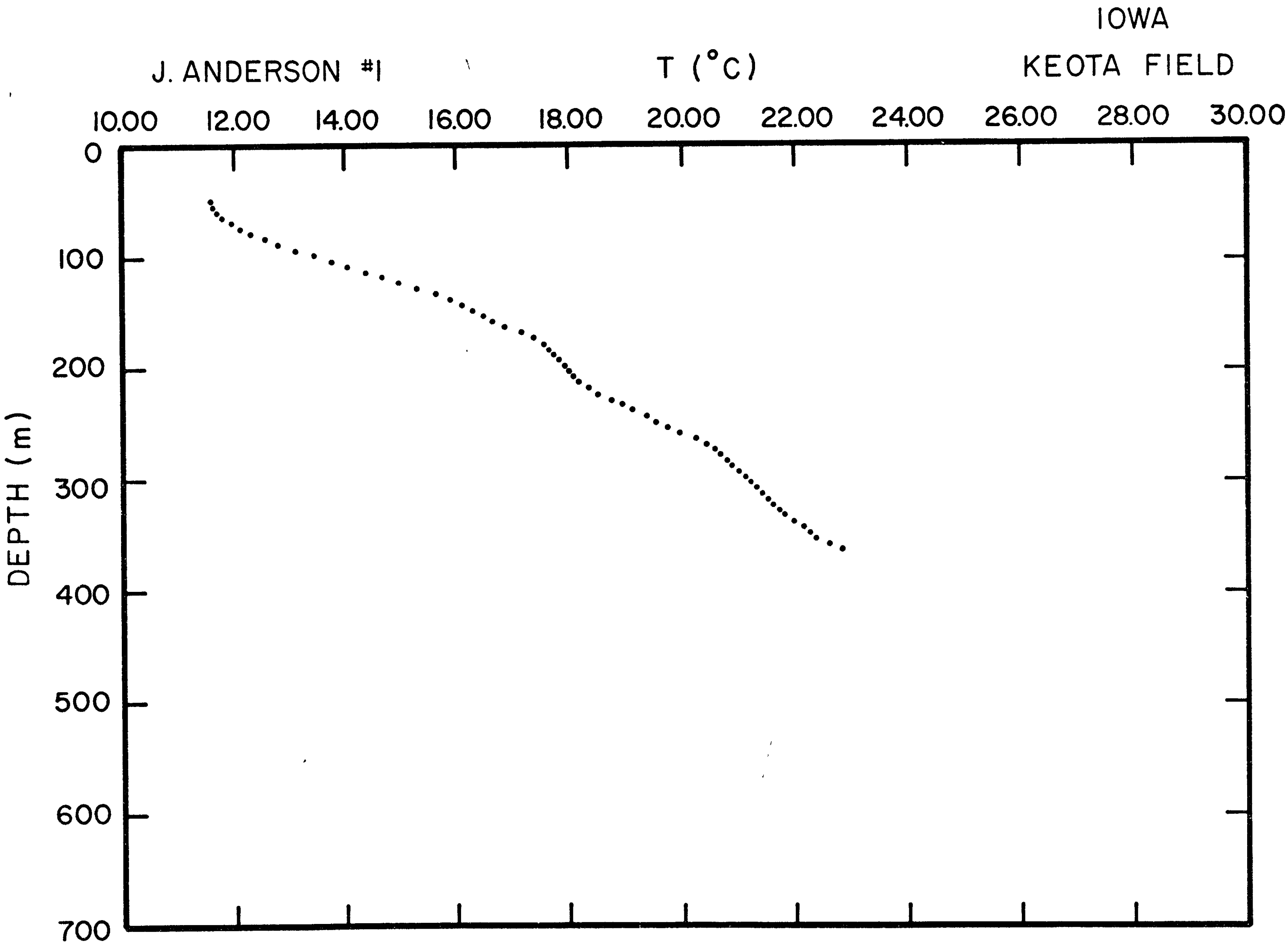

IOWA
KEOTA FIELD
J. ANDERSON #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 6.10 Temperature-depth plot for the L. Vogel #1, Keota, Iowa. Well completed: 7-8-63.

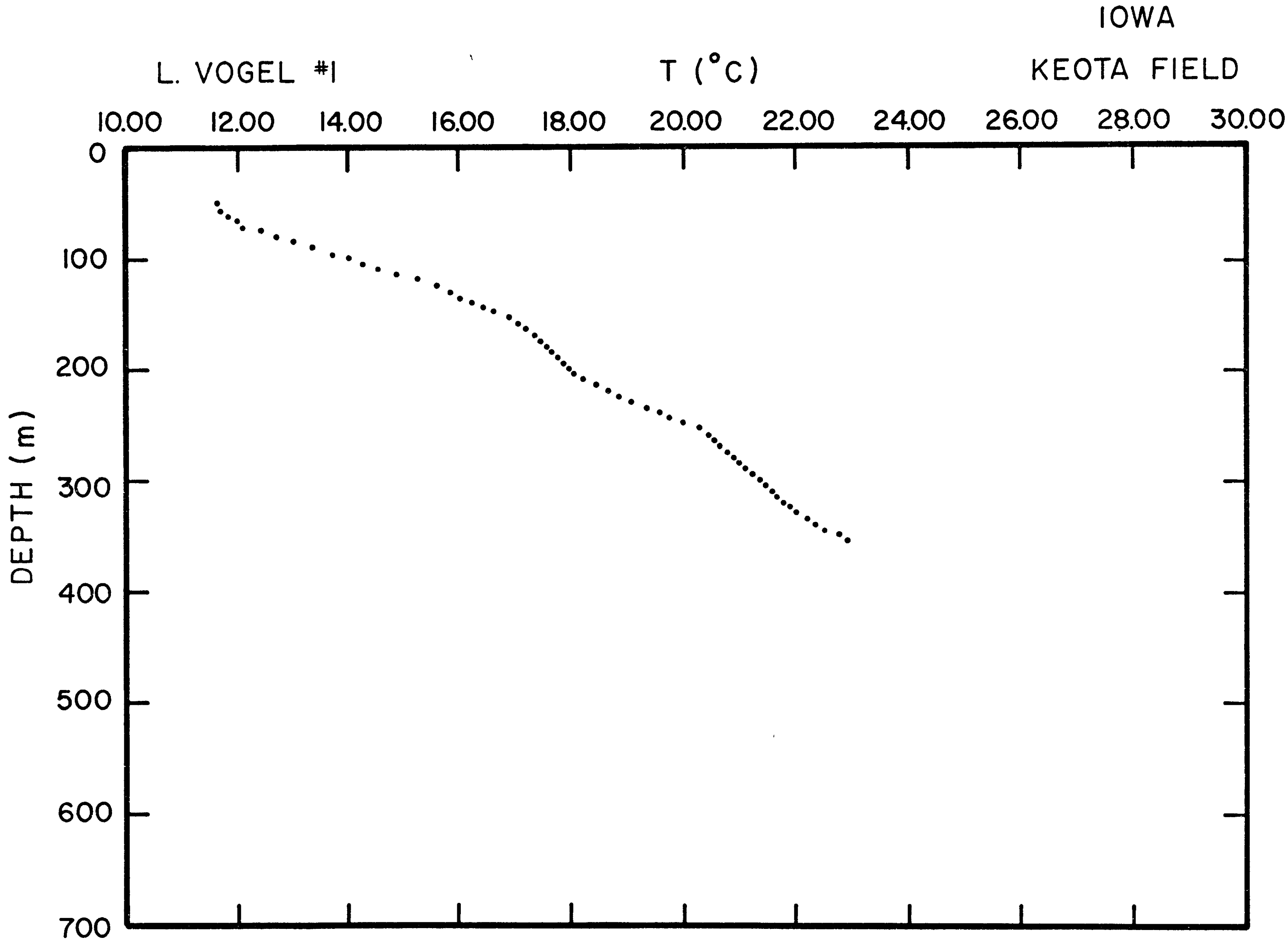

IOWA
KEOTA FIELD
L. VOGEL #1
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

TABLE 6.8 J. ANDERSON #1, KEOTA

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
300-310	7.11 (6)	21.3	1.51
313-315	11.35 (1)	13.4	1.52
317-318	13.02 (1)	11.4	1.48
320-325	12.15 (2)	12.0	1.46
344-346	7.11 (1)	21.0	1.49

TABLE 6.9 L. VOGEL #1, KEOTA

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
300-310	7.14 (6)	20.8	1.49
313-315	11.31 (1)	12.9	1.46
317-319	13.07 (1)	11.2	1.47
320-322	12.38 (1)	12.2	1.51
324-325	12.07 (1)	12.2	1.47
344-348	7.10 (1)	21.6	1.53

The P. Hutchinson #2 borehole was logged twice. The second log was made four hours after the first run was completed. Both sets of measurements are presented in Figure 6.11. The repeatability of the temperature determinations should be noted. Table 6.10 contains the data pertinent to the heat flow calculations.

Figure 6.11 Temperature-depth plot for P. Hutchinson #2, Cairo, Iowa. Well completed: 12-5-62.

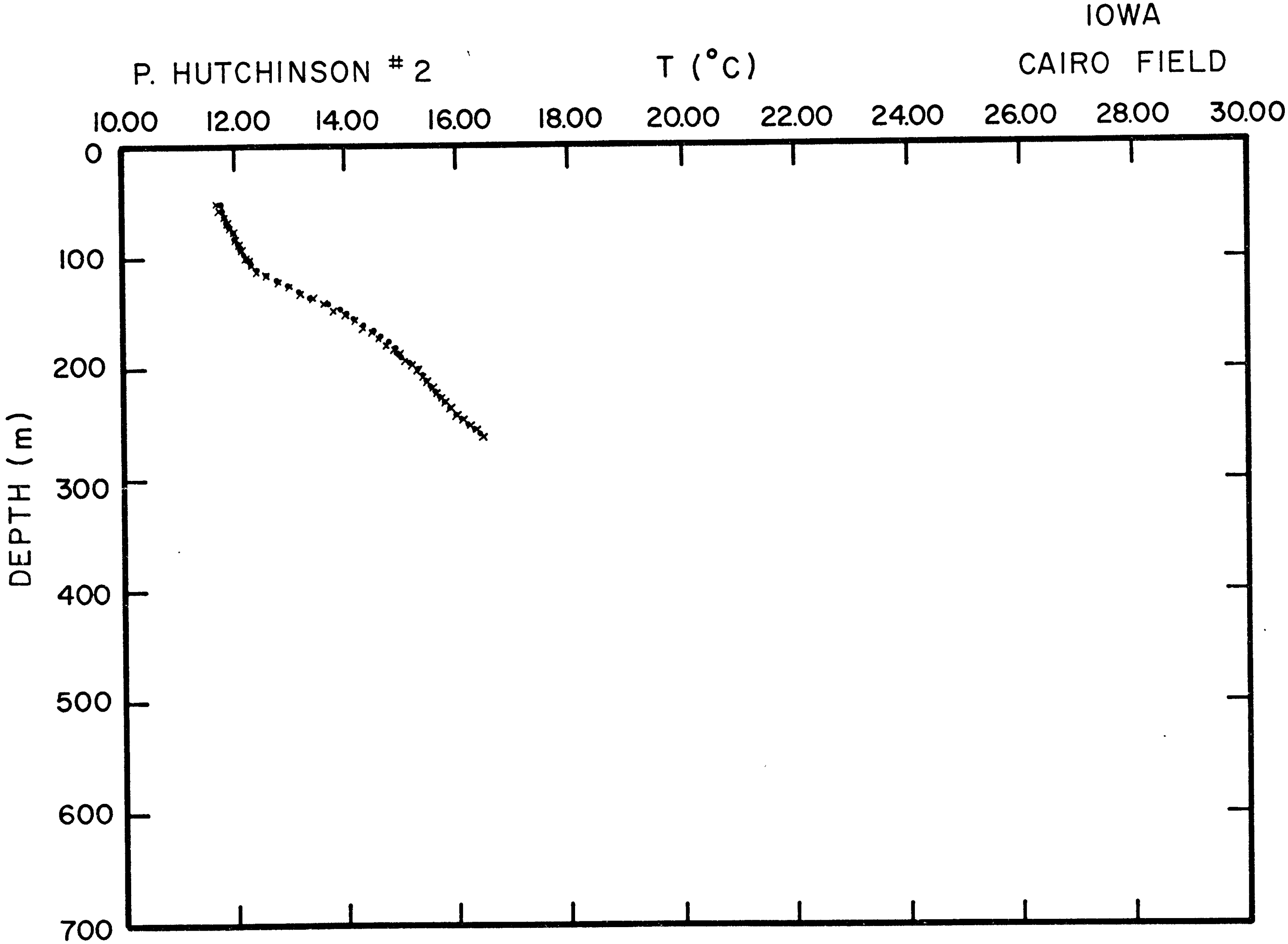

IOWA
CAIRO FIELD
P. HUTCHINSON # 2
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

TABLE 6.10 P. HUTCHINSON #2, CAIRO

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
225-230	7.08 (1)	20.5	1.45
236-240	9.41 (2)	15.9	1.50
246-250	6.89 (2)	20.9	1.44
251-256	7.76 (2)	19.0	1.47

6.3 DISCUSSION AND CONCLUSIONS

Iowa lies on the flank of the Wisconsin arch and its sedimentary strata dip gently southwestward in a broad homocline toward the Forest City basin and southward toward the Illinois basin (King, 1959). The midcontinental gravity and magnetic high extends across the central part of the state in a generally northeast to southwest direction. The combined geophysical and borehole basement sample data indicate that the gravity and magnetic high can be traced northward to areas of the exposed basement where these striking magnetic and gravity anomalies can be correlated with basalt flows and sedimentary rocks of Keweenawan age (Thiel, 1956; Muehlberger, *et al*., 1964; Zietz and Griscom, 1964; Cohen, 1966; Zietz, *et al*., 1966). The positive part of the gravity anomaly originates from dense basalt flows of Keweenawan age and the parallel negative anomalies result from a contrast with low-density Keweenawan sediments. From a plot of lithologic types based on wells that have penetrated the basement, it is known that the remainder of Iowa is a part of the widespread midcontinental granitic province (Aldrich, et al., 1960; Bell, et al., 1964; Muehlberger, et al., 1964; W.J. Yoho, unpub. data).

The best value of the heat flow, as well as the location and elevation, for the nine stations in Iowa are presented in Table 6.10. Roy, et al., (1968) published a value at Spencer, Iowa of 0.44 HFU.

TABLE 6.10 HEAT FLOW DETERMINATIONS IN IOWA

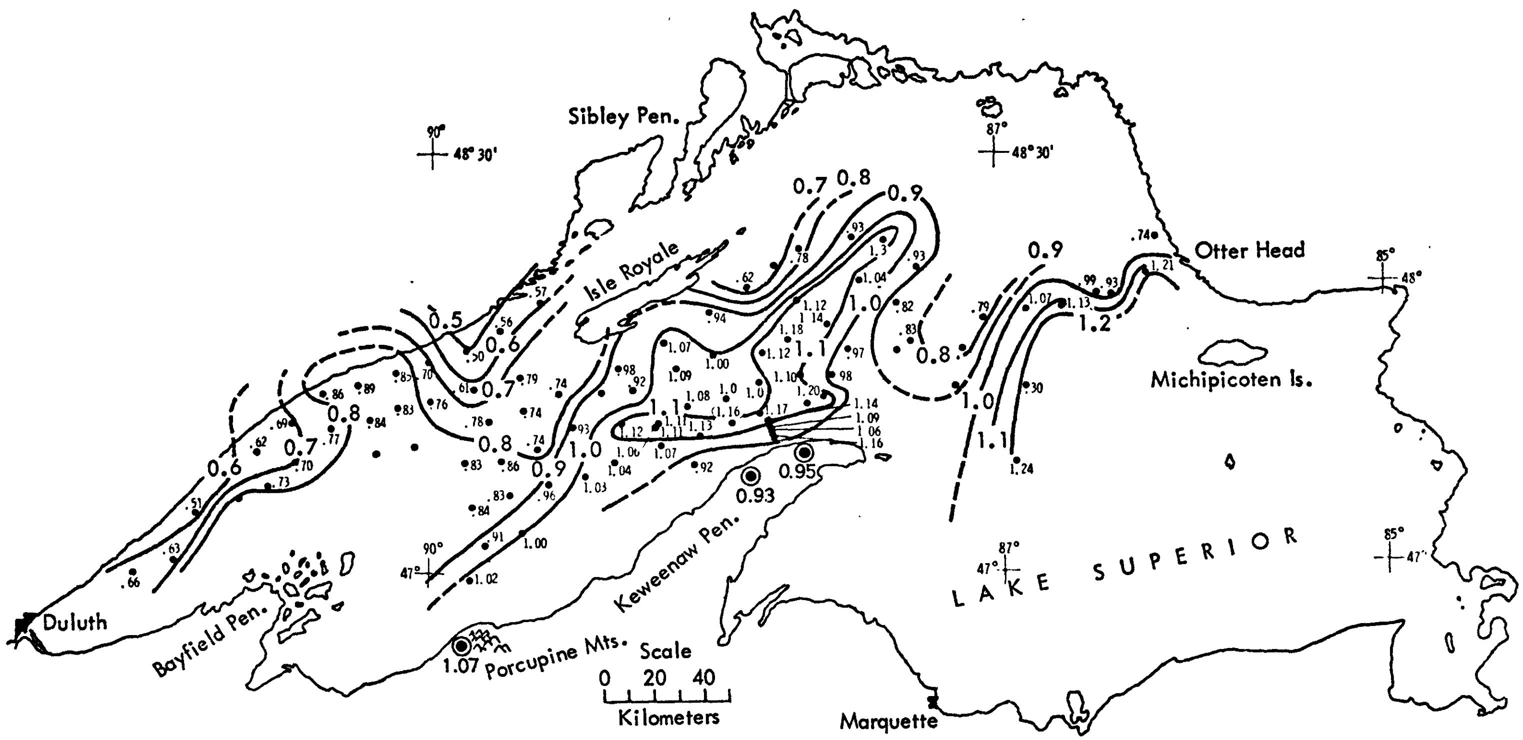
WELL NAME	NORTH LATITUDE	WEST LONGITUDE	ELEVATION	HEAT FLOW
ANDERSON #1, Vincent	42° 38.3'	94° 01.5'	348	0.90±0.02
ANDERSON #3, Vincent	42° 38.3'	94° 01.2'	350	0.92±0.02
BOOK #1, Redfield	41° 33.7'	94° 06.2'	312	1.17±0.03
BRODERICK #1, Redfield	41° 39.6'	94° 09.7'	313	1.17±0.03
HOFFMAN #1, Vincent	42° 37.8'	94° 02.8'	347	0.97±0.09
J. ANDERSON #1, Keota	41° 23.2'	91° 54.9'	231	1.49±0.03
L. VOGEL #1, Keota	41° 21.6'	91° 54.5'	242	1.49±0.04
OLSON #1 "G", Vincent	42° 37.6'	94° 03.2'	349	0.93±0.03
P. HUTCHINSON #2, Cairo	41° 12.3'	91° 19.6'	201	1.46±0.04
PRICE #1, Redfield	41° 41.5'	94° 10.4'	309	1.16±0.02

Hart, et al. (1968) reported 83 heat flow stations in Lake Superior. The values range from 0.50 to 1.24 HFU and characterize two distinct regions: a belt along the western shore characterized by low values (0.5-0.9) and a central region of higher but uniform values (1.0-1.2) (see, Figure 6.12). Some of the heat flow determinations in Iowa as well as those of Hart and his coworkers are associated with the midcontinent gravity and magnetic anomaly. The spatial relationships and the magnitudes of the heat flow are comparable for both regions.

There appears to be no direct correlation between the heat flow determinations and the available gravity and magnetic data. However, there does appear to be a correspondence between the basement lithology and the heat flow data. In particular, three wells in the Vincent field penetrated the basement and all of the samples were diabase (or basalt). Similarly, in the Redfield field, six basement boreholes have all encountered an altered diabase. The low content of radioactive elements of these basic rocks in addition to the large scale thermal conductivity contrasts between the otherwise granitic basement can account for these lower than normal heat flow values.

Although there are no deep boreholes in the Keota or Cairo fields, it is evident from the magnetic data and from the lithologic data in surrounding wells that the basement

Figure 6.12 Terrestrial heat flow for the Lake Superior region (from, Hart et al., 1968).



Contour interval 0.1 $\mu cal/cm^2/sec$

◉ Published land values

is granitic. The values of heat flow are similar to those for northeastern Illinois and northern Indiana. Therefore, the best value for the regional heat flow in Iowa is 1.4 to 1.5 HFU.

CHAPTER 7

HEAT FLOW IN MICHIGAN

7.1 INTRODUCTION

Although three determinations of heat flow in Michigan have already been reported (Birch, 1954; Roy, 1963), they were all located on the northern peninsula of the state. For the present study, three boreholes located on the southern peninsula have been investigated (see Figure 7.0). Borehole 972 in Marion is operated by the Michigan Gas Storage Company, while the other two were made available by the Consumers Power Company.

7.2 RESULTS

The heat flow value determined for 972, Marion, is one of the least precise of the present values. There was only one 15 meter interval that had been cored and there were no other wells available in the Winterfield field that could be used to substantiate the value. Since only this interval was available, the variation in the thermal conductivity, that is, 10%, was used for the variation in the final heat flow. The data for this determination are given in Table 7.1. The temperature depth curve is presented in Figure 7.1.

Figure 7.0 Terrestrial heat flow for the southern peninsula of Michigan. All values are in units of HFU.

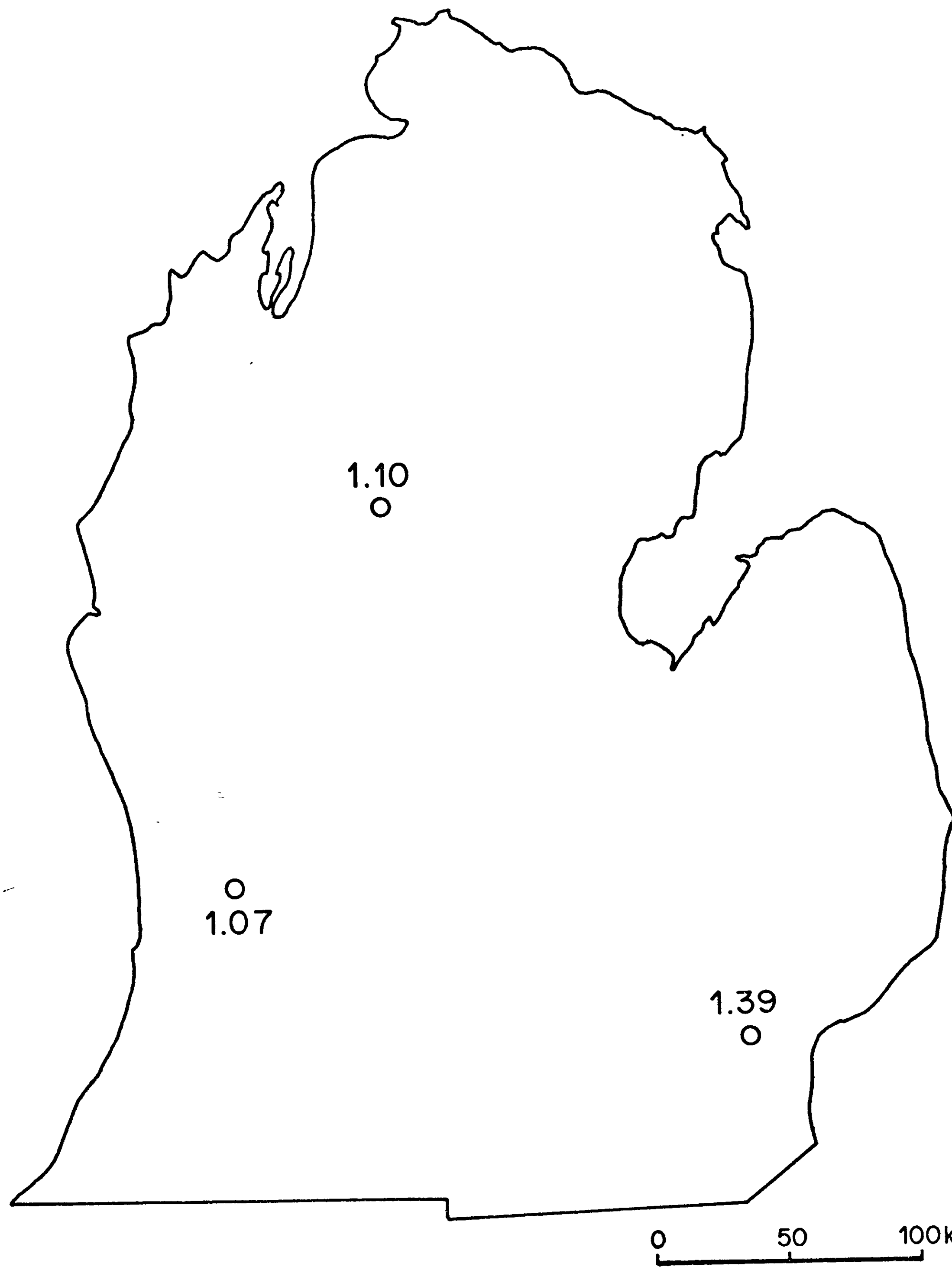

1.10
1.07
1.39
0
50
100km

Figure 7.1 Temperature-depth plot for borehole #972, Marion, Michigan. Well completed: 7-2-65.

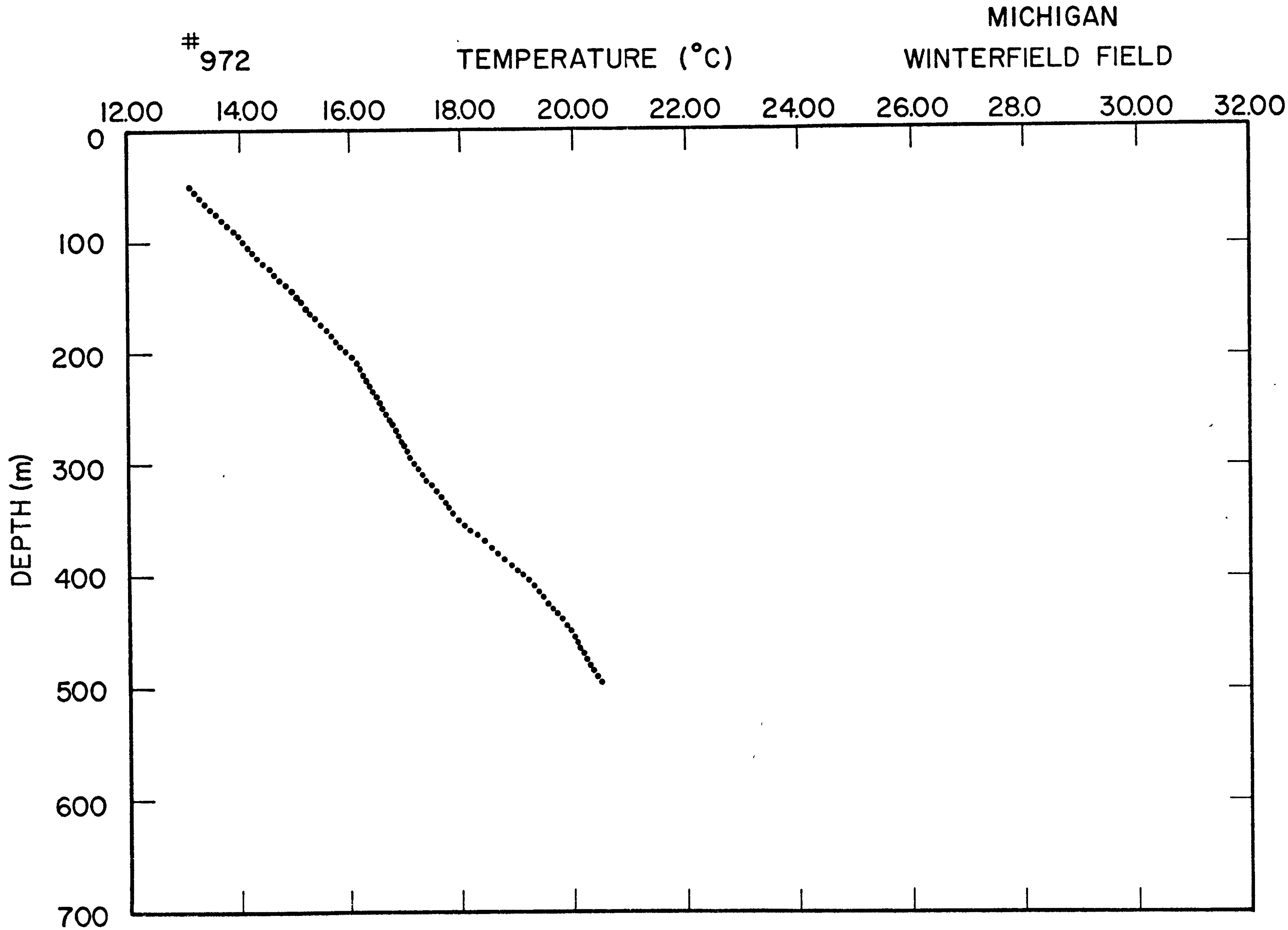

#972
TEMPERATURE (°C)
MICHIGAN
WINTERFIELD FIELD
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.0
30.00
32.00
DEPTH (m)
0
100
200
300
400
500
600
700

TABLE 7.1 972, MARION

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
460-475	9.58±0.90	11.5±0.2	1.10±0.11

Because of the availability of core samples, the well in the Northville field, N-203, provided an opportunity to check the hypothesis that a few thermal conductivity samples in addition to a very precise geothermal gradient yield as precise a value for the heat flow as can be obtained from the measurement of many thermal conductivities. Table 7.2 contains the data that were obtained from an original set of sixteen thermal conductivity samples. Later, 23 more samples were measured. The resulting differences in thermal conductivity and therefore the heat flow can be seen by comparing Table 7.3 with Table 7.2.

TABLE 7.2 N-203, NORTHVILLE

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
988-998	12.58 (3)	10.9	1.37
1000-1035	12.03 (5)	11.6	1.40
1296-1298	9.07 (1)	15.5	1.41
1300-1330	9.68 (4)	14.4	1.39
1342-1362	9.95 (3)	14.0	1.39

TABLE 7.3 N-203, NORTHVILLE

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
988-998	12.58 (5)	10.9	1.37
1000-1035	11.98 (15)	11.6	1.39
1280-1290	9.74 (2)	14.2	1.38
1296-1298	9.07 (1)	15.5	1.41
1300-1330	9.70 (10)	14.4	1.40
1342-1362	9.91 (6)	14.0	1.39

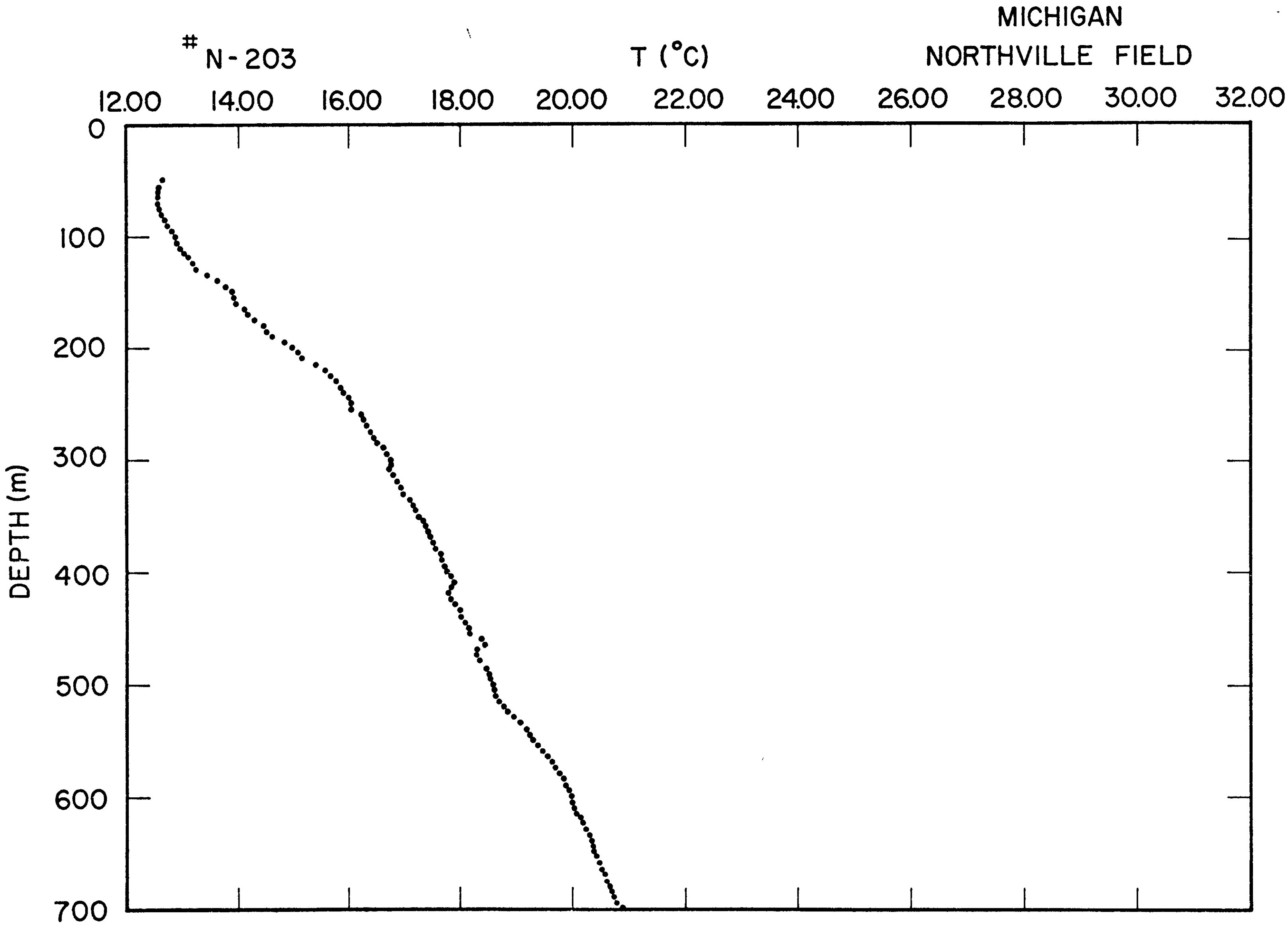
As can be seen from Figures 7.2 to 7.4, the type of fluid in a borehole is critical when attemting to obtain a precise gradient. With air in the vertical column of the borehole, the temperatures are erratic, but this behavior is eliminated if the borehole is filled with water, however, gradients, averaged over considerable depth, may still be obtained from the measurements made in a gas filled borehole.

Only one well in the Salem field, S-503-E, was available for use in the determination of heat flow. The results for S-503-E are presented in Table 7.4 and Figures 7.5 and 7.6.

TABLE 7.4 S-503-E, BURNIPS

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
775-782	10.23 (4)	10.5	1.07
783-793	8.46 (4)	13.2	1.12

Figure 7.2 Temperature-depth plot for borehole #N-203, Northville, Michigan. Well completed: 10-23-64.



MICHIGAN
NORTHVILLE FIELD
#N-203
T (°C)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 7.3 Continuation of temperature-depth plot for #N-203.

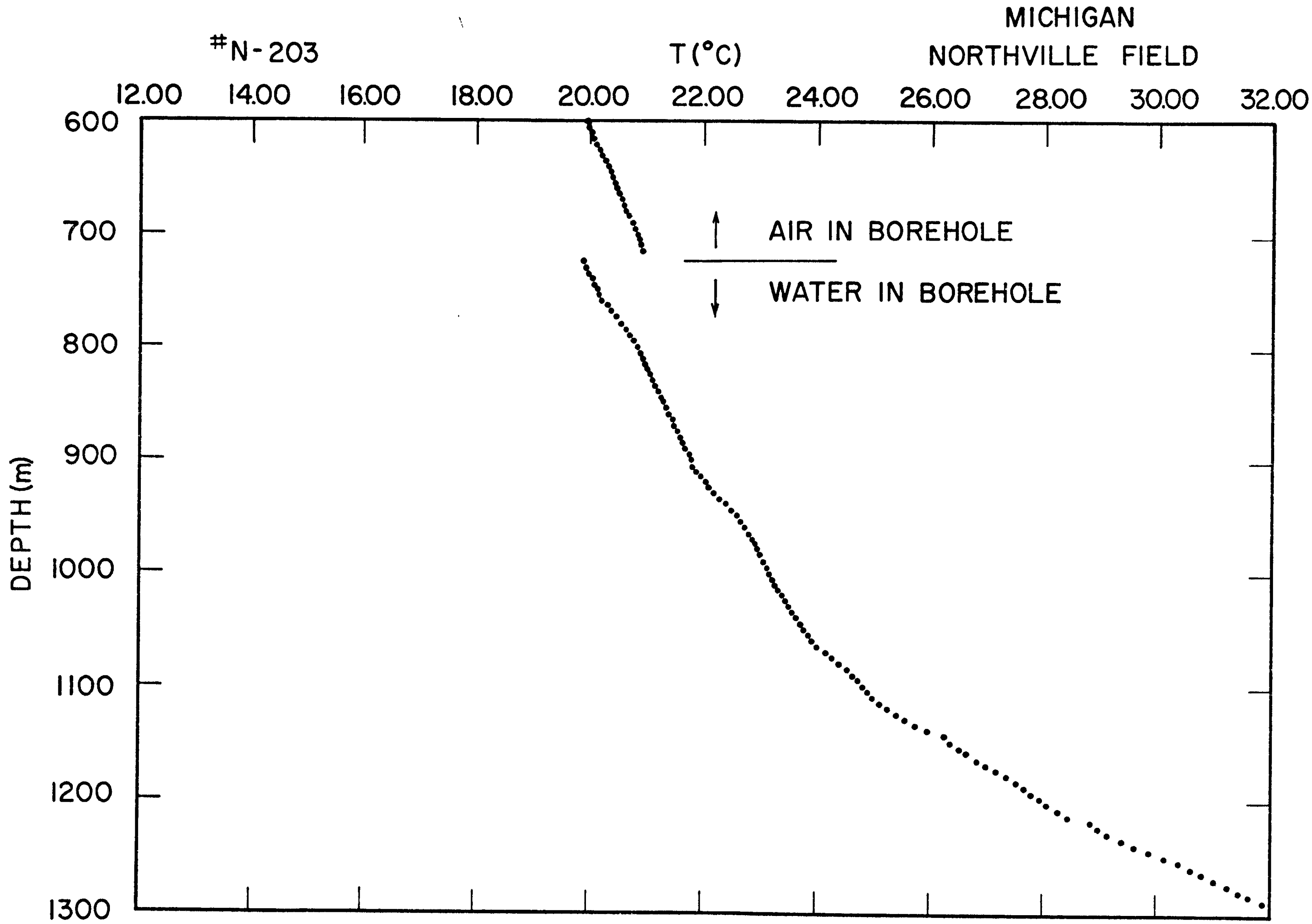

MICHIGAN
NORTHVILLE FIELD
#N-203
T(°C)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
DEPTH (m)
600
700
800
900
1000
1100
1200
1300
AIR IN BOREHOLE
WATER IN BOREHOLE

Figure 7.4 Continuation of temperature-depth plot for #N-203.

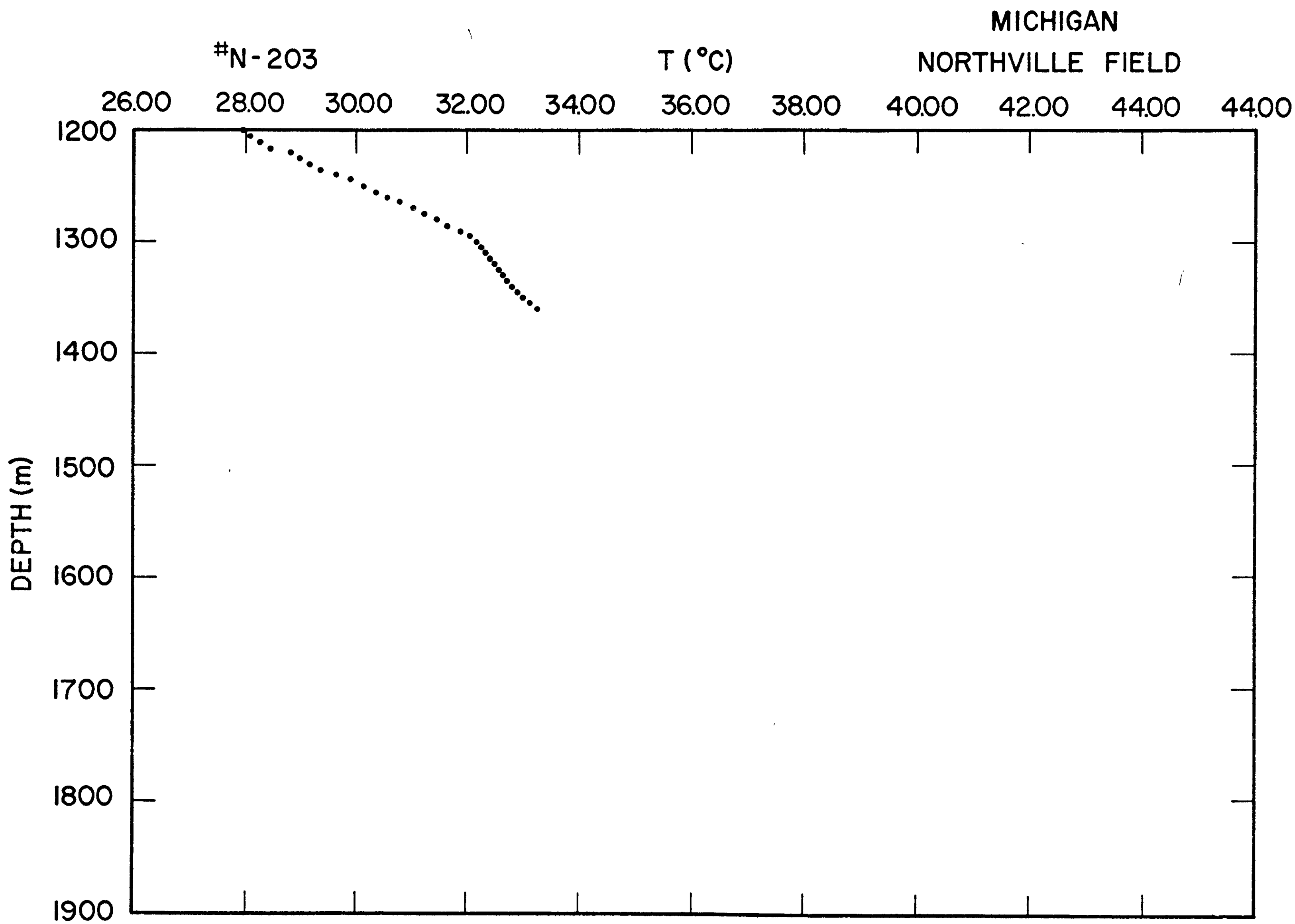

MICHIGAN
NORTHVILLE FIELD
#N-203
T (°C)
26.00
28.00
30.00
32.00
34.00
36.00
38.00
40.00
42.00
44.00
44.00
DEPTH (m)
1200
1300
1400
1500
1600
1700
1800
1900

Figure 7.5 Temperature-depth plot for borehole #S-503-E, Burnips, Michigan. Well completed: 6-2-65.

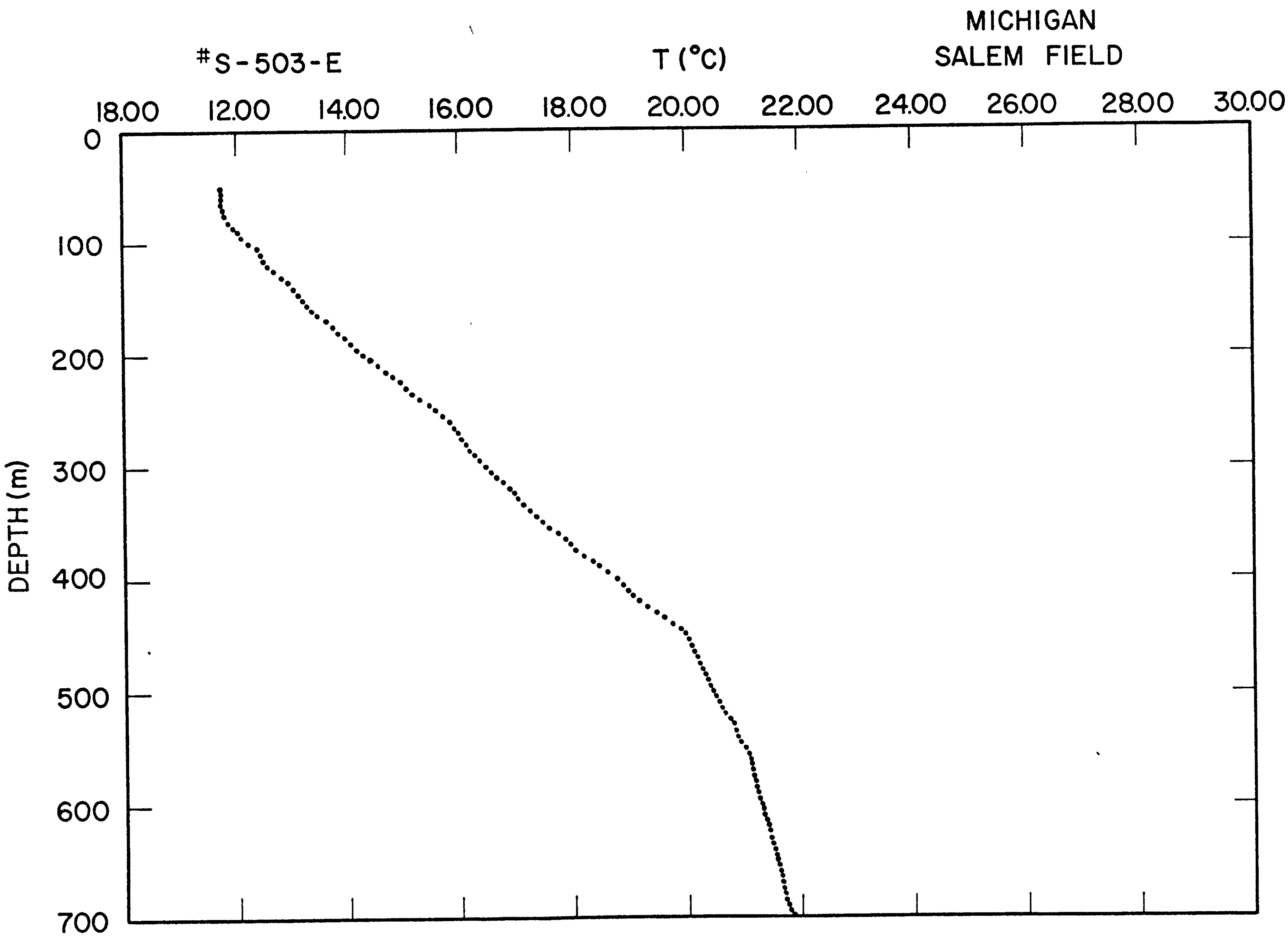

MICHIGAN
SALEM FIELD
#S-503-E
T (°C)
18.00 12.00 14.00 16.00 18.00 20.00 22.00 24.00 26.00 28.00 30.00
DEPTH (m)
0 100 200 300 400 500 600 700

Figure 7.6 Continuation of temperature-depth plot for borehole #S-503-E.

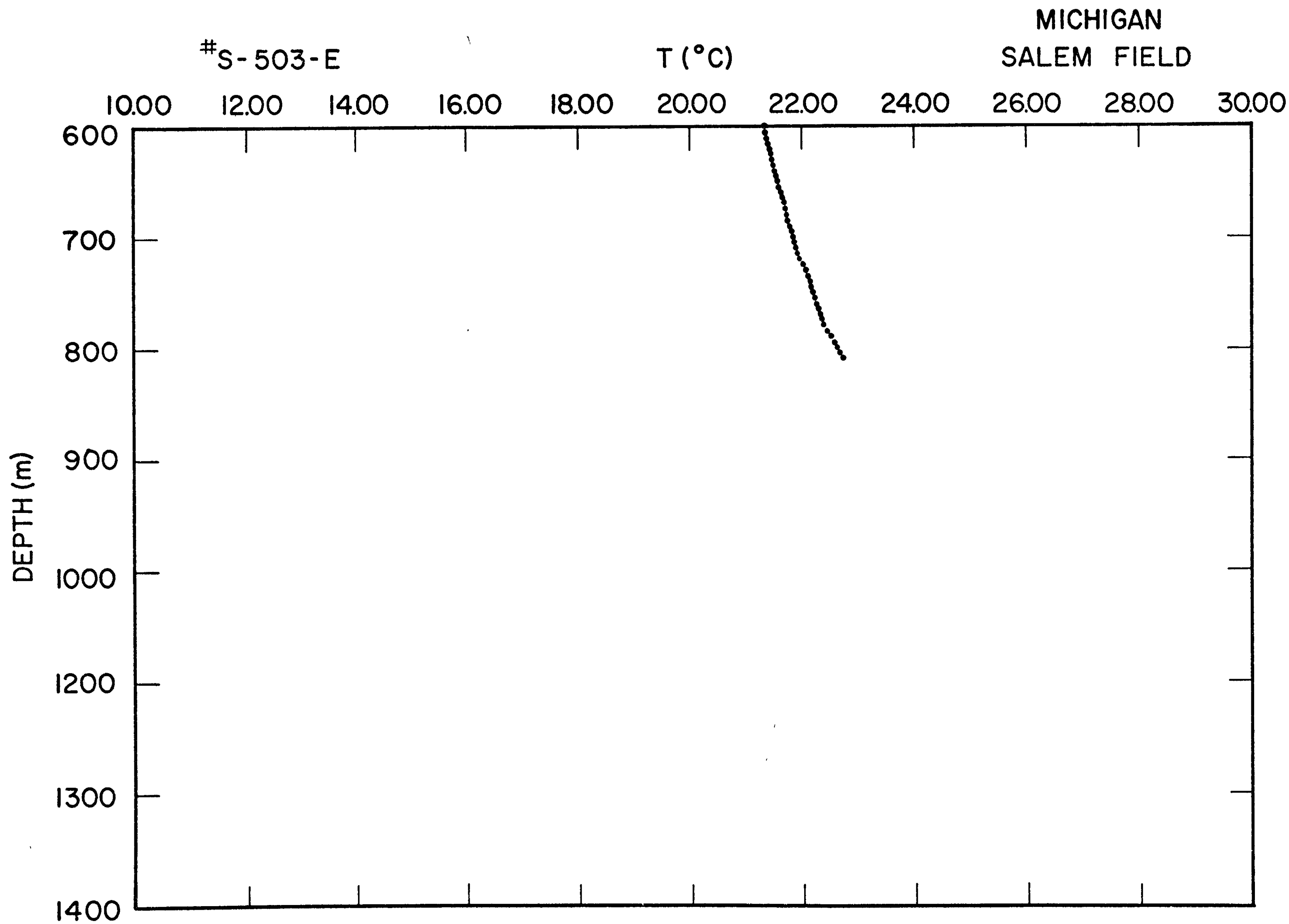

MICHIGAN
SALEM FIELD
#S-503-E
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
600
700
800
900
1000
1200
1300
1400

TABLE 7.4 S-503-E, BURNIPS (con't.)

DEPTH	CONDUCTIVITY	GRADIENT	HEAT FLOW
804	7.13 (1)	14.9	1.06
806	10.86 (1)	9.59	1.04

7.3 DISCUSSION AND CONCLUSIONS

The three heat flow values obtained in Michigan are presented in Table 7.5. From a comparison of these values with the regional gravity and magnetic anomaly (Hinze, 1963), no direct correlation exists among the data. Magnetic data in Michigan (Hinze, 1963), however, show the existence of a linear magnetic anomaly that may be genetically similar to the

TABLE 7.5 HEAT FLOW DETERMINATIONS FOR THE SOUTHERN PENINSULA OF MICHIGAN

WELL NAME	NORTH LATITUDE	WEST LONGITUDE	ELEVATION	HEAT FLOW
972, MARION	44° 03.1'	85° 05.4'	330	1.10±0.11
N-203, NORTHVILLE	42° 25.5'	83° 33.8'	296	1.39±0.02
S-503-E, BURNIPS	42° 43.4'	85° 49.1'	203	1.07±0.05

midcontinent high. Some investigators (for example, Rudman, et al., 1965; Muehlberger, et al., 1964) have postulated that the linear anomalies in Michigan like those in Iowa, Wisconsin, and Minnesota are caused by basalt flows of Keweenawan age.

Disregarding the structure and lithology of the basement rocks, negative gravity and magnetic anomalies should be associated with the Michigan Basin due to the generally less dense, non-magnetic sediments filling the basin as compared to the adjacent basement rocks, but this is not the case. In fact the principal anomaly on both gravity and magnetic maps is positive and extends through the center of the basin (Hinze, 1963). The magnitude of the anomalies as well as the excellent correlation between the gravity and magnetic highs suggests a basic rock in the basement complex as the origin of the anomalies.

Although no basement samples are available from the area, the somewhat low heat flow values for 974, Marion, and S-503-E, Burnips, are compatible with the hypothesis that the basement consists mostly of basic rocks. Further interpretation, perhaps similar to that presented for Iowa, must be delayed until the nature of the basement has been established.

At least six basement samples have been recovered from the southeast corner of the southern peninsula of Michigan (Muehlberger, et al., 1964). All of them are granite or granitic gneiss. The borehole in the Northville field, N-203, has a value of 1.39 HFU. There is an evident similarity between this well and most of those in Illinois, Indiana, and Iowa, that is, a heat flow value of approximately 1.4 is associated with a granitic basement. It is therefore suggested that at least the southeastern part of Michigan has a regional heat flow value of 1.4 HFU.

CHAPTER 8

HEAT FLOW IN NORTH AND SOUTH DAKOTA

8.1 INTRODUCTION

Three boreholes were investigated in North and South Dakota. The well near Winner, South Dakota, Assman #1, is located in the southern part of the Williston Basin between the Sioux uplift to the east and the Black Hills uplift to the west. The two boreholes in North Dakota are also located in the Williston Basin.

Blackwell (1969) has published two heat flow determinations in the Black Hills uplift of South Dakota and an estimate of the heat flow in the North Dakota part of the Williston Basin. These values as well as those obtained in the present investigation will be discussed in a later section.

8.2 RESULTS

A lithologic log of the stratigraphic section from the surface to 305 meters was constructed from drill cuttings when the Assman #1 was drilled. This well was operated by the Geotechnical Corporation. The borehole penetrated low-velocity (0.6 km/sec) Tertiary sediments from the surface to 122 meters and a continuous section of Pierre Shale (Cretaceous) from

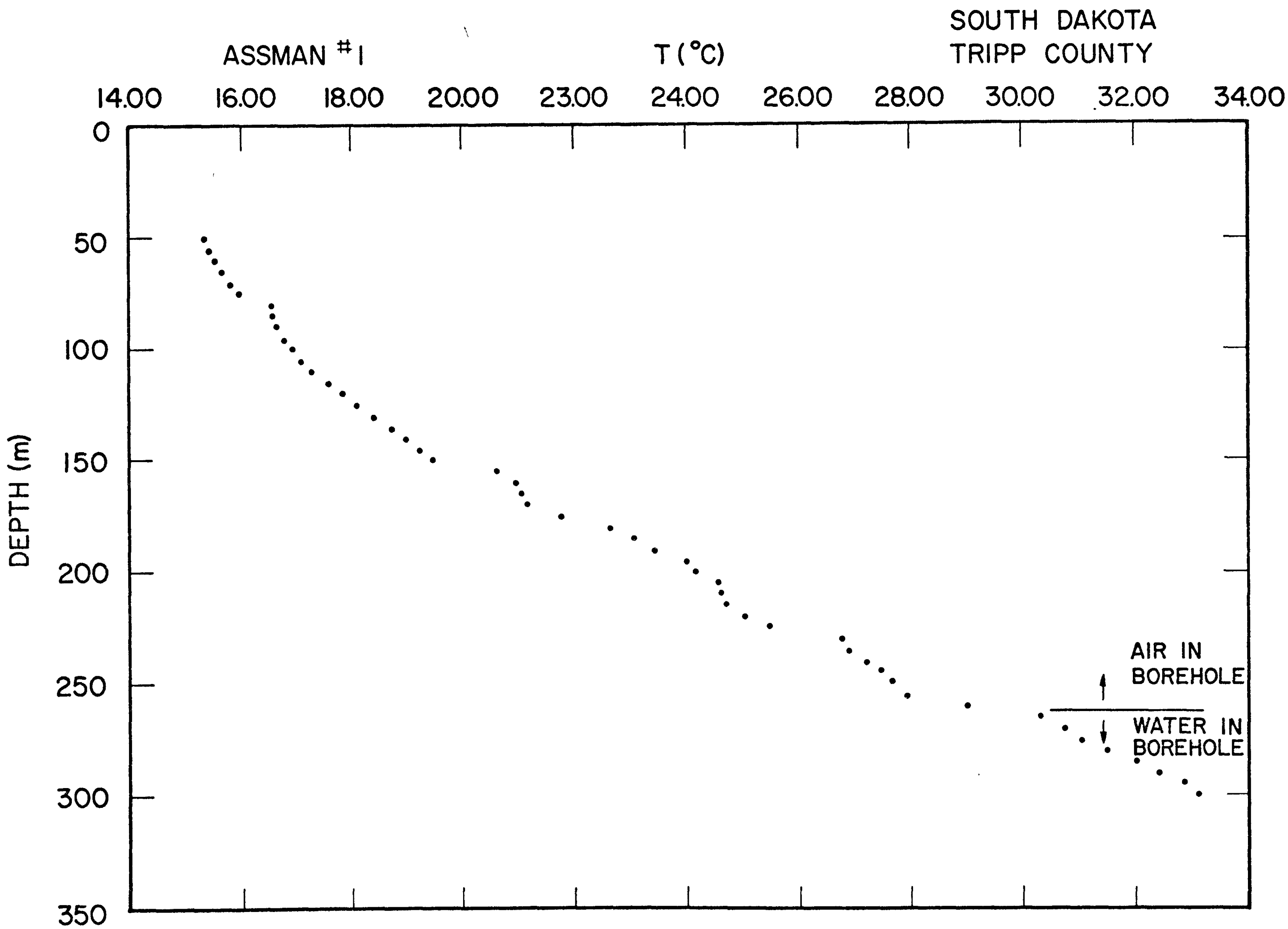
122 meters to the total depth of 305 meters (Geotechnical Corporation, 1964). A Geotech refraction seismograph survey indicated that the average velocity in the continuous shale section was 1.81 km/sec. The density of the Pierre shale was 2.1 gm/cm^3.

As can be seen in Figure 8.1, approximately the bottom 50 meters of the borehole was useful. The temperature in this section of the well was logged twice. The average gradient for this section was 52.1 ^{o}C/km. No samples were available for thermal conductivity measurements, but a representative value will be discussed later in this section.

The temperature-depth curves for two boreholes in North Dakota are presented in Figures 8.2 thru 8.8. Both wells were operated by the E.L.K. Oil Company. The average gradient for the Carrie Hovland #1 was 55.8 ^{o}C/km while the range was from 49 ^{o}C/km to 62 ^{o}C/km. The E.L.K. #1 Nelson had an average geothermal gradient of 54.7 ^{o}C/km with a range of values from 48 ^{o}C/km to 60 ^{o}C/km. Although no core was available for either well, detailed knowledge of the lithology permits one to make reasonable estimates of the average thermal conductivity.

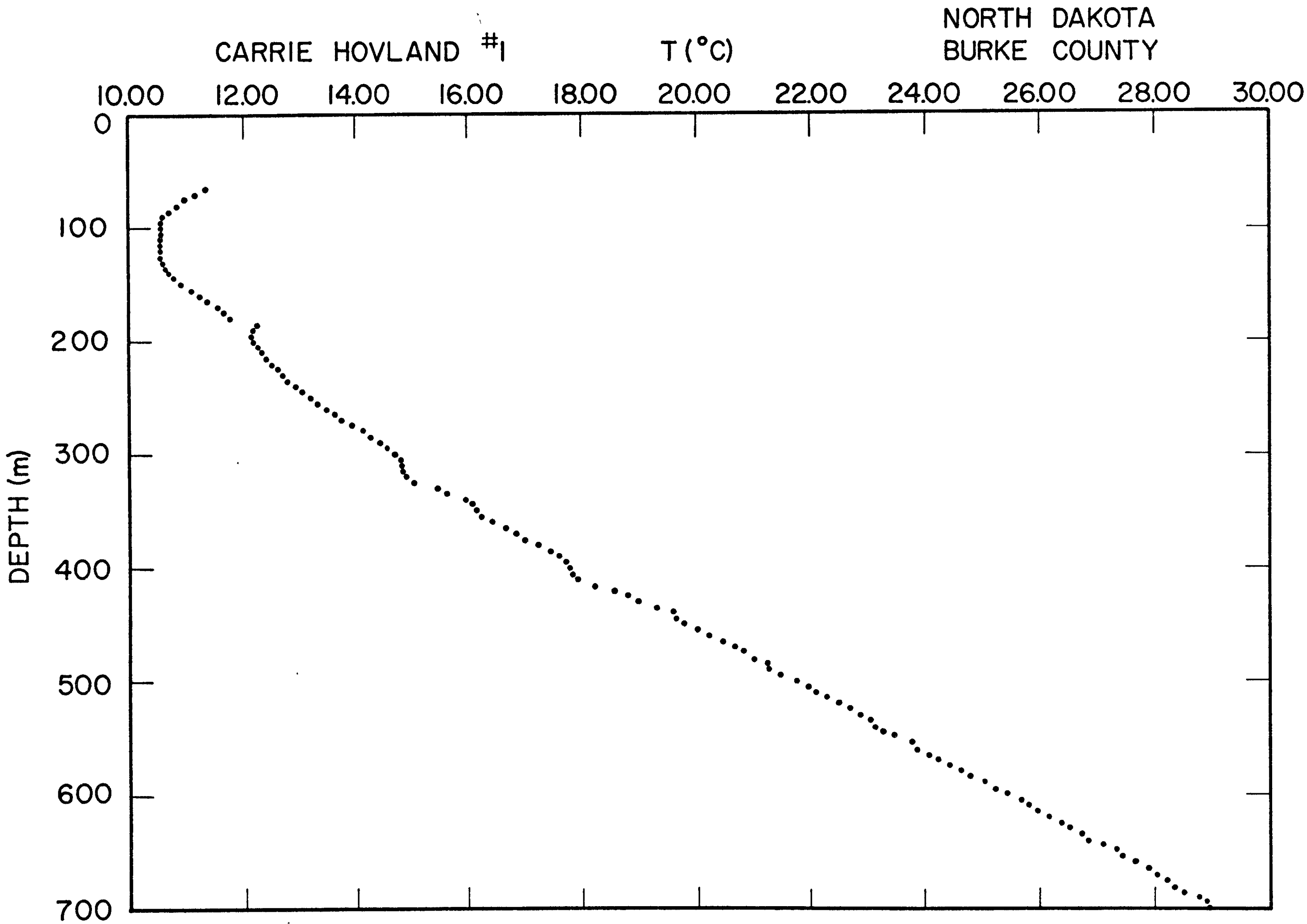
Both boreholes penetrate a thick gray marine shale of Upper Cretaceous age (Carlson and Anderson, 1966). The Pierre formation represents the major part of the lithologic section. No sandstones or carbonates were penetrated by

Figure 8.1 Temperature-depth plot for Assman #1, Winner, South Dakota. Well Completed: 5-9-64.



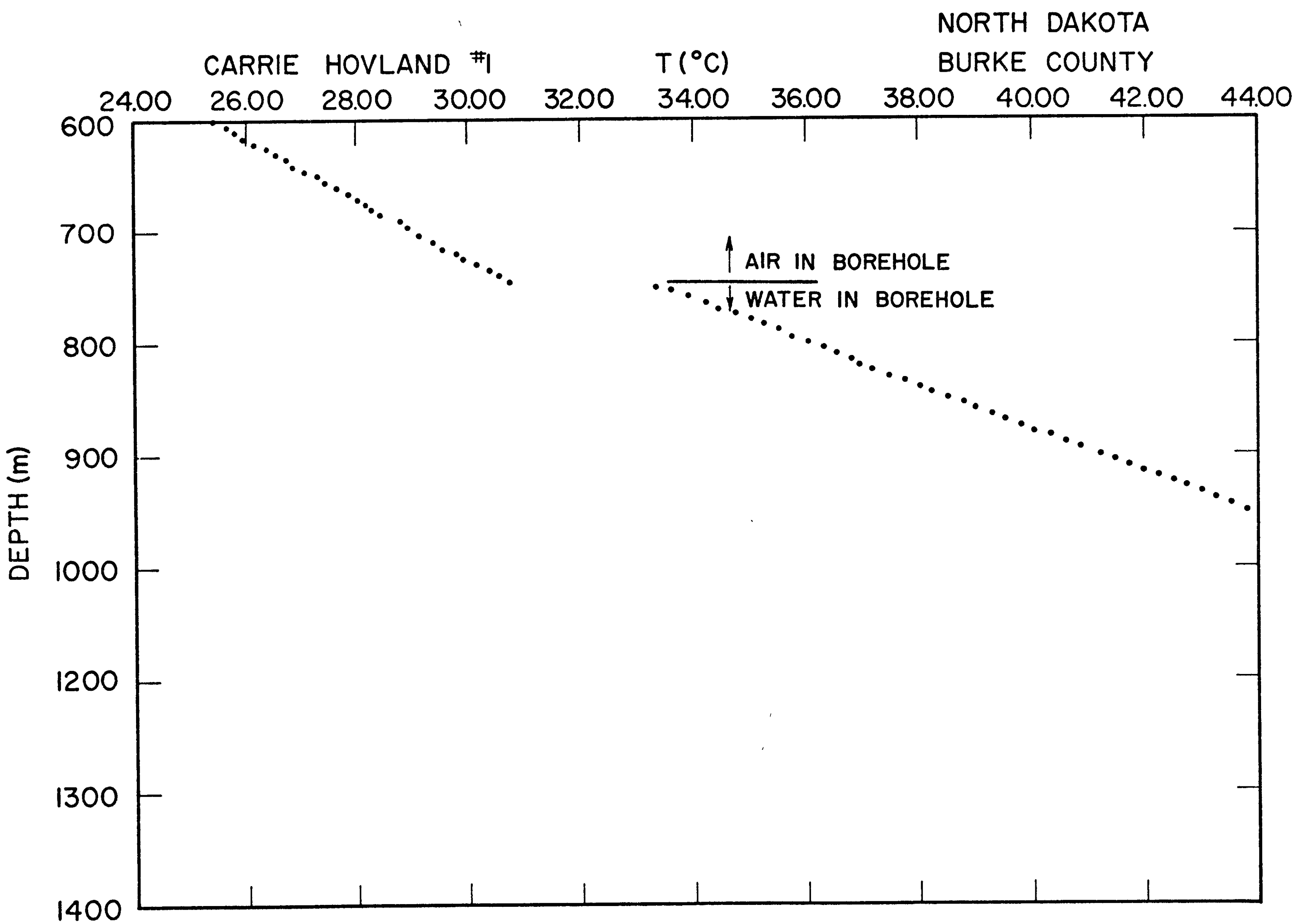
SOUTH DAKOTA
TRIPP COUNTY
ASSMAN #1
T (°C)
14.00
16.00
18.00
20.00
23.00
24.00
26.00
28.00
30.00
32.00
34.00
DEPTH (m)
0
50
100
150
200
250
300
350
AIR IN BOREHOLE
WATER IN BOREHOLE

Figure 8.2 Temperature-depth plot for Carrie Hovland #1, Flaxton, North Dakota. Well completed before 1-1-62.



CARRIE HOVLAND #1
T (°C)
NORTH DAKOTA
BURKE COUNTY
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 8.3 Continuation of temperature-depth plot for the Carrie Hovland #1.



NORTH DAKOTA
BURKE COUNTY
CARRIE HOVLAND #1
T (°C)
24.00
26.00
28.00
30.00
32.00
34.00
36.00
38.00
40.00
42.00
44.00
600
700
800
900
1000
1200
1300
1400
DEPTH (m)
AIR IN BOREHOLE
WATER IN BOREHOLE

Figure 8.4 Continuation of temperature-depth plot for the Carrie Hovland #1.

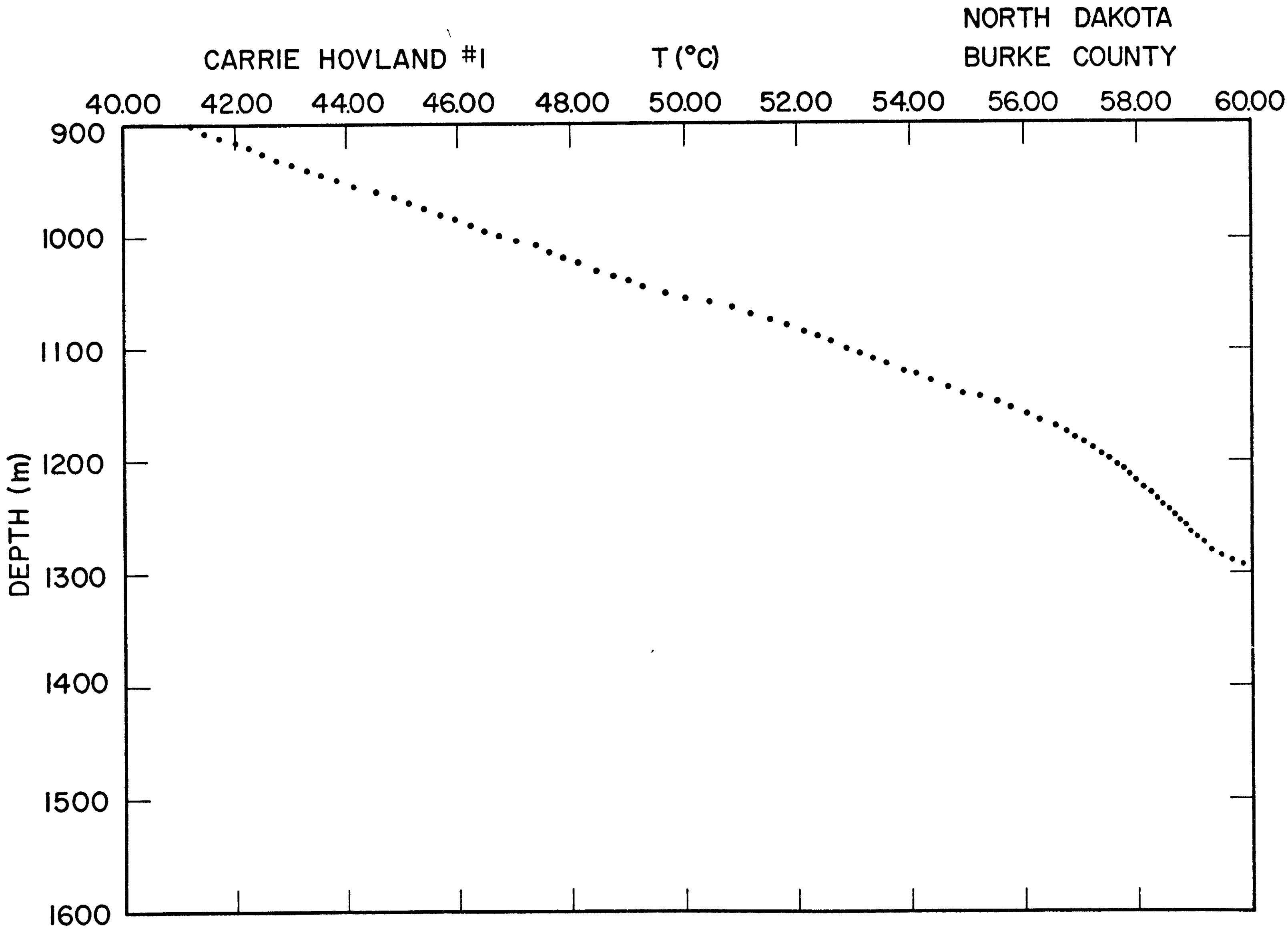

CARRIE HOVLAND #1
T (°C)
NORTH DAKOTA
BURKE COUNTY
40.00
42.00
44.00
46.00
48.00
50.00
52.00
54.00
56.00
58.00
60.00
DEPTH (m)
900
1000
1100
1200
1300
1400
1500
1600

Figure 8.5 Continuation of temperature-depth plot for the Carrie Hovland #1.

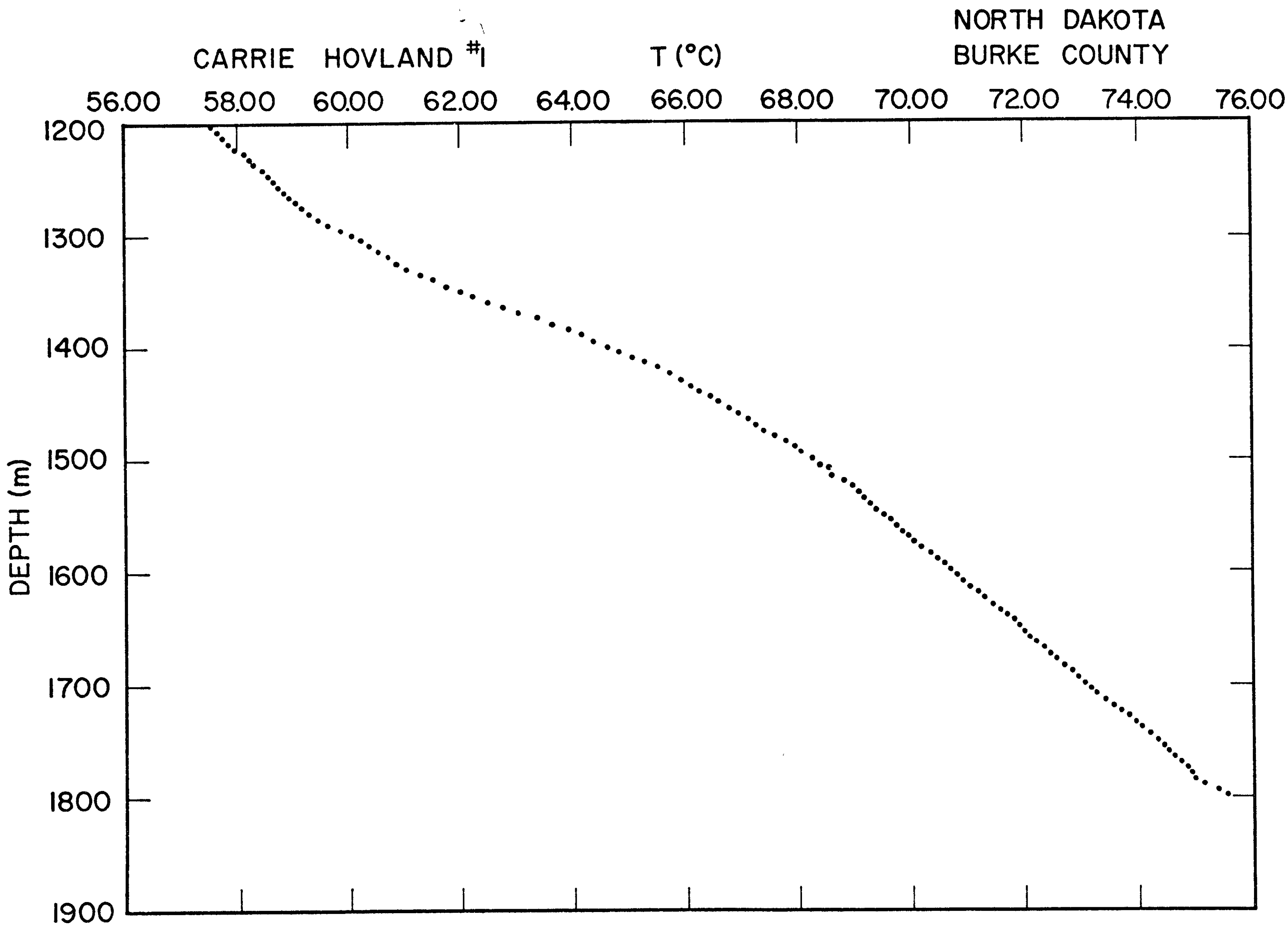

CARRIE HOVLAND #1
T (°C)
NORTH DAKOTA
BURKE COUNTY
56.00
58.00
60.00
62.00
64.00
66.00
68.00
70.00
72.00
74.00
76.00
1200
1300
1400
1500
1600
1700
1800
1900
DEPTH (m)

Figure 8.6 Temperature-depth plot for E.L.K. #1 Nelson, Roth, North Dakota. Well completed before 1-1-62.

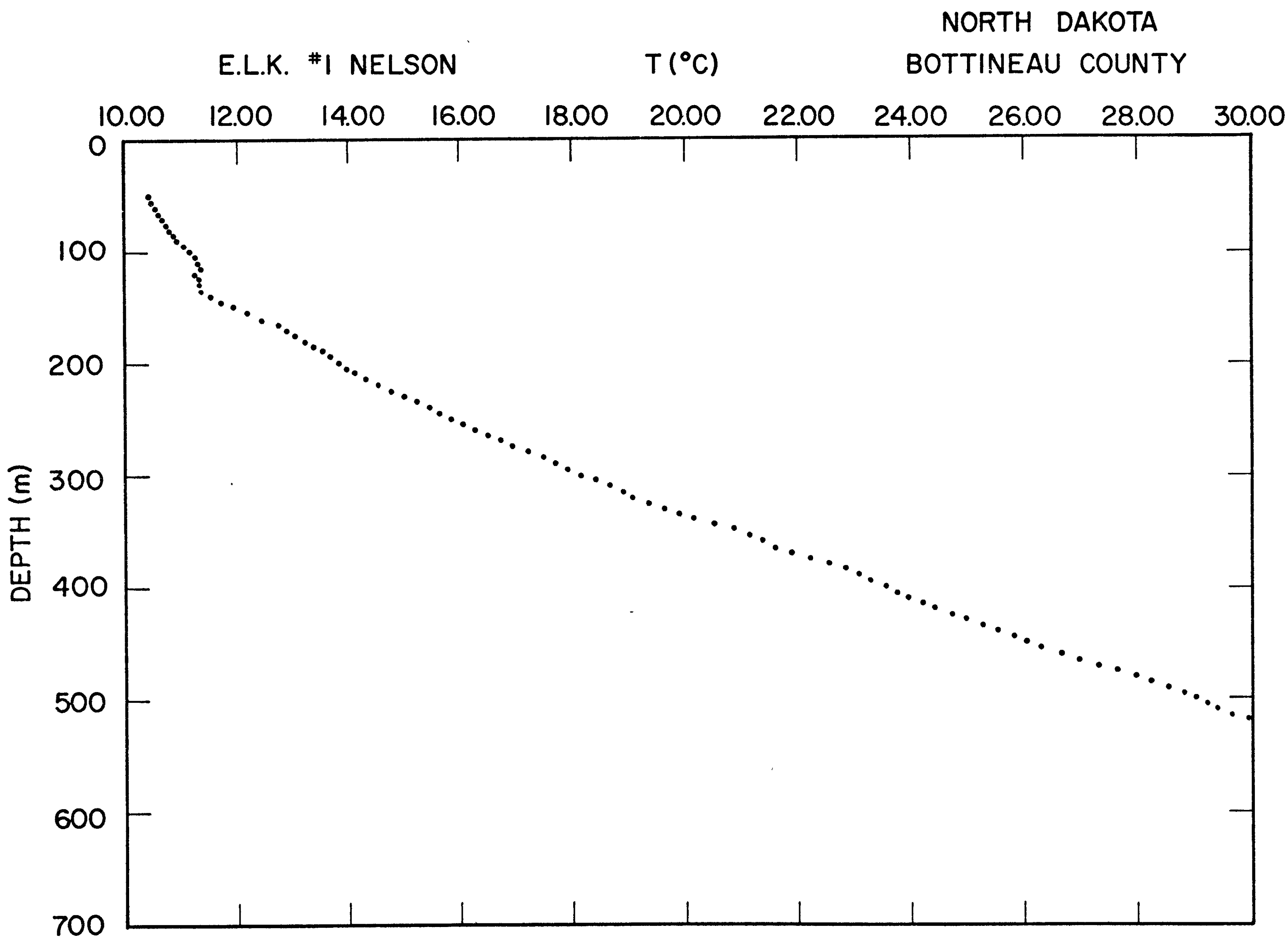

NORTH DAKOTA
BOTTINEAU COUNTY
E.L.K. #1 NELSON
T (°C)
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
DEPTH (m)
0
100
200
300
400
500
600
700

Figure 8.7 Continuation of temperature-depth plot for the E.L.K. #1 Nelson.

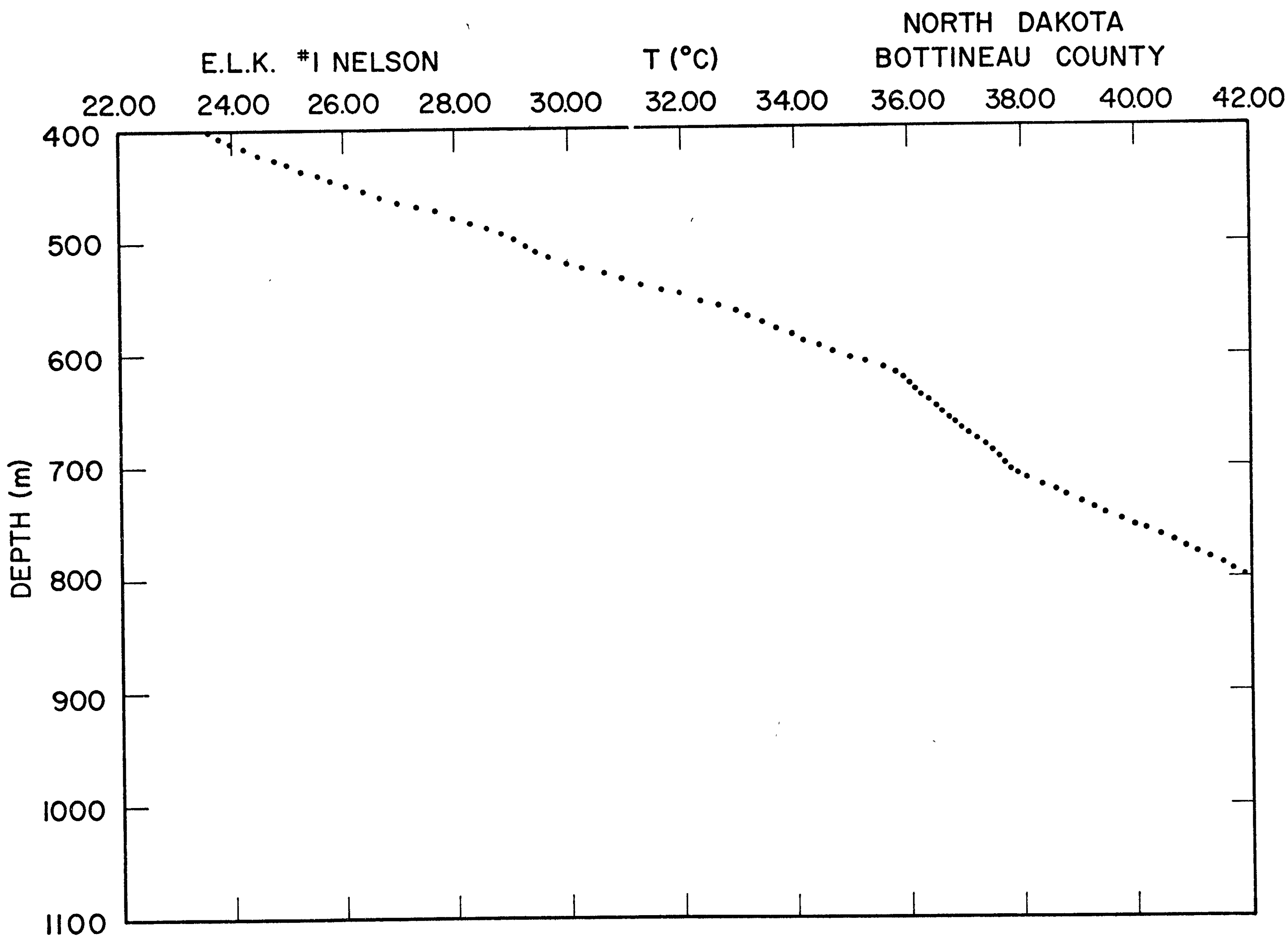
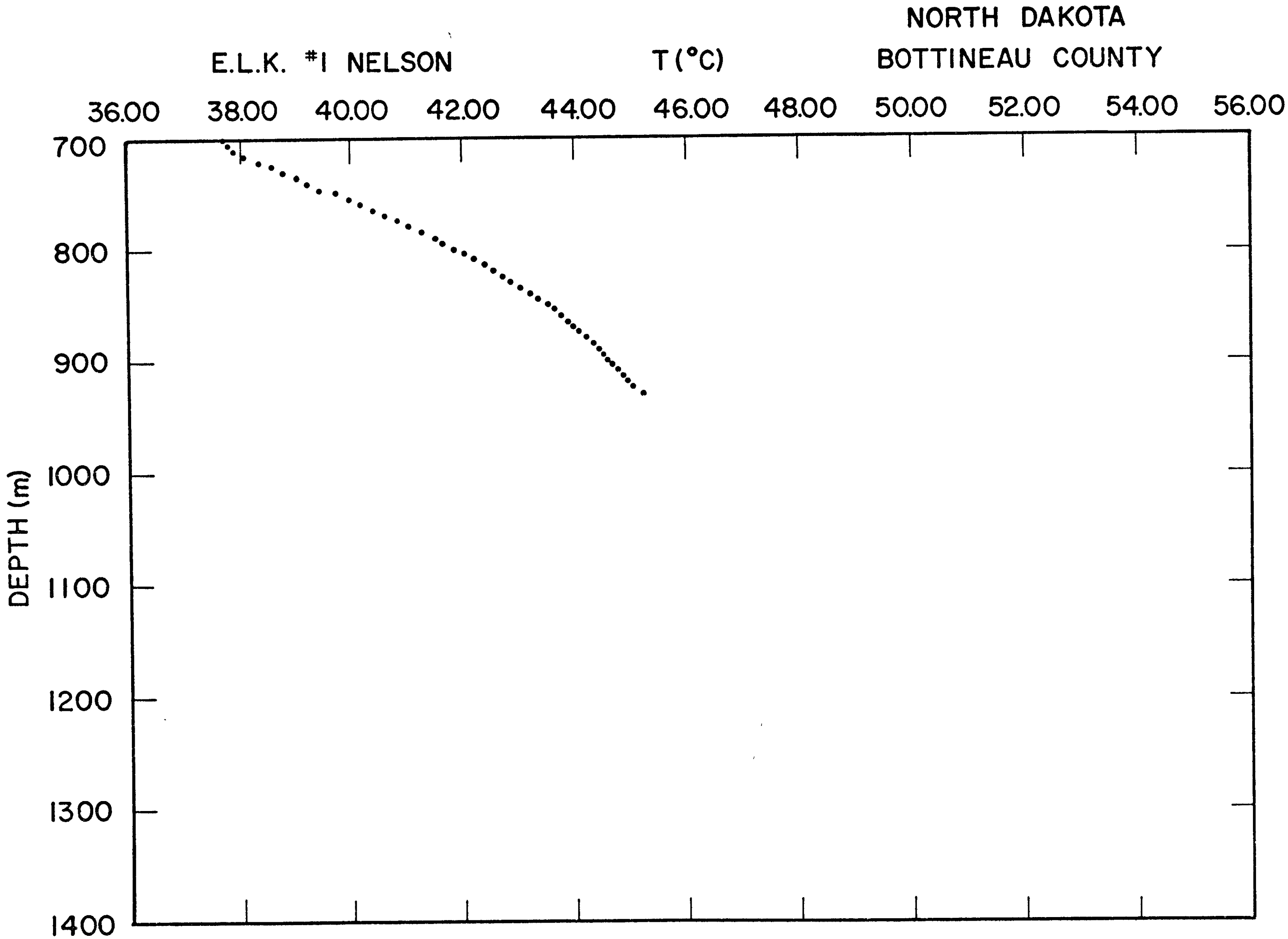

NORTH DAKOTA
BOTTINEAU COUNTY
E.L.K. #1 NELSON
T (°C)
22.00
24.00
26.00
28.00
30.00
32.00
34.00
36.00
38.00
40.00
42.00
DEPTH (m)
400
500
600
700
800
900
1000
1100

Figure 8.8 Continuation of temperature-depth plot for the E.L.K. #1 Nelson.


NORTH DAKOTA
BOTTINEAU COUNTY
E.L.K. #1 NELSON
T(°C)
36.00
38.00
40.00
42.00
44.00
46.00
48.00
50.00
52.00
54.00
56.00
DEPTH (m)
700
800
900
1000
1100
1200
1300
1400

-173-

these wells.

Since the three boreholes in the Dakotas penetrated shale sequences and since no core was available, a best estimate for the thermal conductivity must be made in order to calculate the heat flow. The Pierre shale has been investigated in detail by Tourtelot (1962). From microscope work, in addition to x-ray and chemical analyses, he determined from borehole samples in the two areas where the present boreholes are located that the Pierre shale is composed of 70-85% clay minerals, 15% quartz, 2% feldspar, and two samples contained 5% calcite. It can be inferred from these analyses that the thermal conductivity will be less than 5.0 millicalories/ (centimeter-second-degree-C), but a better estimate is possible.

Benfield (1947) in a heat flow determination for a well in California investigated 31 shale samples. These samples were saturated and the mean wet conductivity was 3.90 with a range of 2.78 to 5.61. In an investigation of heat flow in western Canada, Garland and Lennox (1962) measured 23 samples which they classified as shales. The mean for these saturated samples was 3.97 while the range was from 2.2 to 6.0. The average value for most of the other shale conductivities that have been published is approximately 4.0 (Clark, 1966). Therefore, the estimated average value that was used for the

Pierre shale of this investigation is 4.0 mcal/cm-sec-°C.

The data pertinent to the calculation of the heat flow values are presented in Table 8.1.

TABLE 8.1

WELL NAME	DEPTH	ESTIMATED CONDUCTIVITY	GRADIENT	HEAT FLOW
CARRIE HOVLAND #1, Flaxton	750-1800	4.0±0.5	56.0±6.0	2.2 ± 0.4
E.L.K. #1 NELSON, Roth	200-900	4.0±0.5	55.0±6.0	2.2 ± 0.4
ASSMAN #1, Winner	250-305	4.0±0.5	52.0±4.0	2.1 ± 0.4

8.3 DISCUSSION AND CONCLUSIONS

Heat flow determinations for the Dakotas are presented in Table 8.2 and shown in Figure 8.9. Both the present study and the earlier work of Blackwell (1969) indicate that the best heat flow value for the regional flux is 2.0 HFU. This value is higher than the 1.4 HFU which has been found for the Interior Lowlands.

TABLE 8.2 HEAT FLOW DETERMINATIONS IN NORTH AND SOUTH DAKOTA

WELL NAME	NORTH LATITUDE	WEST LONGITUDE	ELEVATION	HEAT FLOW
ASSMAN #1, Winner	43° 15.1'	100° 11.7'	792	2.1±0.4
CARRIE HOVLAND #1, Flaxton	48° 55.3'	102° 26.0'	593	2.2±0.4

Figure 8.9 Terrestrial heat flow in North and South Dakota. Circles indicate data from this investigation while X's are for published data of Blackwell (1969). All values in units of HFU.

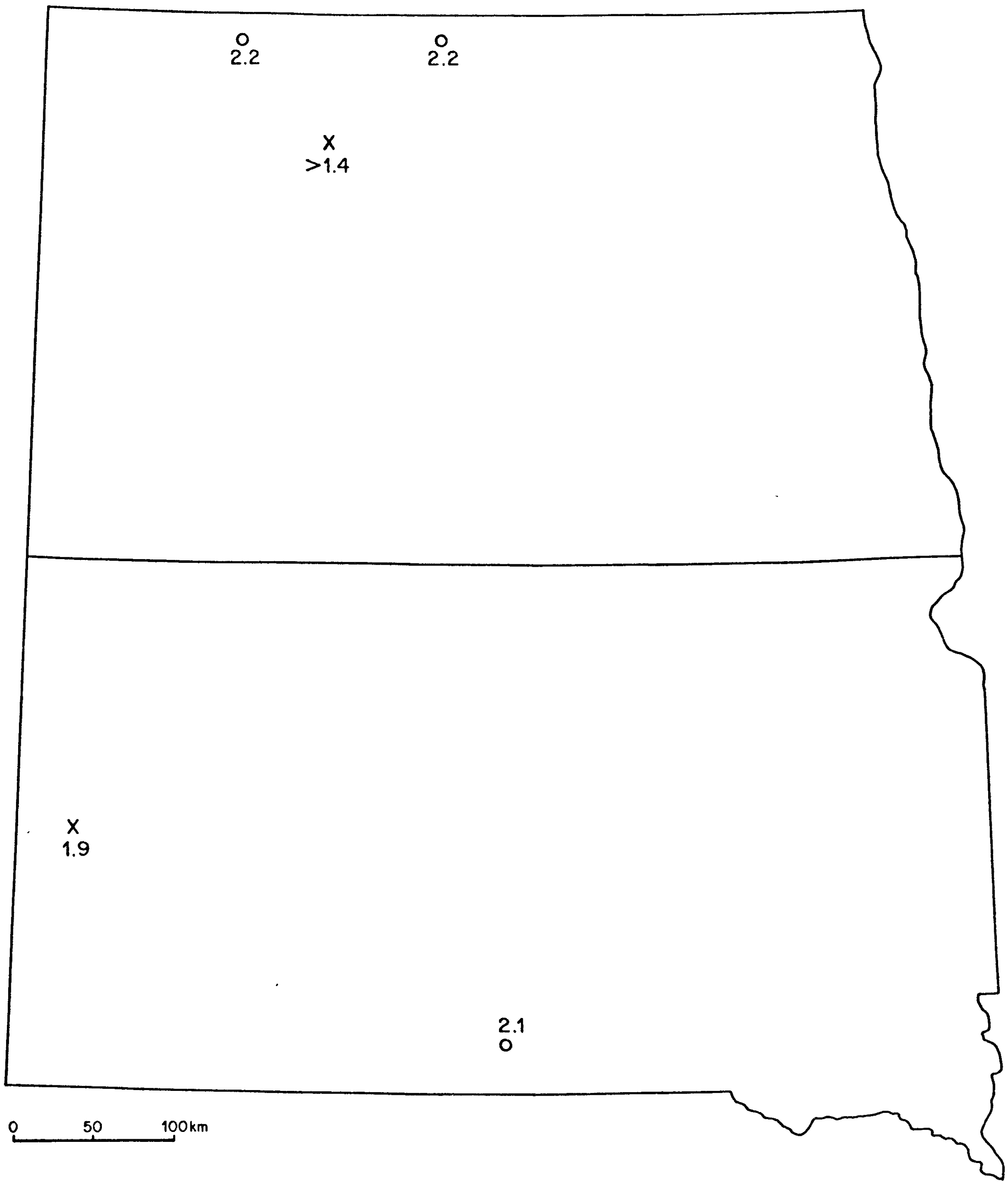

2.2
2.2
>1.4
1.9
2.1
0
50
100km

TABLE 8.2 HEAT FLOW DETERMINATIONS IN NORTH AND SOUTH DAKOTA (con't.)

WELL NAME	NORTH LATITUDE	WEST LONGITUDE	ELEVATION	HEAT FLOW
E.L.K. #1 NELSON, Roth	48° 56.1'	100° 49.6'	457	2.2±0.4
LEAD no.4 SHAFT *	44° 21.0'	103° 45.0'	-	1.84
LONE TREE *	48° 18.0'	101° 40.0'	-	1.4
YATES SHAFT *	44° 21.0'	103° 45.0'	1618	1.96

* Values obtained from Blackwell (1969)

Approximately one hundred basement samples scattered uniformly throughout North Dakota have been studied but only one of these samples was a basic rock type, in particular, a diabase from Oliver County (Muehlberger, et al., 1964). Similarly, Muehlberger and his coworkers have encountered only four basic rocks; two basalts, a gabbro, and a diabase, in the one hundred uniformly spaced wells that they have examined in South Dakota. By considering the correlation of heat flow with basement lithology that was noted for the Interior Lowlands, one would predict that the value of heat flow for the Northern Great Plains should be at least 1.3 to 1.4 HFU, but the occurrence of this higher than normal heat flux will be discussed more completely in the next chapter.

CHAPTER 9

REGIONAL CONSIDERATIONS

9.1 INTRODUCTION

In this chapter we summarize the data that have been described in detail in Chapters 4 through 8. We then attempt to explain the differences in heat flux by considering some reasonable models. Throughout the chapter, we will consider the available geophysical, geochemical and geological data in order to test the plausibility of our models.

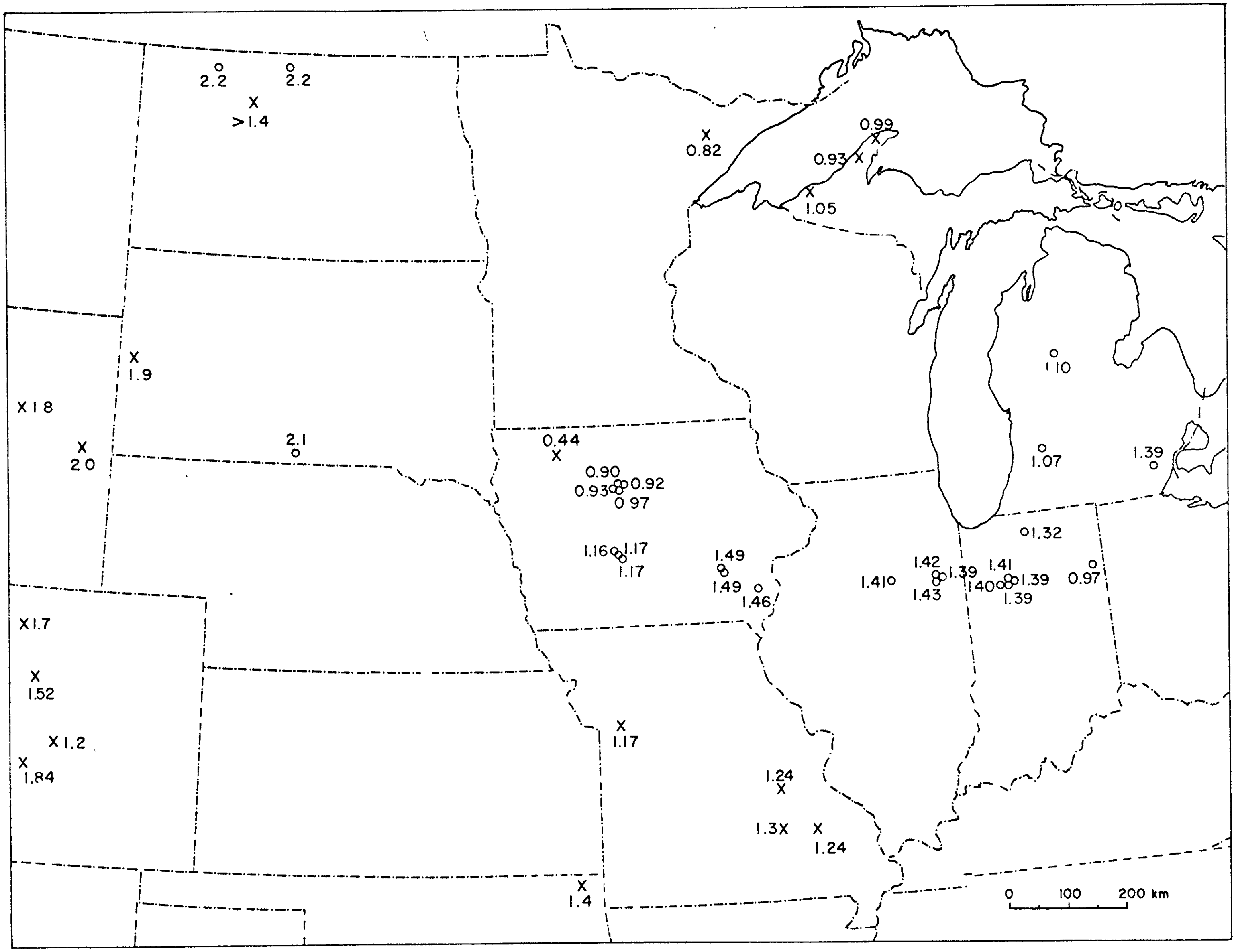
9.2 SUMMARY OF THE DATA

The area investigated in the present study is part of the physiographic province termed by King (1959) the Central Stable Region of North America. It is situated between the Appalachian and Rocky Mountains, is largely covered by a thin layer of sedimentary rocks, and has been subjected to only mild disturbances since Precambrian time.

The average of the twenty-six heat flow determinations in this area is 1.36 ± 0.34 HFU. This value can be compared with the average value of 1.49 ± 0.51 HFU for the "Interior Lowlands of North America" (Horai and Simmons, 1969). Horai and Simmons' average for the Interior Lowlands is based on twenty-six published values. The new determinations as well as the published measurements in North Central United States are plotted in Fig. 9.1.

The values obtained in this investigation range from 0.90 to 2.2 HFU. However, there are two distinct regions both on the basis of physiography and on the basis of heat flow. The Interior Lowlands is characterized by a regional flux of 1.4 HFU, whereas the regional value for the Northern Great Plains is about 2.0 HFU. The sedimentary section in both regions is essentially devoid of radiogenic elements; therefore, any heat sources must be located in the crust below the sediments. From their data on heat flow and heat production, Roy et al. (1968) have suggested that heat flow variations in the Central Stable Region may be expected to reflect changes of heat generation in the basement. Their conclusion has been confirmed in the present study. Local variations from the regional value in the Interior Lowlands can be attributed to the presence of mafic rocks in the basement complex. The attendant contrast in radiogenic elements as well as the thermal conductivity contrasts with the predominantly sialic basement can account for the low heat flow values. Gravity and magnetic data in addition to basement sample studies have indicated these differences in basement lithologies (see Chapters 5 and 6 for details).

Figure 9.1 Terrestrial heat flow in North Central United States. The circles indicate determinations made in this study while the X's refer to published values. All heat flow values are in units of HFU's.


2.2
2.2
X
>1.4
X
0.82
0.99
0.93 X
X
1.05
X
1.9
X 1.8
X
2.0
2.1
0.44
X
0.90
0.92
0.93
0.97
1.16
1.17
1.17
1.49
1.49
1.46
1.10
1.07
1.39
1.32
1.42
1.39
1.41
1.41
1.43
1.40
1.39
1.39
0.97
X 1.7
X
1.52
X 1.2
X
1.84
X
1.17
1.24
X
1.3 X
X
1.24
X
1.4
0 100 200 km

Lithologic data obtained from well samples reveal that the basement throughout the North Central United States is predominately granitic (Muehlberger et al., 1964). Seismic data (see Section 9.4) indicates that the crustal thickness is 50 km throughout both regions; therefore, the difference in heat flux cannot be explained by a thickening of the crust in the Northern Great Plains. Crustal structures determined from seismic data are essentially the same throughout both regions (Slichter, 1951; Steinhart and Meyer, 1961; McCamy and Meyer, 1964; Cohen, 1966; Green and Hales, 1968). Since the crust appears to be essentially homogeneous, heterogenity in the upper mantle must explain the difference in regional heat flux between the Interior Lowlands and the Northern Great Plains.

9.3 CALCULATION OF CRUSTAL TEMPERATURES

The equation of heat conduction with no transfer of material is

$$\nabla(K\nabla T) + A(x,y,z) = 0 \qquad (9.1)$$

where K is the thermal conductivity and A is the rate per unit volume of heat production. If the thermal conductivity is assumed to be constant, and since the curvature of the earth may be neglected at depths less than several hundred kilometers, the calculation of crustal temperatures may be treated as one-dimensional steady state heat flow. The temperature then depends only on depth z and a first integral of Eq. (9.1) is

$$K \frac{\partial T}{\partial z} = -\int_0^z A(z')\,dz' + Q \qquad (9.2)$$

where Q is the heat flow at the surface. Since the surface heat flow, Q, has been determined, with some assumptions about the distribution of heat sources and the thermal conductivity, one can calculate temperatures in the crust.

Birch et al., (1968), Roy et al., (1968), and Lachenbruch (1968) have recently described a linear relationship between heat flow (Q) and heat production (A) of the surface rock in plutons from many localities in the United States. The relationship has the form

$$Q = a + bA \qquad (9.3)$$

where a has the dimensions of heat flow and b has the dimension of depth. Roy et al., (1968) have defined several heat flow provinces based on this relationship of heat flow to basement radioactivity. Of the limited class of radioelement distributions that appear to be consistent with the linear relation between heat flow and heat production, the limiting cases are (1) constant heat production and (2) an exponential decrease in production with depth.

Both types of distributions have been investigated. Lachenbruch (1968) used a distribution of the type

$$A(z) = A \exp(-z/b) \qquad (9.4)$$

Based on the geochemical data of Lambert and Heier (1967), Hyndman et al., (1968) have suggested a constant crustal heat source distribution similar to that of Roy et al., (1968). Hyndman et al., (1968) explained different regional values of heat flow by variations in the thickness of the heat producing layer with the mantle contribution considered to be almost constant everywhere. However, Roy et al., (1968) suggest that the thickness of the heat producing surface layer varies little (7-11 km in the areas they discussed) while the different regional values arise from variations in heat flux from the lower crust and mantle.

In order to obtain crustal temperatures, we can take a second integral of Eq. (9.1) and obtain

$$T = T_0 + \frac{Qz}{K} - \frac{Az^2}{2K}, \qquad (9.5)$$

for the case of constant heat source distribution, or

$$T = T_0 + \frac{Qz}{K} - \frac{bAz}{K} + \frac{b^2A}{K}\left[1 - e^{-z/b}\right] \qquad (9.6)$$

for the case of an exponential heat source distribution. T_o is the surface temperature. The other parameters have been defined earlier in this section.

We will now consider four possible models using both types of heat source distributions for the two regions. In particular, we will use the following models:

(1) assume that the heat sources for both areas are concentrated in the upper 8 km of the crust, as Roy et al., (1968) have suggested is the case for the central and eastern United States;

(2) assume that the heat sources for both areas are concentrated in the upper 20 km of the crust which is the depth to the sialic-mafic interface determined from the seismic data (Steinhart and Meyer, 1961; McCamy and Meyer, 1964; Green and Hales, 1968; Hales et al., 1968).

(3) assume, the extreme case for a crust that is different beneath both areas, in particular,

the crustal layering and the heat source distribution are different for both areas but the mantle contribution to the heat flux is constant,

(4) and, finally, assume that the temperatures at the Mohorovicic discontinuity are the same for both regions.

The crustal thickness of 50 km in all models is based on the seismic data of Steinhart and Meyer (1961), McCamy and Meyer (1964), and Green and Hales (1968). For the constant heat source models, we consider that the crust consists of two layers. Further, for all of the models, we assume that the mean thermal conductivity is 6.0 mcal/cm-sec-^{o}C throughout the crust. Although a change of the thermal conductivity in our models affects the temperatures at all depths, the expected change is small because of the limited range of values of thermal conductivity for crustal rocks at high temperatures (Birch and Clark, 1940). One consequence of assuming constant conductivity is that the temperature-depth curves will be less convex towards the depth axis than they would be for temperature-dependent conductivity. The mean conductivity assumed for the lower layer is, if anything, high. Because the thermal conductivity decreases with temperature, at least over the range considered in the models, the temperatures estimated are minimum values. It is likely that the difference between the two regions would be somewhat larger if the variation of thermal conductivity with temperature was included.

The following are the conclusions that arise for each of the separate models.

(1) For model (1), if we assume values of heat production similar to those of Roy et al., (1968), that is, A=5.5 HGU and A=1.5 HGU, the temperatures at the base of the crust in the Northern Great Plains may be as much as 400 ^{o}C, or more, higher than the corresponding temperatures beneath the Interior Lowlands. Furthermore, the mantle contribution beneath the Northern Great Plains is at least 0.6 HFU higher than the corresponding contribution for the Interior Lowlands. The heat source distributions that were considered are essentially upper limits and if lower values are used the crustal temperatures are increased. The exponential distribution gives slightly lower temperatures throughout the crust, but the conclusions are similar to those for the constant heat source distribution.

(2) For model (2), if we use the same heat productivities are were used in model (1), but assume that the heat sources are concentrated in the 20 km thick layer, all of the crustal temperatures in our models are lowered by less than 100 °C, but more importantly, either (1) the heat production in the upper layer must be considerably less than normal for a sialic layer or (2) the heat production in the lower layer must be less than 0.01 HGU which is an order of magnitude less than the measured value for most basic or ultrabasic rocks (Adams et al., 1959; Heier, 1963; Clark, 1966; Lambert and Heier, 1967).

(3) For model (3), even if reasonable limits for the differences in heat production and the layer thicknesses are used, the temperature difference between the two areas remains greater than 200 °C.

(4) For model (4), if we assume that the temperature at the base of the crust is the same for both regions, the crust in the Northern Great Plains must have an average heat productivity of 3.5 HGU. Such a value is incompatible with estimates of

the composition of the crust based on seismic and geochemical data.

In summary, from the available data, a model similar to (1) or (3) appears to be the most plausible one. Even if the layer thickness and the values of heat production are different for the two regions, the greatest lower bound to the temperature difference between the two areas remains greater than 200 °C. Therefore, it is impossible to obtain a self-consistent interpretation of the differences in heat flux without requiring lateral temperature differences in the upper mantle.

9.4 P_n VELOCITIES AND STATION RESIDUALS

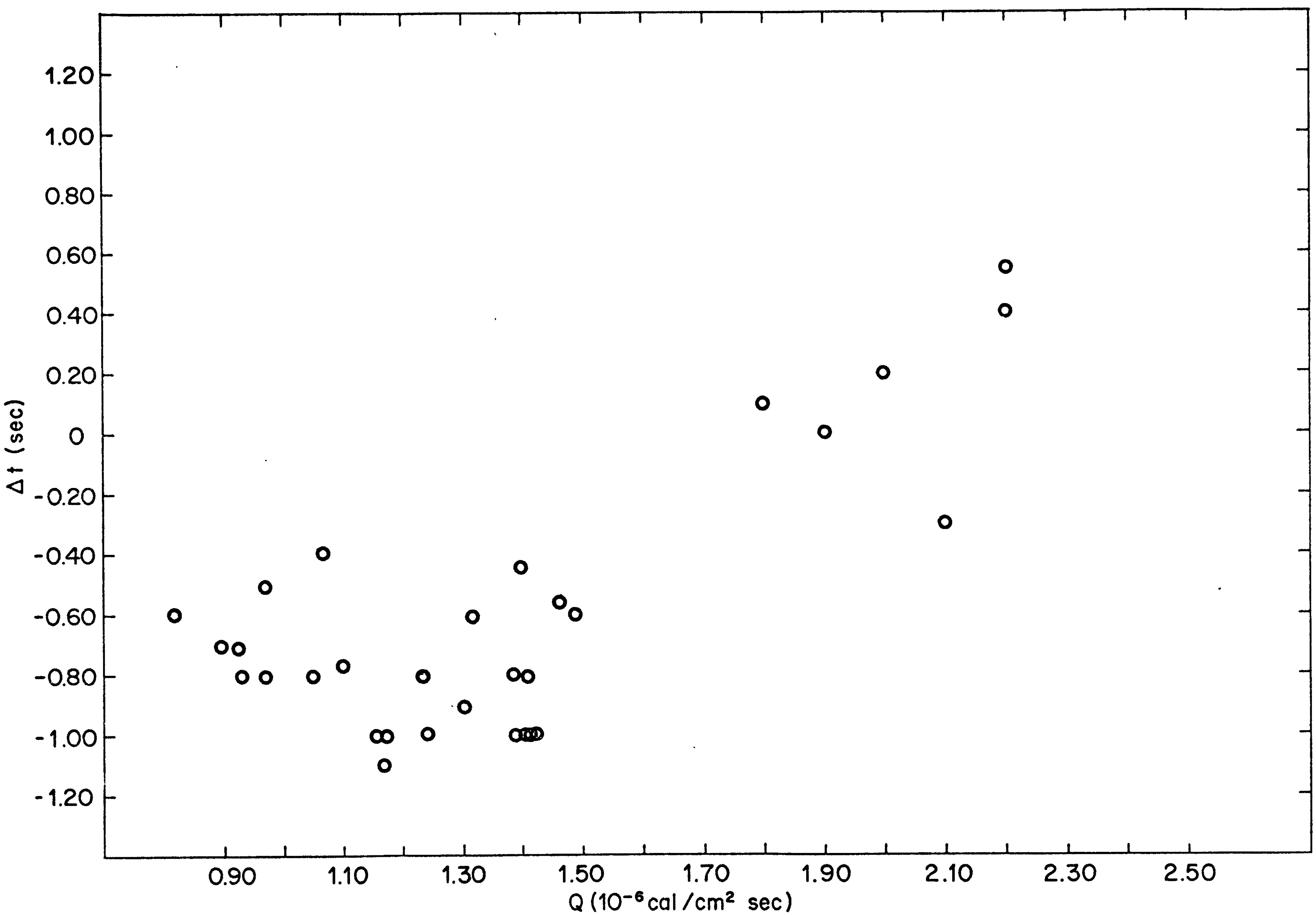
Seismic studies (Slichter, 1951; Steinhart and Meyer, 1961; McCamy and Meyer, 1964; McEvilly, 1964; Cohen, 1966; James and Steinhart, 1966; Green and Hales, 1968) indicate that there is little difference in crustal thickness between the Interior Lowlands and the Northern Great Plains. In particular, the crustal thickness is approximately 45 to 55 km. The difference in heat flow, therefore, cannot be explained on the basis of a thicker crust in the Northern Great Plains.

Hales and Doyle (1967) pointed out that the heat flow values in southeastern Australia are high (LeMarne and Sass, 1962; Sass and LeMarne, 1963; Jaeger and Sass, 1963; Sass, 1964; Sass et al., 1967; Howard and Sass, 1964) and the station anomalies are positive, whereas in Queensland, where the station anomalies are negative, the heat flow is normal (Hyndman, 1967). Similarly, large negative station anomalies (Cleary, 1967) are associated with normal to low heat flow values in southwestern Australia (Howard and Sass, 1964; Sass, 1964). This same correlation has been observed in the western United States (Roy et al., 1968; Decker, 1969; Blackwell, 1969).

Undoubtedly, some parts of the travel time deviations arise from differences of composition in the crust, but the study of Hales and Doyle (1967) strongly suggests that the major part of the deviations can be ascribed to differences in temperature conditions in the upper mantle. In particular, the station anomalies originate largely in the upper mantle, so it would appear that the high heat flows are associated with higher temperatures in the upper mantle.

The relative travel time anomalies for both compressional and shear waves (Cleary and Hales, 1966; Hales and Doyle, 1967; Doyle and Hales, 1967; Herrin, 1967) for the North Central United States indicate a correlation between the station residuals and the heat

Figure 9.2 Correlation of P-wave delay time, Δt, and terrestrial heat flow, Q. Δt is in seconds and Q has the units HFU.


1.20
1.00
0.80
0.60
0.40
0.20
0
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
Δt (sec)
0.90
1.10
1.30
1.50
1.70
1.90
2.10
2.30
2.50
Q (10⁻⁶ cal/cm² sec)

flow. Horai and Simmons (1968) have suggested that the major cause of seismic travel time anomalies is the differences in temperature associated with anomalous heat flow. Travel time delays, were obtained for the location of the heat flow stations by interpolation of the station residuals of Cleary and Hales (1966). Figure 9.2 shows a correlation similar to that indicated in Figure 9 of Horai and Simmons (1968). In particular, the lower heat flow values, 1.5 HFU or less, are associated with negative station anomalies whereas the high values, 1.8 HFU or more, are related to positive station residuals (compare Fig. 9.1 with 9.3 and 9.4). The regional difference in heat flow, therefore, may be attributed to differences in the temperature of the upper mantle.

A similar correlation between P_n velocity and heat flow has been observed. The P_n phase which is used to estimate P-wave velocity in the uppermost mantle is observed to be slower under areas of high heat flow. From a consideration of the difference in apparent P_n velocities for the Interior Lowlands and the Northern Great Plains, a simple model which is consistent with the observed difference in regional heat flux can be constructed. The difference in P_n velocity (see Fig.

Figure 9.3 Relative P-wave delay times in North Central United States. Contours represent mean seismic delay in seconds with allowance made for azimuthal dependence (after Herrin, 1969).

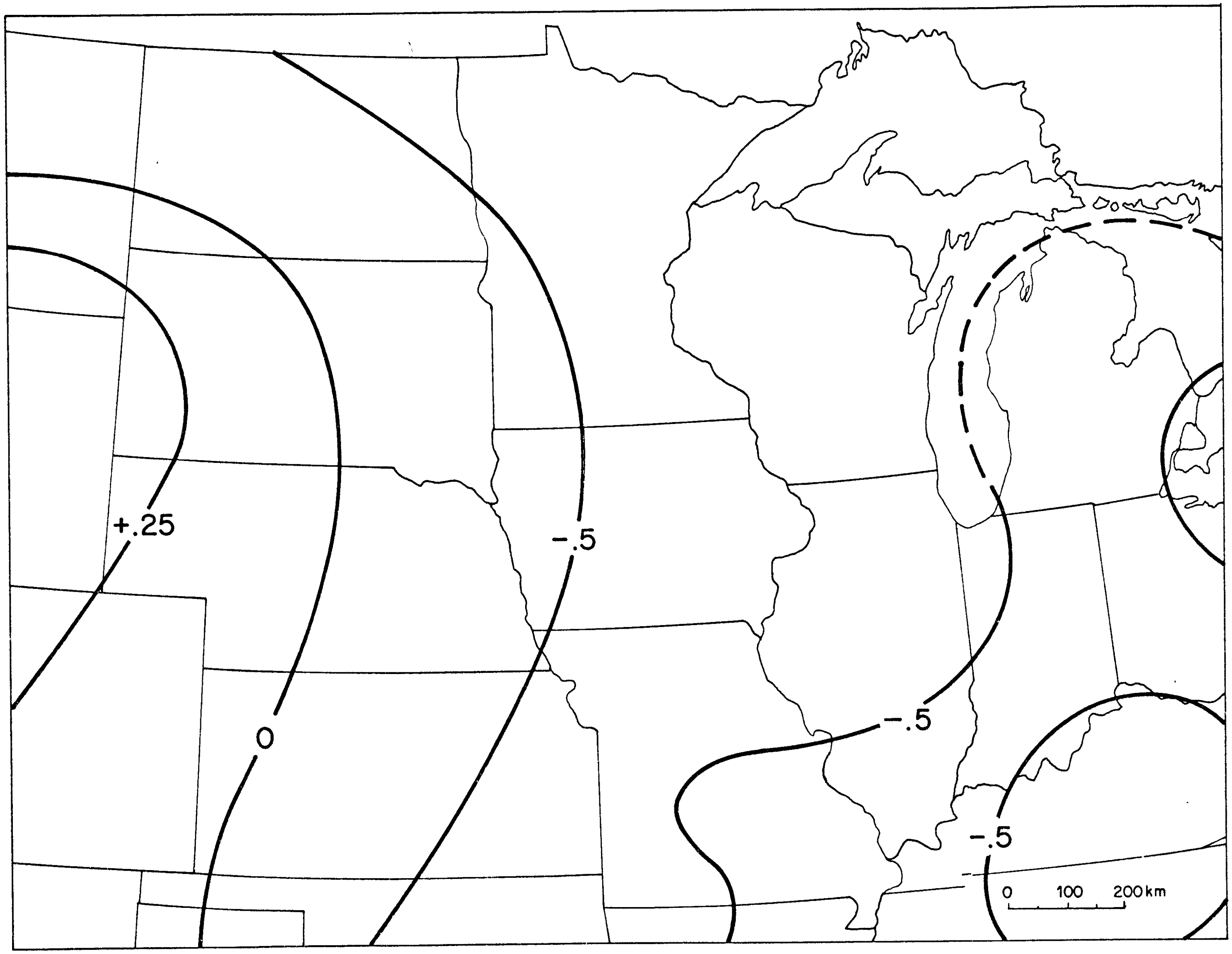
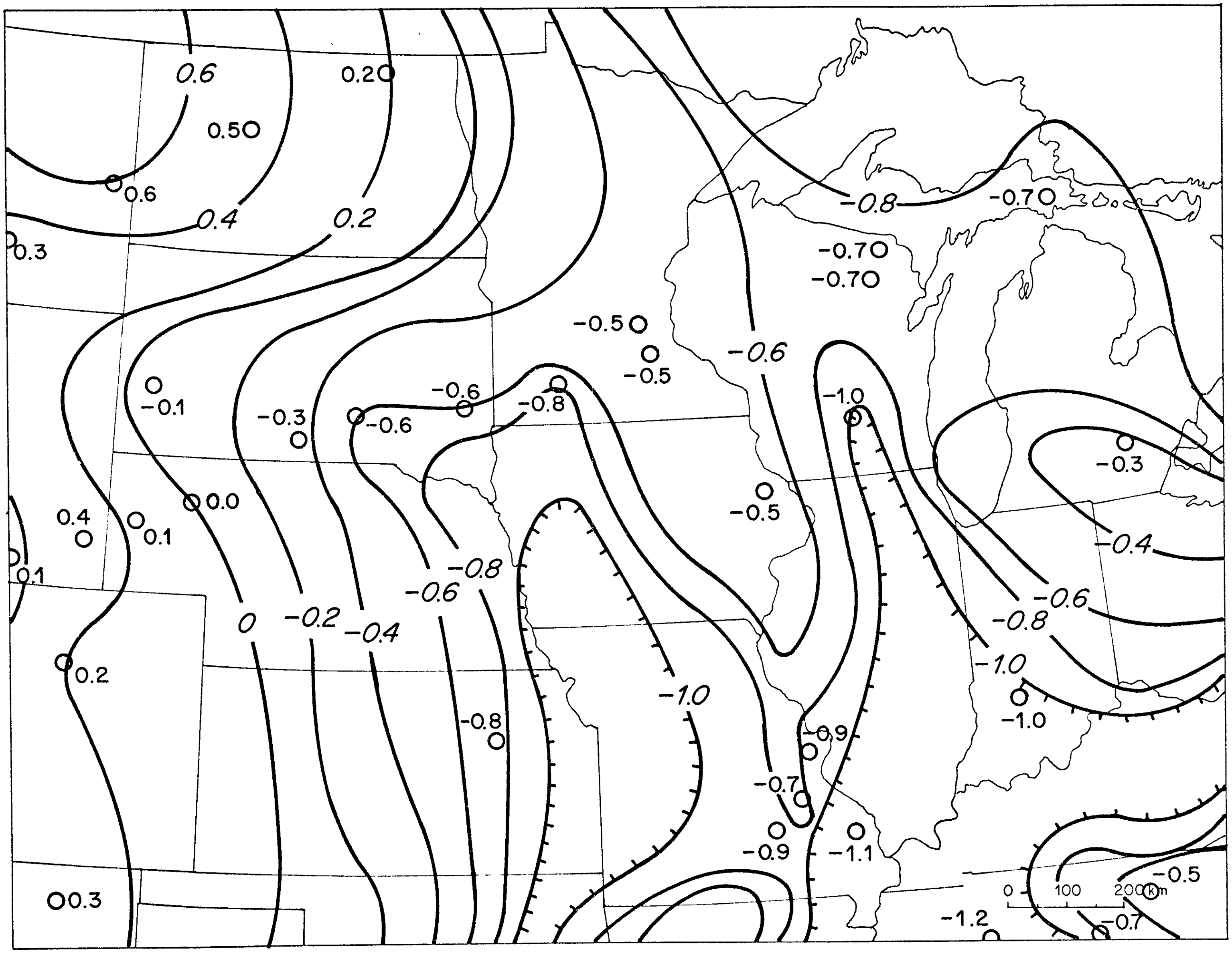

+.25
0
-.5
-.5
-.5
0 100 200 km

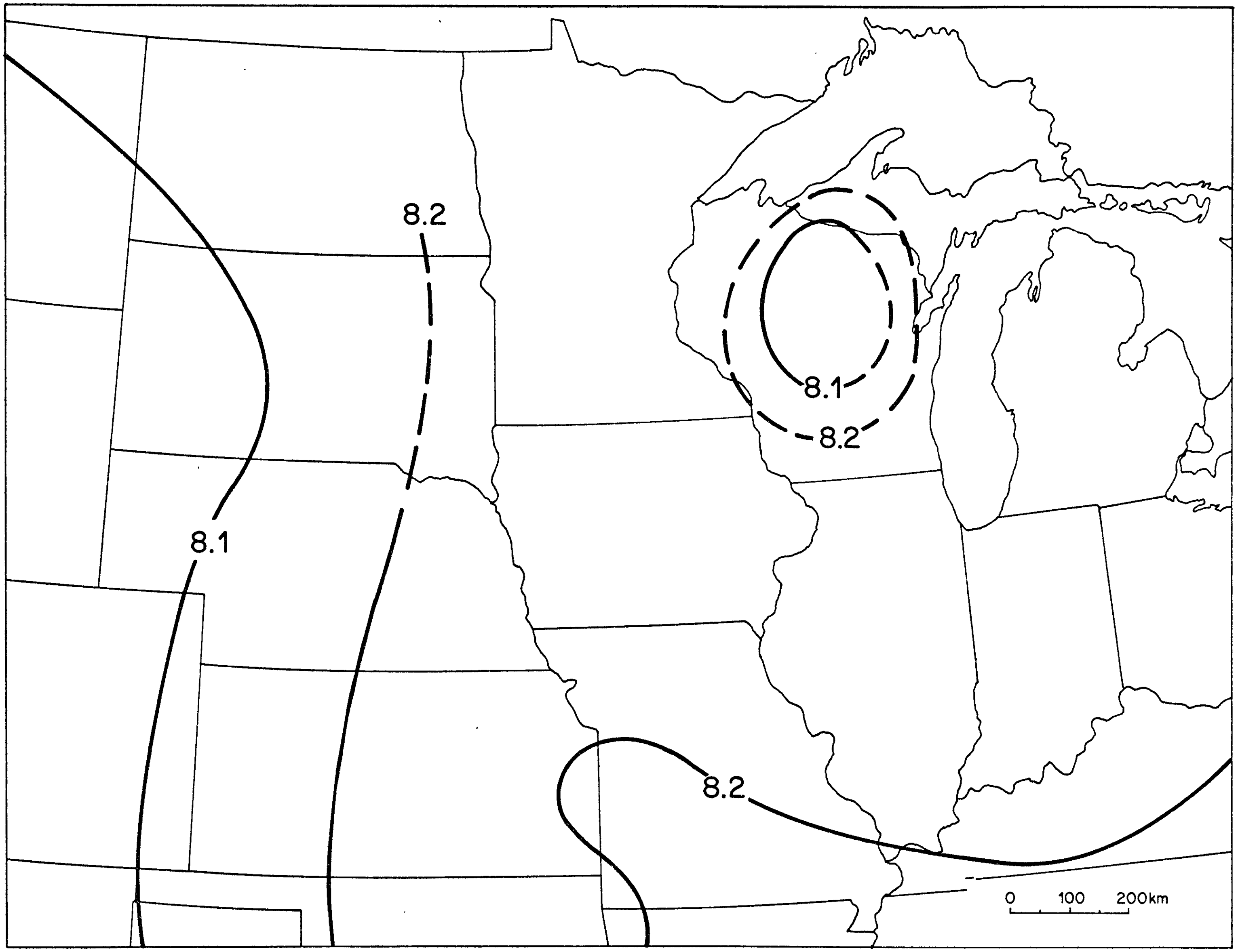
Figure 9.4 Relative travel-time anomalies for compressional waves contoured on a 0.2 second interval, data from Cleary and Hales (1966) with contours similar to Archambeau et al., (1969).


0 100 200 Km

9.5) is approximately 0.12 to 0.15 km/sec (Herrin and Taggart, 1962; Herrin, 1969) while the crustal thickness for both regions is about 50 km. If we assume that the upper mantle is composed of a mineral assemblage characterized by olivine, pyroxene, garnet, and spinel, then the rate of change of the compressional velocity with respect to temperature is approximately -5×10^{-4} km/sec ^{o}C (Hughes and Nishitake, 1963; Anderson et al., 1968; Kumazaiva and Anderson, 1969). From these parameters, there appears to be a temperature difference of about 250 to 300 ^{o}C at the Mohorovicic discontinuity between the two regions.

On the other hand, the difference in the temperature at the Mohorovicic discontinuity calculated from the thermal models can be interpreted in terms of the stable mineral assemblages and their corresponding seismic velocities. Comparison of the temperatures calculated in the several models mentioned above with the "equilibrium" curve for basalt-eclogite (Ringwood and Green, 1966; Fig. 1) indicates that the stable mineral assemblage for the Interior Lowlands is eclogite whereas garnet granulite is the stable assemblage for the Northern Great Plains. Eclogites have seismic P velocities between 8.2 and 8.6

Figure 9.5 Estimated P_n velocity in the North Central United States. Velocities are in km/sec. (after, Herrin, 1969).



8.2
8.1
8.1
8.2
8.2
0 100 200km

km/sec whereas garnet granulites are characterized by a wide range of velocities between 7 and 8 km/sec. Thus, the differences in rock type are essentially in agreement with the observed P_n velocities. From a consideration of the P_n velocity data, we cannot distinguish between temperature differences and compositional differences in the upper mantle. However, the relative travel time anomalies for body waves indicate that the observed differences in regional heat flux can be attributed to differences in the temperatures in the upper mantle.

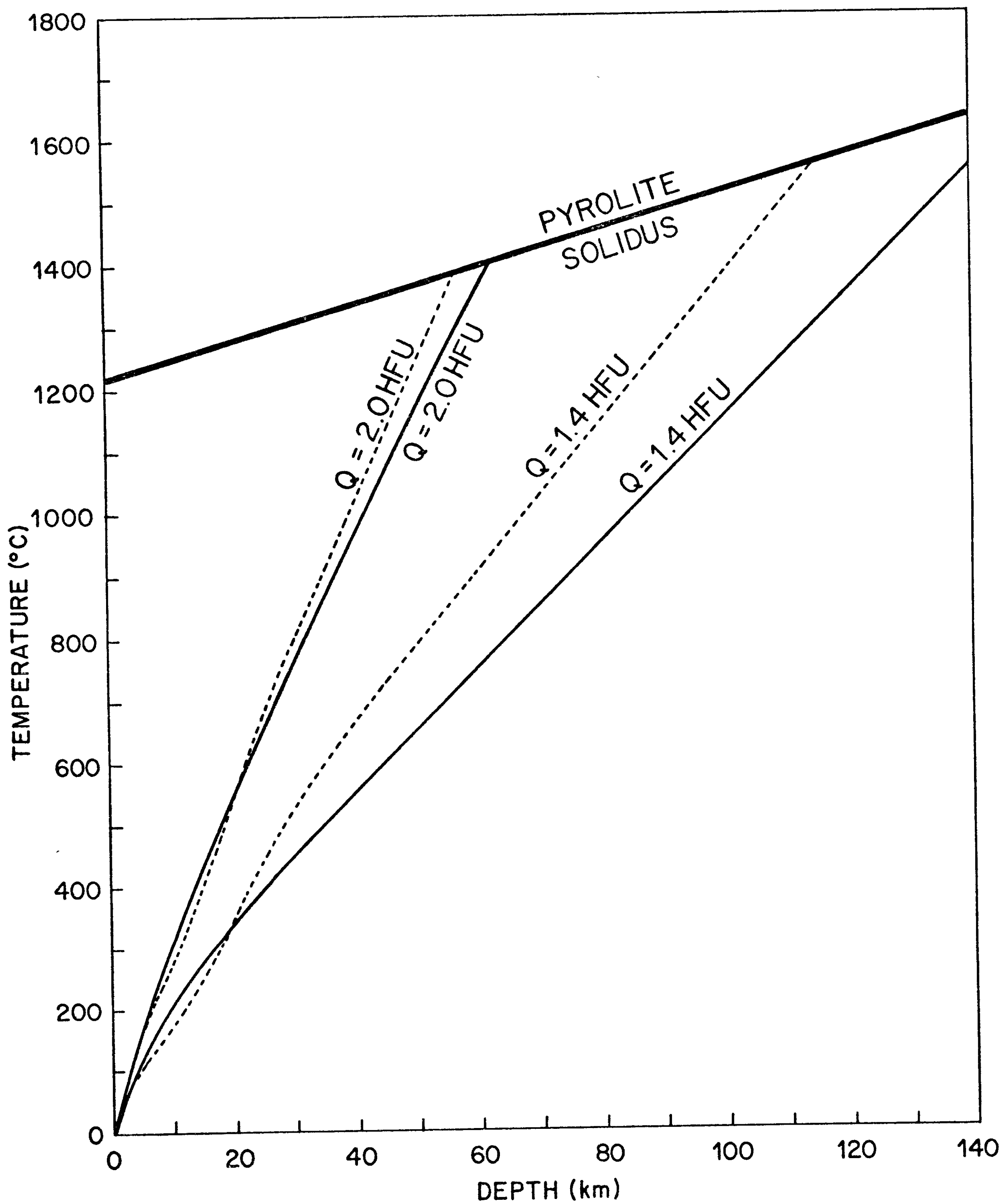
9.5 OTHER DATA

Furthermore, magnetotelluric investigations of Renick (1969) indicate that the temperatures at the Mohorovicic discontinuity obtained form the above models are not unreasonable. In southeastern Montana where the crustal thickness is 50 to 55 km (Steinhart and Meyer, 1961), his modeled resistivities imply a temperature of 1000 to 1300 $^{\circ}$C.

From a study of the regional differences in seismic travel times at teleseismic distances and the corresponding P_n anomalies, Hales et al., (1968) have suggested that the variation in the anomalies between the western and eastern United States can be explained satisfactorily by a change in the thickness of the upper mantle low-velocity layer. In particular, there is a marked low-velocity layer in the west, which either does not exist or is vestigial in the central and eastern United States. (see Fig. 11 in Hales et al., 1968). By using travel-time curves for P waves in the Central United States, Green and Hales (1968) also suggested that the low-velocity layer thins out between 106°W and 98°W. In other words, there is no direct evidence for an upper mantle low-velocity layer in the central United States (Hales et al., 1968).

Because of the high temperatures in the Northern Great Plains, the solidus of pyrolite, a possible mantle material, is probably reached at shallow depths in the mantle. If the modeled temperature-depth curve (see Fig. 9.6) for the Northern Great Plains is extended downward it intersects the solidus for dry pyrolite (Clark and Ringwood, 1964) at 60 to 70 km; furthermore, with a small amount of water partial melting would occur at still shallower depths. The presence of a partially molten zone at shallow depths in the upper mantle is consistent with the seismic data in the Northern Great Plains (Hales et al., 1968; B. Julian, personal com-

Figure 9.6 Temperature depth curves for the models indicated in Figure 9.2. Dashed lines are for constant heat source distribution. Dot-dash lines are for exponential heat heat source distribution.


PYROLITE
SOLIDUS
Q = 2.0 HFU
Q = 2.0 HFU
Q = 1.4 HFU
Q = 1.4 HFU
TEMPERATURE (°C)
DEPTH (km)
0
200
400
600
800
1000
1200
1400
1600
1800
0
20
40
60
80
100
120
140

munication, 1970). The temperature-depth curve for the Interior Lowlands does not intersect the solidus for dry pyrolite above a depth of 100 km. Even if there is no partial melting, there is a considerable temperature difference between the two regions, and thus there would be a small temperature-induced difference in the velocity structure.

CHAPTER 10

CONCLUSIONS

(a) Many boreholes are available from the oil and gas industry.

(b) Continuous temperature logging provides the opportunity to obtain very precise geothermal gradients over short intervals of depth.

(c) Continuous temperature-depth curves provide useful detail that cannot be obtained from discrete logs.

(d) With continuous temperature logs, one can obtain very precise values of the geothermal gradient over short intervals, measure the thermal conductivity on a very few samples for these selected intervals, and obtain precise values for the heat flow.

(e) The thermal variation of conductivity is relatively important, whereas, the pressure variation is relatively unimportant in the determination of terrestrial heat flow.

(f) Complete saturation of specimens before measuring the thermal conductivity is absolutely necessary.

(g) Closely spaced boreholes provide an excellent check on the reliability of each particular heat flow value.

(h) Closely spaced data provide an opportunity to obtain reasonable estimates of the regional heat flux.

(i) Although situated in the stable continental interior, two physiographic regions have different values of heat flow.

(j) A plausible interpretation of the difference in the surface heat flow data is that the upper mantle is heterogeneous beneath the stable continental interior of the United States.

(k) Temperatures at the base of the crust beneath the Northern Great Plains inferred from magnetotelluric data agree well with those estimated from the heat flow data.

(l) The surface heat flow correlates well with basement lithology in the central stable interior.

(m) There is no direct correlation between surface heat flow data and the gravity and magnetic data for the area studied.

(n) Heat flow correlates with P_n velocities and seismic travel time residuals.

(o) Finally, twenty-six new heat flow values for the interior of the United States have been determined.

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APPENDIX I

TEMPERATURE MEASUREMENTS

In this appendix, DEPTH refers to the depth in meters below ground level and TEMPERATURE is in degrees Centigrade.

CONTENTS

Condit #1, Crescent City, Illinois

Temperatures Measured: 7/13/64

Depth	Temperature	Depth	Temperature
50	11.51	215	14.16
55	11.58	220	14.24
60	11.65	225	14.32
65	11.72	230	14.44
70	11.79	235	14.59
75	11.87	240	14.74
80	11.94	245	14.90
85	12.09	250	15.00
90	12.16	255	15.11
95	12.24	260	15.26
100	12.33	265	15.40
105	12.37	270	15.60
110	12.43	275	15.80
115	12.52	280	16.04
120	12.61	285	16.21
125	12.72	290	16.30
130	12.82	295	16.44
135	12.92	300	16.53
140	13.00	305	16.69
145	13.08	310	16.73
150	13.15	315	16.79
155	13.36	320	16.86
160	13.40	325	16.92
165	13.46	330	16.99
170	13.53	335	17.05
175	13.60	340	17.13
180	13.68	345	17.22
185	13.74	350	17.29
190	13.81	355	17.38
195	13.88	360	17.46
200	13.94	365	17.54
205	14.01	370	17.61
210	14.09	375	17.70

Depth	Temperature	Depth	Temperature
380	17.79	580	20.25
385	17.86	585	20.32
390	17.94	590	20.38
395	18.00	595	20.45
400	18.06	600	20.51
405	18.15	605	20.57
410	18.23	610	20.68
415	18.29	615	20.72
420	18.35	620	20.77
425	18.40	625	20.81
430	18.45	630	20.87
435	18.49	635	20.92
440	18.54	640	20.98
445	18.59	645	21.05
450	18.62	650	21.10
455	18.67	655	21.16
460	18.72	660	21.24
465	18.77	665	21.29
470	18.81	670	21.36
475	18.86	675	21.42
480	18.93	680	21.47
485	19.00	685	21.53
490	19.06	690	21.59
495	19.12	695	21.64
500	19.20	700	21.69
505	19.27	705	21.75
510	19.32	710	21.80
515	19.40	715	21.86
520	19.46	720	21.92
525	19.52	725	21.97
530	19.57	730	22.02
535	19.64	735	22.07
540	19.70	740	22.13
545	19.76	745	22.17
550	19.82	750	22.24
555	19.89	755	22.31
560	19.95	760	22.38
565	20.06	765	22.45
570	20.12	770	22.51
575	20.19	775	22.57

Depth	Temperature	Depth	Temperature
780	22.62	925	25.88
785	22.68	930	26.07
790	22.74	935	26.29
795	22.81	940	26.51
800	22.86	945	26.68
805	22.91	950	26.88
810	22.98	955	27.02
815	23.01	960	27.19
820	23.07	965	27.37
825	23.13	970	27.59
830	23.18	975	27.91
835	23.23	980	28.24
840	23.31	985	28.60
845	23.35	990	28.93
850	23.42	995	28.24
855	23.48	1000	28.58
860	23.58	1005	28.93
865	23.73	1010	29.35
870	23.88	1015	29.69
875	24.10	1020	29.98
880	24.32	1025	30.29
885	24.52	1030	30.58
890	24.69	1035	30.82
895	24.84	1040	31.01
900	25.00	1045	31.15
905	25.14	1050	31.23
910	25.31	1055	31.31
915	25.50	1060	31.40
920	25.72	1065	31.76

Musser #1, Ancona, Illinois

Temperatures Measured: 7/2/64

Depth	Temperature	Depth	Temperature
50	12.15	215	14.74
55	12.25	220	14.80
60	12.44	225	14.84
65	12.53	230	14.94
70	12.77	235	14.96
75	12.90	240	15.07
80	13.00	245	15.13
85	13.09	250	15.20
90	13.17	255	15.30
95	13.25	260	15.33
100	13.34	265	15.44
105	13.40	270	15.51
110	13.48	275	15.59
115	13.55	280	15.64
120	13.65	285	15.68
125	13.72	290	15.76
130	13.81	295	15.84
135	13.90	300	15.91
140	13.97	305	16.06
145	14.04	310	16.08
150	14.10	315	16.14
155	14.16	320	16.20
160	14.20	325	16.26
165	14.22	330	16.34
170	14.27	335	16.40
175	14.30	340	16.45
180	14.35	345	16.55
185	14.42	350	16.61
190	14.45	355	16.70
195	14.52	360	16.78
200	14.55	365	16.85
205	14.63	370	16.91
210	14.69	375	16.98

Depth	Temperature	Depth	Temperature
380	17.03	575	19.39
385	17.09	580	19.49
390	17.16	585	19.59
395	17.23	590	19.73
400	17.27	595	19.88
405	17.35	600	19.98
410	17.42	605	20.23
415	17.47	610	20.42
420	17.52	615	20.68
425	17.59	620	20.81
430	17.66	625	20.96
435	17.71	630	21.13
440	17.78	635	21.30
445	17.83	640	21.50
450	17.90	645	21.70
455	17.97	650	21.89
460	18.04	655	22.06
465	18.10	660	22.25
470	18.15	665	22.53
475	18.22	670	22.83
480	18.28	675	23.15
485	18.35	680	23.48
490	18.43	685	23.80
495	18.49	690	24.09
500	18.54	695	24.28
505	18.59	700	24.50
510	18.66	705	24.65
515	18.74	710	24.75
520	18.80	715	24.81
525	18.86	720	24.88
530	18.91	725	24.93
535	18.98	730	24.96
540	19.02	735	25.00
545	19.08	740	25.09
550	19.13	745	25.16
555	19.18	750	25.23
560	19.24	755	25.30
565	19.28	760	25.38
570	19.34	765	25.48

Taden #1, Crescent City, Illinois

Temperatures Measured: 7/14/64

Depth	Temperature	Depth	Temperature
50	12.03	215	15.15
55	12.09	220	15.29
60	12.15	225	15.47
65	12.20	230	15.69
70	12.27	235	15.90
75	12.31	240	16.07
80	12.38	245	16.25
85	12.43	250	16.44
90	12.49	255	16.60
95	12.59	260	16.72
100	12.67	265	16.80
105	12.77	270	16.89
110	12.90	275	16.97
115	12.99	280	17.03
120	13.07	285	17.12
125	13.19	290	17.18
130	13.27	295	17.26
135	13.33	300	17.35
140	13.40	305	17.49
145	13.46	310	17.54
150	13.52	315	17.60
155	13.63	320	17.67
160	13.71	325	17.76
165	13.78	330	17.83
170	13.85	335	17.90
175	13.91	340	17.97
180	13.99	345	18.06
185	14.07	350	18.15
190	14.21	355	18.21
195	14.43	360	18.27
200	14.63	365	18.35
205	14.86	370	18.42
210	15.01	375	18.49

Depth	Temperature	Depth	Temperature
380	18.57	580	20.94
385	18.61	585	20.99
390	18.66	590	21.05
395	18.71	595	21.11
400	18.76	600	21.17
405	18.79	605	21.22
410	18.83	610	21.32
415	18.88	615	21.35
420	18.93	620	21.40
425	18.98	625	21.47
430	19.03	630	21.52
435	19.10	635	21.59
440	19.17	640	21.65
445	19.22	645	21.71
450	19.30	650	21.77
455	19.36	655	21.82
460	19.46	660	21.87
465	19.50	665	21.93
470	19.55	670	21.99
475	19.60	675	22.04
480	19.66	680	22.09
485	19.71	685	22.15
490	19.79	690	22.20
495	19.84	695	22.25
500	19.91	700	22.31
505	19.98	705	22.35
510	20.11	710	22.41
515	20.17	715	22.46
520	20.21	720	22.52
525	20.29	725	22.60
530	20.33	730	22.66
535	20.39	735	22.74
540	20.46	740	22.82
545	20.52	745	22.87
550	20.58	750	22.94
555	20.63	755	23.00
560	20.69	760	23.06
565	20.77	765	23.13
570	20.84	770	23.19
575	20.89	775	23.23

Depth	Temperature
780	23.28
785	23.34
790	23.39
795	23.46
800	23.51
805	23.58
810	23.62
815	23.67
820	23.73
825	23.84
830	23.97
835	24.19
840	24.40
845	24.59
850	24.79
855	24.93
860	25.09
865	25.24
870	25.39
875	25.57
880	25.75
885	25.95
890	26.15
895	26.36
900	26.58
905	26.80
910	26.97

Depth	Temperature
915	27.17
920	27.35
925	27.58
930	27.85
935	28.17
940	28.49
945	28.83
950	29.18
955	29.51
960	29.86
965	30.22
970	30.56
975	30.86
980	31.13
985	31.43
990	31.65
995	31.84
1000	31.98
1005	32.09
1010	32.17
1015	32.27
1020	32.33
1025	32.39
1030	32.43
1035	32.49
1040	32.50

Wessel #1, Crescent City, Illinois

Temperatures Measured: 7/13/64

Depth	Temperature	Depth	Temperature
50	12.08	235	15.57
55	12.13	240	15.75
60	12.18	245	15.97
65	12.27	250	16.18
70	12.29	255	16.37
75	12.34	260	16.60
80	12.40	265	16.72
85	12.48	270	16.84
90	12.55	275	16.93
95	12.61	280	17.01
100	12.68	285	17.10
105	12.75	290	17.18
110	12.82	295	17.26
115	12.90	300	17.32
120	12.98	305	17.48
125	13.06	310	17.52
130	13.15	315	17.58
135	13.25	320	17.66
140	13.34	325	17.72
145	13.43	330	17.81
150	13.51	335	17.88
155	13.63	340	17.96
160	13.71	345	18.03
165	13.77	350	18.11
170	13.85	355	18.20
175	13.91	360	18.29
180	13.99	365	18.35
185	14.06	370	18.43
190	14.14	375	18.49
195	14.23	380	18.58
200	14.33	385	18.66
205	14.50	390	18.72
210	14.70	395	18.78
215	14.90	400	18.82
220	15.11	405	18.88
225	15.23	410	18.92
230	15.39	415	18.97

Leuenberger Well, Monroeville, Indiana

Temperatures Measured: 9/4/64

Depth	Temperature	Depth	Temperature
50	14.55	235	16.56
55	14.57	240	16.65
60	14.60	245	16.76
65	14.63	250	16.84
70	14.65	255	17.00
75	14.67	260	17.15
80	14.71	265	17.30
85	14.74	270	17.45
90	14.75	275	17.60
95	14.78	280	17.75
100	14.81	285	17.94
105	14.83	290	18.05
110	14.85	295	18.27
115	14.88	300	18.52
120	14.92	305	18.74
125	14.96	310	18.96
130	15.00	315	19.16
135	15.04	320	19.39
140	15.09	325	19.59
145	15.13	330	19.82
150	15.16	335	19.98
155	15.21	340	20.25
160	15.26	345	20.47
165	15.30	350	20.74
170	15.34	355	20.92
175	15.38	360	21.15
180	15.43	365	21.34
185	15.47	370	21.62
190	15.55	375	21.79
195	15.65	380	21.97
200	15.76	385	22.10
205	15.86	390	22.40
210	15.94	395	22.66
215	16.10	400	22.88
220	16.21	405	23.10
225	16.31	410	23.33
230	16.44	415	23.56
		420	23.75

L W -25-1, Linkville, Indiana

Temperatures Measured: 9/1/64

Depth	Temperature	Depth	Temperature
50	14.53	100	15.77
55	14.58	105	15.82
60	14.61	110	15.89
65	14.75	115	15.92
70	14.88	120	16.00
75	15.03	125	16.06
80	15.20	130	16.11
85	15.35	135	16.17
90	15.55	140	16.21
95	15.67	145	16.27

L W -25-2, Linkville, Indiana

Temperatures Measured: 8/29/64

Depth	Temperature	Depth	Temperature
50	14.55	95	15.71
55	14.63	100	15.82
60	14.67	105	15.88
65	14.76	110	15.93
70	14.88	115	16.00
75	15.02	120	16.05
80	15.20	125	16.12
85	15.37	130	16.18
90	15.55	135	16.23
		140	16.30

L W -41, Linkville, Indiana

Temperatures Measured: 8/25/64

Depth	Temperature	Depth	Temperature
50	14.73	100	16.10
55	14.80	105	16.27
60	14.90	110	16.40
65	15.02	115	16.51
70	15.14	120	16.57
75	15.27	125	16.63
80	15.45	130	16.71
85	15.64	135	16.78
90	15.72	140	16.83
95	15.95	145	16.91

L W -57-1, Linkville, Indiana

Temperatures Measured: 9/2/64

Depth	Temperature	Depth	Temperature
50	14.51	100	15.88
55	14.65	105	16.05
60	14.78	110	16.17
65	14.85	115	16.26
70	14.97	120	16.33
75	15.10	125	16.38
80	15.23	130	16.44
85	15.37	135	16.52
90	15.53	140	16.58
95	15.71	145	16.63
		150	16.71

L W -57-2, Linkville, Indiana

Temperatures Measured: 8/30/64

Depth	Temperature	Depth	Temperature
50	14.58	100	15.84
55	14.64	105	16.02
60	14.70	110	16.12
65	14.82	115	16.22
70	14.92	120	16.27
75	15.07	125	16.33
80	15.20	130	16.41
85	15.32	135	16.47
90	15.50	140	16.54
95	15.67	145	16.60

L W -62, Linkville, Indiana

Temperatures Measured: 8/26/64

Depth	Temperature	Depth	Temperature
50	14.58	100	16.05
55	14.66	105	16.22
60	14.78	110	16.35
65	14.92	115	16.44
70	15.05	120	16.50
75	15.18	125	16.55
80	15.33	130	16.62
85	15.48	135	16.68
90	15.69	140	16.75
95	15.87	145	16.80

L W -65-1, Linkville, Indiana

Temperatures Measured: 9/1/64

Depth	Temperature	Depth	Temperature
50	14.57	100	16.13
55	14.74	105	16.29
60	14.87	110	16.40
65	14.97	115	16.47
70	15.12	120	16.53
75	15.27	125	16.59
80	15.42	130	16.65
85	15.52	135	16.72
90	15.78	140	16.78
95	15.92	145	16.83

L W -65-2, Linkville, Indiana

Temperatures Measured: 8/28/64

Depth	Temperature	Depth	Temperature
50	14.75	100	16.18
55	14.80	105	16.37
60	14.87	110	16.49
65	15.03	115	16.55
70	15.17	120	16.61
75	15.35	125	16.65
80	15.53	130	16.73
85	15.62	135	16.81
90	15.83	140	16.87
95	16.02	145	16.93

L W -70, Linkville, Indiana

Temperatures Measured: 8/24/64

Depth	Temperature	Depth	Temperature
65	14.88	105	16.02
70	15.00	110	16.07
75	15.13	115	16.13
80	15.32	120	16.19
85	15.47	125	16.25
90	15.65	130	16.32
95	15.82	135	16.37
100	15.93	140	16.41
		145	16.48

L W -77, Linkville, Indiana

Temperatures Measured: 8/25/64

Depth	Temperature	Depth	Temperature
50	14.72	100	15.57
55	14.75	105	15.63
60	14.80	110	15.69
65	14.83	115	15.76
70	14.94	120	15.82
75	15.03	125	15.89
80	15.17	130	15.93
85	15.34	135	16.00
90	15.44	140	16.08
95	15.51	145	16.10

L W -80, Linkville, Indiana

Temperatures Measured: 8/31/64

Depth	Temperature	Depth	Temperature
50	14.59	100	15.53
55	14.62	105	15.61
60	14.67	110	15.68
65	14.82	115	15.75
70	14.96	120	15.80
75	15.12	125	15.85
80	15.25	130	15.92
85	15.33	135	15.96
90	15.42	140	16.00
95	15.46	145	16.05
		150	16.10

S -36, Royal Center, Indiana

Temperatures Measured: 8/1/64

Depth	Temperature	Depth	Temperature
50	11.21	235	14.48
55	11.25	240	14.61
60	11.30	245	14.98
65	11.35	250	15.18
70	11.39	255	15.37
75	11.44	260	15.60
80	11.48	265	15.78
85	11.52	270	16.00
90	11.56	275	16.26
95	11.60	280	16.46
100	11.65	285	16.70
105	11.71	290	16.90
110	11.78	295	17.04
115	11.83	300	17.13
120	11.88	305	17.29
125	11.92	310	17.34
130	11.96	315	17.42
135	12.00	320	17.49
140	12.13	325	17.57
145	12.28	330	17.63
150	12.42	335	17.69
155	12.57	340	17.76
160	12.62	345	17.80
165	12.68	350	17.86
170	12.72	355	17.93
175	12.76	360	18.00
180	12.81	365	18.08
185	12.91	370	18.19
190	12.98	375	18.23
195	13.03	380	18.32
200	13.08	385	18.41
205	13.34	390	18.49
210	13.44	395	18.55
215	13.75	400	18.62
220	13.87	405	18.69
225	14.00	410	18.79
230	14.30	415	18.86
		420	18.96

S -38, Royal Center, Indiana

Temperatures Measured: 8/4/64

Depth	Temperature	Depth	Temperature
50	12.32	225	15.95
55	12.40	230	16.24
60	12.48	235	16.48
65	12.56	240	16.73
70	12.64	245	16.97
75	12.72	250	17.22
80	12.80	255	17.47
85	12.87	260	17.74
90	12.96	265	17.98
95	13.04	270	18.24
100	13.11	275	18.50
105	13.18	280	18.76
110	13.26	285	18.94
115	13.34	290	19.06
120	13.42	295	19.12
125	13.50	300	19.18
130	13.57	305	19.26
135	13.64	310	19.32
140	13.71	315	19.40
145	13.78	320	19.47
150	13.85	325	19.55
155	13.92	330	19.62
160	13.98	335	19.68
165	14.07	340	19.75
170	14.14	345	19.82
175	14.26	350	19.92
180	14.32	355	20.01
185	14.45	360	20.10
190	14.59	365	20.20
195	14.72	370	20.29
200	14.86	375	20.37
205	15.00	380	20.46
210	15.25	385	20.53
215	15.50	390	20.63
220	15.72	395	20.70
		400	20.82
		405	20.93

S -44, Royal Center, Indiana

Temperatures Measured: 8/1/64

Depth	Temperature
50	11.28
55	11.36
60	11.44
65	11.52
70	11.60
75	11.68
80	11.75
85	11.83
90	11.90
95	11.97
100	12.07
105	12.13
110	12.22
115	12.26
120	12.32
125	12.37
130	12.42
135	12.48
140	12.56
145	12.67
150	12.75
155	12.83
160	12.86
165	12.90
170	12.94
175	12.99
180	13.01
185	13.08
190	13.17
195	13.27
200	13.37
205	13.47
210	13.56
215	13.70
220	13.82
225	13.95
230	14.07

Depth	Temperature
235	14.41
240	14.97
245	15.05
250	15.24
255	15.43
260	15.67
265	15.90
270	16.09
275	16.33
280	16.57
285	16.79
290	17.05
295	17.21
300	17.34
305	17.43
310	17.52
315	17.57
320	17.63
325	17.71
330	17.79
335	17.88
340	18.00
345	18.08
350	18.16
355	18.20
360	18.23
365	18.26
370	18.30
375	18.35
380	18.41
385	18.48
390	18.54
395	18.61
400	18.67
405	18.75
410	18.84
415	18.90
420	18.97

S -46-1, Royal Center, Indiana

Temperatures Measured: 8/3/64

Depth	Temperature	Depth	Temperature
50	12.84	230	16.05
55	12.87	235	16.28
60	12.92	240	16.50
65	12.97	245	16.74
70	13.00	250	16.98
75	13.05	255	17.20
80	13.13	260	17.43
85	13.20	265	17.67
90	13.27	270	17.89
95	13.35	275	18.10
100	13.42	280	18.37
105	13.49	285	18.60
110	13.57	290	18.84
115	13.63	295	19.03
120	13.69	300	19.13
125	13.77	305	19.22
130	13.83	310	19.28
135	13.91	315	19.35
140	13.98	320	19.42
145	14.09	325	19.48
150	14.16	330	19.55
155	14.23	335	19.62
160	14.30	340	19.68
165	14.38	345	19.76
170	14.45	350	19.83
175	14.53	355	19.91
180	14.61	360	19.98
185	14.69	365	20.05
190	14.78	370	20.13
195	14.91	375	20.22
200	15.02	380	20.32
205	15.13	385	20.40
210	15.26	390	20.47
215	15.43	395	20.55
220	15.63	400	20.63
225	15.85	405	20.73
		410	20.84

S -46-2, Royal Center, Indiana

Temperatures Measured: 8/3/64

Depth	Temperature	Depth	Temperature
50	13.59	195	15.70
55	13.63	200	15.82
60	13.65	205	15.91
65	13.71	210	16.10
70	13.76	215	16.25
75	13.82	220	16.44
80	13.89	225	16.66
85	13.96	230	16.88
90	14.10	235	17.10
95	14.15	240	17.33
100	14.24	245	17.57
105	14.29	250	17.80
110	14.34	255	18.07
115	14.41	260	18.28
120	14.49	265	18.50
125	14.55	270	18.74
130	14.62	275	18.96
135	14.69	280	19.23
140	14.74	285	19.45
145	14.81	290	19.68
150	14.88	295	19.89
155	14.93	300	19.98
160	15.00	305	20.11
165	15.19	310	20.15
170	15.26	315	20.20
175	15.33	320	20.26
180	15.38	325	20.32
185	15.50	330	20.38
190	15.57	335	20.44

S -55, Royal Center, Indiana

Temperatures Measured: 7/15/64

Depth	Temperature	Depth	Temperature
50	14.68	215	16.73
55	14.66	220	17.04
60	14.66	225	17.35
65	14.71	230	17.50
70	14.74	235	17.66
75	14.77	240	17.81
80	14.77	245	17.98
85	14.86	250	18.21
90	14.88	255	18.32
95	14.88	260	18.43
100	14.87	265	18.55
105	14.90	270	18.68
110	14.92	275	18.85
115	14.96	280	18.98
120	14.96	285	19.12
125	15.04	290	19.26
130	15.04	295	19.32
135	15.04	300	19.36
140	15.04	305	19.39
145	15.04	310	19.43
150	15.10	315	19.49
155	15.18	320	19.55
160	15.20	325	19.63
165	15.26	330	19.70
170	15.28	335	19.76
175	15.32	340	19.82
180	15.39	345	19.86
185	15.56	350	19.93
190	15.66	355	20.02
195	15.79	360	20.11
200	15.98	365	20.19
205	16.14	370	20.28
210	16.52	375	20.32

Depth	Temperature	Depth	Temperature
380	20.38	580	22.45
385	20.45	585	22.51
390	20.56	590	22.55
395	20.64	595	22.59
400	20.74	600	22.64
405	20.81	605	22.70
410	20.90	610	22.75
415	20.98	615	22.85
420	21.02	620	22.95
425	21.05	625	23.01
430	21.09	630	23.04
435	21.12	635	23.05
440	21.14	640	23.08
445	21.18	645	23.12
450	21.23	650	23.16
455	21.27	655	23.19
460	21.33	660	23.24
465	21.40	665	23.32
470	21.48	670	23.42
475	21.53	675	23.55
480	21.58	680	23.68
485	21.63	685	23.83
490	21.65	690	23.99
495	21.71	695	24.20
500	21.85	700	24.40
505	21.93	705	24.60
510	21.91	710	24.70
515	21.92	715	24.83
520	21.99	720	24.96
525	22.01	725	25.08
530	22.01	730	25.18
535	22.01	735	25.27
540	22.04	740	25.46
545	22.09	745	25.57
550	22.13	750	25.69
555	22.16	755	25.82
560	22.22	760	25.92
565	22.25	765	26.04
570	22.32	770	26.10
575	22.39	775	26.17

Depth	Temperature	Depth	Temperature
780	26.24	915	28.22
785	26.31	920	28.28
790	26.39	925	28.34
795	26.53	930	28.40
800	26.63	935	28.46
805	26.71	940	28.52
810	26.80	945	28.60
815	26.88	950	28.66
820	26.98	955	28.70
825	27.02	960	28.77
830	27.17	965	28.82
835	27.28	970	28.87
840	27.34	975	28.93
845	27.40	980	28.98
850	27.45	985	29.03
855	27.48	990	29.08
860	27.52	995	29.16
865	27.57	1000	29.26
870	27.63	1005	29.29
875	27.70	1010	29.34
880	27.78	1015	29.37
885	27.85	1020	29.42
890	27.92	1025	29.46
895	28.00	1030	29.50
900	28.06	1035	29.57
905	28.12	1040	29.65
910	28.17	1045	29.71
		1050	29.80

Anderson #1, Vincent, Iowa

Temperatures Measured: 9/6/66

Depth	Temperature	Depth	Temperature
50	10.62	215	11.85
55	10.54	220	11.88
60	10.53	225	11.95
65	10.53	230	12.00
70	10.53	235	12.00
75	10.55	240	12.06
80	10.57	245	12.12
85	10.62	250	12.19
90	10.65	255	12.25
95	10.69	260	12.31
100	10.73	265	12.36
105	10.76	270	12.41
110	10.80	275	12.46
115	10.84	280	12.51
120	10.87	285	12.57
125	10.91	290	12.63
130	10.96	295	12.68
135	11.00	300	12.72
140	11.05	305	12.74
145	11.10	310	12.80
150	11.15	315	12.85
155	11.20	320	12.90
160	11.24	325	12.96
165	11.30	330	13.00
170	11.36	335	13.06
175	11.40	340	13.13
180	11.45	345	13.20
185	11.48	350	13.30
190	11.55	355	13.43
195	11.60	360	13.62
200	11.62	365	13.81
205	11.70	370	13.94
210	11.78	375	14.00

Depth	Temperature
380	14.10
385	14.15
390	14.20
395	14.24
400	14.30
405	14.34
410	14.39
415	14.44
420	14.48
425	14.53
430	14.58
435	14.63
440	14.68
445	14.73
450	14.77
455	14.82
460	14.87
465	14.92
470	14.97
475	15.01
480	15.05
485	15.10
490	15.15
495	15.20
500	15.24

Depth	Temperature
505	15.30
510	15.30
515	15.36
520	15.41
525	15.48
530	15.56
535	15.65
540	15.75
545	15.84
550	15.95
555	16.02
560	16.06
565	16.17
570	16.24
575	16.27
580	16.34
585	16.44
590	16.54
595	16.67
600	16.77
605	16.86
610	16.93
615	17.00
620	17.11
625	17.20
630	17.27

Anderson #3, Vincent, Iowa

Temperatures Measured: 9/6/66

Depth	Temperature	Depth	Temperature
50	11.00	215	12.00
55	10.89	220	12.02
60	10.78	225	12.08
65	10.76	230	12.13
70	10.75	235	12.18
75	10.76	240	12.23
80	10.78	245	12.29
85	10.81	250	12.34
90	10.84	255	12.41
95	10.88	260	12.47
100	10.93	265	12.52
105	10.97	270	12.57
110	10.99	275	12.62
115	11.02	280	12.68
120	11.06	285	12.74
125	11.10	290	12.80
130	11.14	295	12.86
135	11.17	300	12.90
140	11.21	305	12.98
145	11.26	310	13.02
150	11.31	315	13.06
155	11.35	320	13.11
160	11.40	325	13.16
165	11.45	330	13.21
170	11.49	335	13.26
175	11.54	340	13.31
180	11.59	345	13.36
185	11.64	350	13.44
190	11.70	355	13.52
195	11.74	360	13.62
200	11.79	365	13.78
205	11.84	370	13.98
210	11.91	375	14.21

Depth	Temperature	Depth	Temperature
380	14.33	515	15.64
385	14.38	520	15.69
390	14.44	525	15.74
395	14.47	530	15.79
400	14.52	535	15.86
405	14.57	540	15.95
410	14.62	545	16.01
415	14.66	550	16.04
420	14.70	555	16.10
425	14.74	560	16.14
430	14.79	565	16.22
435	14.84	570	16.30
440	14.90	575	16.35
445	14.96	580	16.44
450	15.02	585	16.50
455	15.08	590	16.52
460	15.12	595	16.54
465	15.17	600	16.55
470	15.20	605	16.65
475	15.24	610	16.75
480	15.28	615	16.85
485	15.32	620	16.93
490	15.38	625	17.03
495	15.43	630	17.10
500	15.49	635	17.14
505	15.53	640	17.20
510	15.59	645	17.30

Book #1, Redfield, Iowa

Temperatures Measured: 9/4/64

Depth	Temperature	Depth	Temperature
50	11.34	215	15.53
55	11.39	220	15.63
60	11.48	225	15.71
65	11.61	230	15.80
70	11.72	235	15.88
75	11.83	240	15.96
80	11.95	245	16.05
85	12.09	250	16.15
90	12.21	255	16.25
95	12.37	260	16.34
100	12.50	265	16.42
105	12.66	270	16.49
110	12.80	275	16.58
115	12.98	280	16.63
120	13.22	285	16.72
125	13.47	290	16.78
130	13.72	295	16.94
135	13.92	300	17.11
140	14.03	305	17.30
145	14.17	310	17.43
150	14.27	315	17.53
155	14.43	320	17.61
160	14.54	325	17.70
165	14.62	330	17.80
170	14.71	335	17.90
175	14.78	340	17.98
180	14.88	345	18.06
185	14.96	350	18.12
190	15.08	355	18.21
195	15.17	360	18.29
200	15.25	365	18.38
205	15.34	370	18.46
210	15.43	375	18.53

Depth	Temperature	Depth	Temperature
380	18.60	530	21.21
385	18.66	535	21.31
390	18.75	540	21.41
395	18.84	545	21.53
400	18.91	550	21.62
405	19.00	555	21.71
410	19.01	560	21.80
415	19.08	565	21.88
420	19.16	570	21.97
425	19.25	575	22.04
430	19.32	580	22.11
435	19.41	585	22.19
440	19.51	590	22.25
445	19.60	595	22.32
450	19.67	600	22.40
455	19.76	605	22.47
460	19.86	610	22.56
465	19.95	615	22.62
470	20.12	620	22.69
475	20.20	625	22.75
480	20.27	630	22.81
485	20.35	635	22.87
490	20.41	640	22.94
495	20.47	645	23.00
500	20.54	650	23.07
505	20.63	655	23.15
510	20.74	660	23.25
515	20.83	665	23.37
520	20.97	670	23.43
525	21.11	675	23.44

Brodeick #1, Redfield, Iowa

Temperatures Measured: 9/2/64

Depth	Temperature	Depth	Temperature
50	13.58	210	15.17
55	13.60	215	15.32
60	13.63	220	15.42
65	13.65	225	15.50
70	13.66	230	15.57
75	13.67	235	15.64
80	13.70	240	15.71
85	13.69	245	15.82
90	13.71	250	15.85
95	13.76	255	15.92
100	13.77	260	15.98
105	13.82	265	16.02
110	13.92	270	16.08
115	13.97	275	16.19
120	14.01	280	16.23
125	14.11	285	16.27
130	14.18	290	16.33
135	14.22	295	16.38
140	14.26	300	16.45
145	14.29	305	16.51
150	14.37	310	16.54
155	14.44	315	16.60
160	14.52	320	16.66
165	14.61	325	16.70
170	14.67	330	16.77
175	14.72	335	16.86
180	14.75	340	16.92
185	14.75	345	16.95
190	14.78	350	17.07
195	14.84	355	17.16
200	14.94	360	17.22
205	15.05	365	17.27

Hoffman #1, Vincent, Iowa

Temperatures Measured: 9/5/64

Depth	Temperature	Depth	Temperature
50	15.67	215	11.95
55	14.58	220	12.03
60	12.57	225	12.08
65	12.30	230	12.15
70	12.49	235	12.26
75	12.45	240	12.20
80	11.57	245	12.21
85	11.24	250	12.30
90	11.25	255	12.40
95	11.23	260	12.46
100	11.23	265	12.54
105	11.18	270	12.63
110	11.16	275	12.67
115	11.14	280	12.69
120	11.14	285	12.70
125	11.21	290	12.75
130	11.27	295	12.78
135	11.19	300	12.82
140	11.40	305	12.82
145	11.58	310	12.86
150	11.61	315	12.90
155	11.66	320	12.94
160	11.62	325	12.95
165	11.59	330	12.95
170	11.60	335	13.02
175	11.66	340	13.07
180	11.68	345	13.12
185	11.76	350	13.17
190	11.79	355	13.20
195	11.81	360	13.22
200	11.95	365	13.25
205	12.00	370	13.30
210	11.95	375	13.37

Depth	Temperature	Depth	Temperature
380	13.40	535	15.36
385	13.41	540	15.40
390	13.43	545	15.44
395	13.52	550	15.52
400	13.60	555	15.66
405	13.71	560	16.00
410	13.93	565	16.37
415	14.17	570	16.42
420	14.47	575	16.23
425	14.47	580	16.10
430	14.47	585	16.10
435	14.57	590	16.17
440	14.80	595	16.27
445	14.79	600	16.35
450	14.67	605	16.38
455	14.68	610	16.47
460	14.75	615	16.51
465	14.77	620	16.58
470	14.80	625	16.68
475	14.83	630	16.80
480	14.87	635	16.95
485	14.93	640	17.07
490	14.97	645	17.14
495	15.02	650	17.21
500	15.07	655	17.29
505	15.12	660	17.36
510	15.18	665	17.44
515	15.23	670	17.51
520	15.26	675	17.59
525	15.28	680	17.63
530	15.32	685	17.66
		690	17.68

J. Anderson #1, Keota, Iowa

Temperatures Measured: 9/1/64

Depth	Temperature	Depth	Temperature
50	11.56	210	18.09
55	11.62	215	18.19
60	11.69	220	18.32
65	11.80	225	18.50
70	11.95	230	18.73
75	12.10	235	18.90
80	12.30	240	19.10
85	12.54	245	19.35
90	12.79	250	19.53
95	13.12	255	19.72
100	13.44	260	19.95
105	13.76	265	20.26
110	14.07	270	20.42
115	14.37	275	20.58
120	14.67	280	20.68
125	14.97	285	20.79
130	15.30	290	20.88
135	15.62	295	20.98
140	15.89	300	21.07
145	16.07	305	21.21
150	16.29	310	21.31
155	16.48	315	21.41
160	16.64	320	21.50
165	16.86	325	21.61
170	17.16	330	21.71
175	17.37	335	21.82
180	17.53	340	21.95
185	17.65	345	22.14
190	17.73	350	22.26
195	17.83	355	22.38
200	17.91	360	22.60
205	18.00	365	22.82

L. Vogel #1, Keota, Iowa

Temperatures Measured: 9/1/64

Depth	Temperature	Depth	Temperature
50	11.61	205	18.04
55	11.70	210	18.21
60	11.84	215	18.42
65	12.00	220	18.66
70	12.10	225	18.87
75	12.42	230	19.05
80	12.70	235	19.31
85	13.00	240	19.51
90	13.35	245	19.74
95	13.73	250	19.98
100	14.00	255	20.28
105	14.28	260	20.43
110	14.57	265	20.54
115	14.87	270	20.66
120	15.28	275	20.80
125	15.62	280	20.90
130	15.86	285	20.98
135	16.02	290	21.10
140	16.25	295	21.23
145	16.42	300	21.34
150	16.63	305	21.47
155	16.90	310	21.57
160	17.07	315	21.66
165	17.20	320	21.77
170	17.31	325	21.89
175	17.41	330	22.02
180	17.54	335	22.21
185	17.66	340	22.35
190	17.76	345	22.50
195	17.84	350	22.78
200	17.93	355	22.91

Olson #1 "G", Vincent, Iowa

Temperatures Measured: 9/5/64

Depth	Temperature	Depth	Temperature
50	10.24	215	11.52
55	10.25	220	11.58
60	10.27	225	11.62
65	10.28	230	11.66
70	10.29	235	11.74
75	10.31	240	11.75
80	10.32	245	11.83
85	10.32	250	11.86
90	10.35	255	11.91
95	10.33	260	12.00
100	10.35	265	12.08
105	10.38	270	12.15
110	10.42	275	12.19
115	10.48	280	12.25
120	10.54	285	12.30
125	10.60	290	12.35
130	10.68	295	12.41
135	10.80	300	12.45
140	10.83	305	12.53
145	10.84	310	12.60
150	10.88	315	12.62
155	10.92	320	12.66
160	11.00	325	12.68
165	11.10	330	12.72
170	11.12	335	12.78
175	11.17	340	12.82
180	11.25	345	12.89
185	11.30	350	12.92
190	11.36	355	12.96
195	11.37	360	13.04
200	11.38	365	13.12
205	11.44	370	13.17
210	11.48	375	13.24

Depth	Temperature
380	13.29
385	13.32
390	13.37
395	13.41
400	13.48
405	13.59
410	13.77
415	14.00
420	14.09
425	14.18
430	14.23
435	14.27
440	14.30
445	14.33
450	14.39
455	14.45
460	14.54
465	14.56
470	14.60
475	14.63
480	14.66
485	14.70
490	14.76
495	14.79
500	14.84
505	14.91
510	14.96
515	14.98
520	15.07
525	15.11
530	15.16
535	15.19
540	15.25

Depth	Temperature
545	15.29
550	15.32
555	15.37
560	15.44
565	15.51
570	15.57
575	15.61
580	15.67
585	15.71
590	15.77
595	15.85
600	15.93
605	16.00
610	16.11
615	16.21
620	16.36
625	16.47
630	16.57
635	16.64
640	16.71
645	16.75
650	16.82
655	16.95
660	17.10
665	17.25
670	17.32
675	17.38
680	17.46
685	17.54
690	17.62
695	17.71
700	17.80
705	17.86
710	17.92

P. Hutchinson #2-1, Cairo, Iowa

Temperatures Measured: 8/31/64

Depth	Temperature	Depth	Temperature
50	11.76	155	14.23
55	11.77	160	14.39
60	11.82	165	14.57
65	11.86	170	14.69
70	11.92	175	14.82
75	11.97	180	14.93
80	12.01	185	15.02
85	12.06	190	15.12
90	12.12	195	15.20
95	12.17	200	15.29
100	12.23	205	15.39
105	12.32	210	15.48
110	12.45	215	15.56
115	12.62	220	15.66
120	12.88	225	15.74
125	13.01	230	15.83
130	13.22	235	15.93
135	13.43	240	16.02
140	13.62	245	16.14
145	13.83	250	16.26
150	14.02	255	16.37

P. Hutchinson #2-2, Cairo, Iowa

Temperatures Measured: 8/31/64

Depth	Temperature	Depth	Temperature
50	11.74	155	14.10
55	11.75	160	14.27
60	11.77	165	14.45
65	11.81	170	14.60
70	11.86	175	14.72
75	11.91	180	14.83
80	11.97	185	14.87
85	12.01	190	14.96
90	12.07	195	15.12
95	12.12	200	15.23
100	12.18	205	15.32
105	12.25	210	15.41
110	12.37	215	15.50
115	12.52	220	15.58
120	12.73	225	15.67
125	12.91	230	15.74
130	13.12	235	15.84
135	13.36	240	15.93
140	13.65	245	16.03
145	13.87	250	16.17
150	13.96	255	16.28
		260	16.38

Price #1, Redfield, Iowa

Temperatures Measured: 9/4/64

Depth	Temperature	Depth	Temperature
50	11.41	215	14.30
55	11.51	220	14.50
60	11.61	225	14.67
65	11.72	230	14.85
70	11.81	235	14.94
75	11.90	240	15.06
80	12.00	245	15.17
85	12.10	250	15.26
90	12.20	255	15.35
95	12.25	260	15.44
100	12.33	265	15.51
105	12.40	270	15.60
110	12.47	275	15.68
115	12.55	280	15.78
120	12.65	285	15.85
125	12.73	290	15.92
130	12.83	295	15.99
135	12.91	300	16.04
140	13.02	305	16.14
145	13.11	310	16.21
150	13.20	315	16.27
155	13.32	320	16.34
160	13.40	325	16.39
165	13.47	330	16.48
170	13.60	335	16.58
175	13.67	340	16.66
180	13.79	345	16.75
185	13.86	350	16.83
190	13.93	355	16.94
195	13.99	360	17.08
200	14.04	365	17.18
205	14.12	370	17.25
210	14.19	375	17.32

Depth	Temperature	Depth	Temperature
380	17.46	485	19.29
385	17.55	490	19.36
390	17.62	495	19.43
395	17.70	500	19.52
400	17.76	505	19.58
405	17.83	510	19.65
410	17.88	515	19.73
415	17.97	520	19.80
420	18.04	525	19.85
425	18.19	530	19.93
430	18.33	535	19.98
435	18.42	540	20.07
440	18.52	545	20.14
445	18.62	550	20.21
450	18.71	555	20.29
455	18.78	560	20.36
460	18.90	565	20.46
465	18.98	570	20.56
470	19.06	575	20.64
475	19.13	580	20.73
480	19.21	585	20.80

#972, Marion, Michigan

Temperatures Measured: 7/9/65

Depth	Temperature	Depth	Temperature
50	13.08	215	16.18
55	13.18	220	16.24
60	13.28	225	16.29
65	13.38	230	16.36
70	13.48	235	16.41
75	13.58	240	16.47
80	13.68	245	16.52
85	13.78	250	16.58
90	13.88	255	16.64
95	13.98	260	16.70
100	14.05	265	16.75
105	14.14	270	16.81
110	14.24	275	16.86
115	14.34	280	16.92
120	14.44	285	16.98
125	14.53	290	17.01
130	14.63	295	17.05
135	14.72	300	17.13
140	14.82	305	17.21
145	14.92	310	17.29
150	15.01	315	17.36
155	15.10	320	17.45
160	15.20	325	17.53
165	15.29	330	17.61
170	15.38	335	17.68
175	15.47	340	17.76
180	15.57	345	17.84
185	15.66	350	17.92
190	15.75	355	18.03
195	15.84	360	18.15
200	15.93	365	18.27
205	16.07	370	18.38
210	16.13	375	18.51

Depth	Temperature	Depth	Temperature
380	18.62	440	19.75
385	18.75	445	19.83
390	18.88	450	19.91
395	18.98	455	19.98
400	19.12	460	20.03
405	19.19	465	20.09
410	19.27	470	20.15
415	19.36	475	20.20
420	19.43	480	20.26
425	19.51	485	20.32
430	19.59	490	20.38
435	19.68	495	20.43
		500	20.49

N-203, Northville, Michigan

Temperatures Measured: 7/12/65

Depth	Temperature	Depth	Temperature
50	12.65	215	15.40
55	12.60	220	15.58
60	12.58	225	15.65
65	12.57	230	15.78
70	12.58	235	15.83
75	12.58	240	15.90
80	12.63	245	15.97
85	12.68	250	16.06
90	12.74	255	16.06
95	12.81	260	16.22
100	12.85	265	16.24
105	12.89	270	16.33
110	12.94	275	16.40
115	13.00	280	16.45
120	13.08	285	16.54
125	13.18	290	16.64
130	13.23	295	16.70
135	13.45	300	16.77
140	13.61	305	16.75
145	13.79	310	16.72
150	13.91	315	16.82
155	13.92	320	16.89
160	13.93	325	16.94
165	14.10	330	16.99
170	14.18	335	17.10
175	14.28	340	17.15
180	14.45	345	17.20
185	14.50	350	17.27
190	14.61	355	17.33
195	14.82	360	17.38
200	14.98	365	17.43
205	15.05	370	17.48
210	15.14	375	17.52

Depth	Temperature	Depth	Temperature
380	17.56	580	19.74
385	17.67	585	19.81
390	17.67	590	19.88
395	17.71	595	19.92
400	17.73	600	19.97
405	17.83	605	19.99
410	17.88	610	20.01
415	17.83	615	20.05
420	17.77	620	20.12
425	17.81	625	20.18
430	17.90	630	20.22
435	18.00	635	20.27
440	18.01	640	20.31
445	18.10	645	20.35
450	18.15	650	20.38
455	18.17	655	20.43
460	18.37	660	20.47
465	18.43	665	20.52
470	18.29	670	20.57
475	18.29	675	20.60
480	18.34	680	20.64
485	18.49	685	20.68
490	18.50	690	20.73
495	18.51	695	20.77
500	18.57	700	20.81
505	18.60	705	20.85
510	18.65	710	20.88
515	18.70	715	20.93
520	18.77	720	20.01
525	18.83	725	19.89
530	18.96	730	19.94
535	19.07	735	19.99
540	19.16	740	20.03
545	19.22	745	20.08
550	19.29	750	20.13
555	19.38	755	20.20
560	19.45	760	20.24
565	19.55	765	20.33
570	19.63	770	20.39
575	19.69	775	20.48

Depth	Temperature	Depth	Temperature
780	20.56	980	22.97
785	20.64	985	23.02
790	20.72	990	23.07
795	20.79	995	23.12
800	20.85	1000	23.17
805	20.90	1005	23.23
810	20.94	1010	23.29
815	20.99	1015	23.34
820	21.02	1020	23.40
825	21.07	1025	23.46
830	21.12	1030	23.52
835	21.17	1035	23.58
840	21.20	1040	23.63
845	21.25	1045	23.71
850	21.30	1050	23.78
855	21.36	1055	23.83
860	21.42	1060	23.91
865	21.45	1065	24.02
870	21.49	1070	24.17
875	21.55	1075	24.30
880	21.60	1080	24.41
885	21.63	1085	24.53
890	21.68	1090	24.64
895	21.72	1095	24.76
900	21.77	1100	24.85
905	21.82	1105	24.93
910	21.88	1110	24.99
915	21.98	1115	25.15
920	22.05	1120	25.27
925	22.11	1125	25.45
930	22.20	1130	25.60
935	22.30	1135	25.77
940	22.41	1140	25.97
945	22.50	1145	26.25
950	22.60	1150	26.39
955	22.69	1155	26.53
960	22.76	1160	26.67
965	22.81	1165	26.83
970	22.88	1170	27.02
975	22.93	1175	27.19

Depth	Temperature
1180	27.35
1185	27.52
1190	27.67
1195	27.81
1200	27.95
1205	28.08
1210	28.26
1215	28.45
1220	28.81
1225	28.99
1230	29.15
1235	29.38
1240	29.61
1245	29.87
1250	30.13
1255	30.38
1260	30.60
1265	30.79

Depth	Temperature
1270	31.01
1275	31.23
1280	31.45
1285	31.67
1290	31.90
1295	32.06
1300	32.18
1305	32.26
1310	32.34
1315	32.42
1320	32.50
1325	32.58
1330	32.66
1335	32.74
1340	32.82
1345	32.91
1350	33.00
1355	33.13
1360	33.23

S -503-E, Burnips, Michigan

Temperatures Measured: 7/8/65

Depth	Temperature	Depth	Temperature
50	11.71	215	14.70
55	11.71	220	14.83
60	11.71	225	14.95
65	11.72	230	15.05
70	11.75	235	15.18
75	11.79	240	15.31
80	11.86	245	15.44
85	11.93	250	15.55
90	12.02	255	15.71
95	12.08	260	15.83
100	12.22	265	15.90
105	12.40	270	15.99
110	12.45	275	16.04
115	12.48	280	16.10
120	12.58	285	16.16
125	12.68	290	16.25
130	12.81	295	16.35
135	12.94	300	16.47
140	13.01	305	16.55
145	13.10	310	16.68
150	13.17	315	16.79
155	13.28	320	16.88
160	13.36	325	16.98
165	13.47	330	17.04
170	13.61	335	17.16
175	13.72	340	17.25
180	13.84	345	17.34
185	13.98	350	17.46
190	14.04	355	17.60
195	14.16	360	17.74
200	14.28	365	17.85
205	14.43	370	17.95
210	14.56	375	18.04

Depth	Temperature	Depth	Temperature
380	18.20	595	21.28
385	18.34	600	21.31
390	18.44	605	21.34
395	18.61	610	21.37
400	18.77	615	21.39
405	18.89	620	21.42
410	18.99	625	21.45
415	19.05	630	21.47
420	19.16	635	21.50
425	19.32	640	21.52
430	19.47	645	21.55
435	19.60	650	21.57
440	19.74	655	21.59
445	19.89	660	21.61
450	19.99	665	21.65
455	20.03	670	21.67
460	20.09	675	21.70
465	20.14	680	21.71
470	20.18	685	21.73
475	20.23	690	21.78
480	20.28	695	21.82
485	20.32	700	21.84
490	20.37	705	21.87
495	20.41	710	21.89
500	20.46	715	21.90
505	20.51	720	21.95
510	20.55	725	22.02
515	20.61	730	22.06
520	20.67	735	22.10
525	20.75	740	22.13
530	20.81	745	22.16
535	20.85	750	22.19
540	20.89	755	22.23
545	20.94	760	22.25
550	21.01	765	22.27
555	21.07	770	22.30
560	21.09	775	22.35
565	21.12	780	22.40
570	21.15	785	22.47
575	21.18	790	22.52
580	21.20	795	22.57
585	21.23	800	22.63
590	21.26	805	22.68
		810	22.73

Assman #1, Winner, South Dakota

Temperatures Measured: 7/2/65

Depth	Temperature	Depth	Temperature
50	15.34	180	22.64
55	15.41	185	23.06
60	15.51	190	23.43
65	15.68	195	24.00
70	15.81	200	24.15
75	15.97	205	24.55
80	16.55	210	24.60
85	16.57	215	24.72
90	16.66	220	25.09
95	16.80	225	25.48
100	16.95	230	26.79
105	17.10	235	26.90
110	17.28	240	27.20
115	17.58	245	27.49
120	17.85	250	27.65
125	18.10	255	27.91
130	18.42	260	29.02
135	18.73	265	30.31
140	19.00	270	30.74
145	19.23	275	31.07
150	19.48	280	31.55
155	20.66	285	32.02
160	20.98	290	32.40
165	21.05	295	32.87
170	21.17	300	33.12
175	21.79		

Carrie Hovland #1, Flaxton, North Dakota

Temperatures Measured: 9/13/64

Depth	Temperature	Depth	Temperature
65	11.33	230	12.70
70	11.18	235	12.79
75	10.98	240	12.92
80	10.85	245	13.06
85	10.70	250	13.17
90	10.60	255	13.34
95	10.55	260	13.52
100	10.55	265	13.63
105	10.55	270	13.75
110	10.55	275	13.92
115	10.55	280	14.12
120	10.55	285	14.29
125	10.55	290	14.45
130	10.60	295	14.59
135	10.63	300	14.73
140	10.69	305	14.80
145	10.78	310	14.83
150	10.93	315	14.84
155	11.10	320	14.91
160	11.24	325	15.04
165	11.35	330	15.48
170	11.55	335	15.64
175	11.66	340	15.97
180	11.78	345	16.10
185	12.25	350	16.16
190	12.19	355	16.26
195	12.17	360	16.46
200	12.19	365	16.67
205	12.24	370	16.85
210	12.32	375	17.00
215	12.41	380	17.26
220	12.51	385	17.43
225	12.60	390	17.61

Depth	Temperature	Depth	Temperature
395	17.73	595	25.21
400	17.80	600	25.42
405	17.83	605	25.67
410	17.92	610	25.80
415	18.21	615	25.96
420	18.55	620	26.13
425	18.80	625	26.38
430	18.98	630	26.55
435	19.30	635	26.74
440	19.57	640	26.85
445	19.61	645	27.10
450	19.79	650	27.32
455	20.00	655	27.44
460	20.20	660	27.66
465	20.46	665	27.88
470	20.67	670	28.01
475	20.82	675	28.20
480	21.00	680	28.34
485	21.22	685	28.48
490	21.25	690	28.79
495	21.47	695	28.91
500	21.74	700	28.98
505	21.97	705	29.15
510	22.08	710	29.37
515	22.28	715	29.56
520	22.48	720	29.78
525	22.67	725	29.91
530	22.85	730	30.17
535	23.02	735	30.39
540	23.14	740	30.56
545	23.27	745	30.72
550	23.48	750	33.33
555	23.77	755	33.61
560	23.87	760	33.95
565	24.07	765	34.22
570	24.25	770	34.45
575	24.44	775	34.76
580	24.63	780	35.03
585	24.80	785	35.28
590	25.02	790	35.52

Depth	Temperature	Depth	Temperature
795	35.73	995	46.48
800	36.02	1000	46.74
805	36.34	1005	47.02
810	36.56	1010	47.37
815	36.80	1015	47.64
820	36.97	1020	47.88
825	37.20	1025	48.16
830	37.48	1030	48.44
835	37.75	1035	48.75
840	38.04	1040	49.03
845	38.28	1045	49.27
850	38.56	1050	49.66
855	38.81	1055	50.00
860	39.02	1060	50.45
865	39.31	1065	50.82
870	39.51	1070	51.14
875	39.80	1075	51.50
880	40.02	1080	51.82
885	40.32	1085	52.10
890	40.60	1090	52.35
895	40.89	1095	52.60
900	41.20	1100	52.85
905	41.46	1105	53.10
910	41.71	1110	53.34
915	42.00	1115	53.58
920	42.25	1120	53.86
925	42.50	1125	54.10
930	42.75	1130	54.37
935	43.00	1135	54.67
940	43.28	1140	54.96
945	43.53	1145	55.23
950	43.83	1150	55.51
955	44.16	1155	55.76
960	44.53	1160	56.02
965	44.85	1165	56.27
970	45.11	1170	56.54
975	45.40	1175	56.77
980	45.68	1180	56.94
985	45.97	1185	57.08
990	46.22	1190	57.21

Depth	Temperature	Depth	Temperature
1195	57.35	1395	64.39
1200	57.50	1400	64.61
1205	57.64	1405	64.83
1210	57.76	1410	65.02
1215	57.87	1415	65.25
1220	57.98	1420	65.49
1225	58.14	1425	65.71
1230	58.22	1430	65.91
1235	58.32	1435	66.07
1240	58.45	1440	66.23
1245	58.55	1445	66.42
1250	58.66	1450	66.59
1255	58.76	1455	66.77
1260	58.86	1460	66.91
1265	58.95	1465	67.07
1270	59.04	1470	67.21
1275	59.17	1475	67.37
1280	59.30	1480	67.57
1285	59.48	1485	67.77
1290	59.66	1490	67.92
1295	59.85	1495	68.08
1300	60.06	1500	68.23
1305	60.22	1505	68.39
1310	60.38	1510	68.54
1315	60.53	1515	68.58
1320	60.71	1520	68.82
1325	60.89	1525	68.93
1330	61.08	1530	69.05
1335	61.31	1535	69.16
1340	61.53	1540	69.27
1345	61.78	1545	69.39
1350	62.00	1550	69.51
1355	62.23	1555	69.63
1360	62.50	1560	69.75
1365	62.78	1565	69.86
1370	63.07	1570	69.98
1375	63.37	1575	70.05
1380	63.66	1580	70.18
1385	63.92	1585	70.31
1390	64.14	1590	70.43

Depth	Temperature	Depth	Temperature
1595	70.56	1700	73.05
1600	70.68	1705	73.17
1605	70.81	1710	73.29
1610	70.93	1715	73.42
1615	71.05	1720	73.56
1620	71.17	1725	73.69
1625	71.29	1730	73.81
1630	71.42	1735	73.93
1635	71.54	1740	74.08
1640	71.67	1745	74.20
1645	71.77	1750	74.31
1650	71.87	1755	74.43
1655	72.00	1760	74.54
1660	72.10	1765	74.66
1665	72.23	1770	74.76
1670	72.36	1775	74.84
1675	72.46	1780	74.92
1680	72.58	1785	74.99
1685	72.72	1790	75.17
1690	72.85	1795	75.40
1695	72.97	1800	75.53

E.L.K. #1 Nelson, Roth, North Dakota

Temperatures Measured: 9/12/64

Depth	Temperature	Depth	Temperature
50	10.41	215	14.33
55	10.47	220	14.58
60	10.53	225	14.80
65	10.59	230	15.02
70	10.65	235	15.23
75	10.71	240	15.44
80	10.76	245	15.65
85	10.88	250	15.86
90	10.93	255	16.07
95	11.06	260	16.28
100	11.16	265	16.50
105	11.27	270	16.73
110	11.28	275	16.94
115	11.33	280	17.24
120	11.25	285	17.46
125	11.31	290	17.69
130	11.31	295	17.92
135	11.34	300	18.14
140	11.52	305	18.42
145	11.69	310	18.65
150	11.90	315	18.89
155	12.18	320	19.09
160	12.42	325	19.34
165	12.74	330	19.63
170	12.90	335	19.89
175	13.04	340	20.22
180	13.21	345	20.50
185	13.39	350	20.83
190	13.53	355	21.10
195	13.68	360	21.36
200	13.82	365	21.63
205	13.97	370	21.89
210	14.13	375	22.20

Depth	Temperature
380	22.53
385	22.82
390	23.04
395	23.28
400	23.51
405	23.75
410	23.98
415	24.22
420	24.47
425	24.72
430	24.98
435	25.24
440	25.52
445	25.79
450	26.02
455	26.33
460	26.65
465	26.98
470	27.30
475	27.65
480	27.98
485	28.25
490	28.56
495	28.81
500	29.04
505	29.26
510	29.44
515	29.68
520	29.97
525	30.25
530	30.61
535	30.94
540	31.27
545	31.62
550	31.94
555	32.32
560	32.63
565	32.97
570	33.18
575	33.43

Depth	Temperature
580	33.68
585	33.92
590	34.18
595	34.42
600	34.69
605	34.98
610	35.24
615	35.52
620	35.74
625	35.91
630	36.00
635	36.10
640	36.24
645	36.37
650	36.49
655	36.57
660	36.67
665	36.80
670	36.93
675	37.06
680	37.21
685	37.34
690	37.46
695	37.56
700	37.67
705	37.77
710	37.89
715	38.08
720	38.31
725	38.54
730	38.78
735	39.02
740	39.22
745	39.46
750	39.74
755	39.98
760	40.19
765	40.41
770	40.63
775	40.86

Depth	Temperature	Depth	Temperature
780	41.08	860	43.80
785	41.29	865	43.89
790	41.51	870	43.98
795	41.69	875	44.10
800	41.89	880	44.21
805	42.04	885	44.30
810	42.22	890	44.37
815	42.40	895	44.45
820	42.55	900	44.52
825	42.73	905	44.59
830	42.86	910	44.68
835	43.03	915	44.78
840	43.22	920	44.87
845	43.36	925	44.97
850	43.52	930	45.06
855	43.65	935	45.23
		940	45.31

APPENDIX II

THERMAL CONDUCTIVITY MEASUREMENTS

In this appendix, DEPTH refers to the depth in meters below ground level, TEMPERATURE is the in situ temperature in degrees centigrade, CONDUCTIVITY is the thermal conductivity in units of 10^{-3} cal/cm sec ^{o}C, and DENSITY is the density in gm/cm^{3}.

CONTENTS

CONDIT #1, CRESCENT CITY, ILLINOIS

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
386	17.89	2.74	11.66
391	17.97	2.63	10.63
428	18.44	2.25	12.95
431	18.47	2.43	14.21
441	18.55	2.35	14.58
781	22.64	2.79	11.88
784	22.68	2.77	11.38
793	22.79	2.68	13.05
795	22.81	2.23	11.20
799	22.86	2.75	13.43
804	22.93	2.21	12.36
853	23.46	3.00	9.96
1049	32.23	2.43	13.77
1062	32.45	2.34	12.36

MUSSER #1, ANCONA, ILLINOIS

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
697	24.42	6.79	2.35
707	24.71	13.25	2.41
724	24.92	12.90	2.28
728	24.96	13.00	2.29
729	24.98	13.92	2.34
733	25.00	12.28	2.22
736	25.04	13.74	2.33
750	25.24	11.41	2.19

TADEN #1, CRESCENT CITY, ILLINOIS

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
205	14.89	7.25	2.67
250	16.48	7.31	2.62
254	16.60	7.23	2.66
262	16.78	7.79	2.65
269	16.91	7.99	2.65
308	17.52	8.10	2.62
312	17.59	8.12	2.67
328	17.82	8.08	2.66
337	17.96	7.29	2.69
344	18.07	7.38	2.61
413	18.87	13.60	2.39
416	18.91	13.15	2.31
778	23.28	13.60	2.70
785	23.35	12.39	2.75
799	23.52	13.00	2.39
978	31.17	7.27	2.78
988	31.65	9.86	2.60
1005	32.12	14.22	2.40
1013	32.27	10.76	2.31

WESSEL #1, CRESCENT CITY, ILLINOIS

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
353	18.17	7.59	2.69
362	18.33	9.60	2.87
366	18.37	9.25	2.73
372	18.46	7.57	2.69
374	18.49	7.57	2.71
381	18.61	9.69	2.72
388	18.70	12.60	2.24
393	18.77	12.94	2.29
404	18.88	14.37	2.45
407	18.91	13.30	2.31

LEUENBERGER WELL, MONROEVILLE, INDIANA

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
111	14.86	11.72	2.44
115	14.91	10.55	2.35
117	14.93	11.00	2.55
133	15.03	10.23	2.51
143	15.10	11.98	2.60
147	15.13	11.01	2.55
152	15.18	11.60	2.65
155	15.21	12.14	2.65
162	15.27	12.25	2.64
167	15.30	9.87	2.20
172	15.36	11.20	2.50
176	15.39	11.21	2.53

LINKVILLE FIELD, LINKVILLE, INDIANA

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
110	16.40	7.10	2.69
110	16.42	7.05	2.66
115	16.48	6.65	2.62
119	16.50	8.14	2.61
120	16.52	7.71	2.24
124	16.53	9.71	2.63
127	16.60	10.23	2.67
131	16.70	9.43	2.52
132	16.71	10.28	2.72
135	16.73	12.35	2.67
139	16.75	11.34	2.47
141	16.76	10.62	2.36
145	16.78	10.18	2.33
148	16.82	10.47	2.46
150	16.87	11.11	2.46

S-36, ROYAL CENTER, INDIANA

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
301	17.12	10.79	2.75
302	17.13	10.46	2.68
306	17.21	8.77	2.63
312	17.35	11.76	2.73
317	17.41	11.34	2.79
319	17.45	10.71	2.75
328	17.58	11.18	2.73
330	17.60	11.51	2.74
333	17.64	9.21	2.66
335	17.72	9.92	2.67
340	17.79	7.41	2.62
343	17.81	7.78	2.66

S-38, ROYAL CENTER, INDIANA

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
366	20.21	7.17	2.71
369	20.27	7.57	2.68
371	20.31	7.01	2.66

S-46, ROYAL CENTER, INDIANA

DEPTH	TEMPERATURE	CONDUCTIVITY	DENSITY
158	14.27	8.56	2.53
162	14.32	7.86	2.64
166	14.38	8.29	2.61
183	14.65	9.95	2.76
186	14.71	5.72	2.60

S-55, ROYAL CENTER, INDIANA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
308	19.41	2.79	11.46
315	19.49	2.66	11.40
328	19.69	2.75	11.45
343	19.84	2.68	7.66
348	19.90	2.68	7.10
698	24.29	2.27	5.77
712	24.76	2.25	5.82
736	25.31	2.47	8.43
782	26.27	2.41	8.95
801	26.64	2.41	8.75
808	26.80	2.45	8.84
860	27.52	2.43	14.91
991	29.15	2.36	13.69
1011	29.34	2.22	12.50

ANDERSON #1, VINCENT, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
218	11.87	2.67	7.20
222	11.92	2.56	8.04
229	12.00	2.69	7.74
291	12.64	2.38	9.66
293	12.66	2.63	10.06
306	12.78	2.39	9.99
311	12.83	2.30	7.52
320	12.91	2.32	9.86
325	12.96	2.29	9.11
446	14.74	2.42	13.07
577	16.32	2.56	8.82
580	16.35	2.02	9.09
587	16.47	2.27	8.65
617	17.07	2.49	7.15
618	17.08	2.33	6.67
622	17.13	2.42	6.78

ANDERSON #3, VINCENT, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
217	11.98	2.67	7.20
221	12.03	2.56	8.04
228	12.11	2.69	7.74
290	12.80	2.38	9.65
292	12.82	2.63	10.05
305	12.97	2.39	9.98
310	13.02	2.30	7.52
319	13.09	2.32	9.85
324	13.15	2.29	9.11
445	14.98	2.42	13.06
576	16.37	2.56	8.81
579	16.42	2.02	9.09
586	16.50	2.27	8.65
616	16.87	2.49	7.15
617	16.89	2.33	6.67
621	16.94	2.42	6.78

BOOK #1, REDFIELD, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
648	23.04	2.47	6.41
651	23.08	2.66	10.86
653	23.12	2.54	8.26
658	23.21	2.71	7.32
664	23.37	2.56	11.49

BRODERICK #1, REDFIELD, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
155	14.44	2.16	7.79
160	14.51	2.66	7.61
166	14.61	2.71	9.53

J. ANDERSON #1, KEOTA, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
300	21.08	2.67	7.22
301	21.13	2.66	7.04
303	21.16	2.65	6.55
305	21.20	2.65	6.12
308	21.28	2.64	8.58
309	21.30	2.61	7.12
314	21.38	2.41	11.35
318	21.47	2.32	13.02
320	21.51	2.32	12.25
325	21.61	2.20	12.04
344	22.09	2.68	7.11

L. VOGEL #1, KEOTA, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
300	21.33	2.67	7.21
301	21.37	2.66	7.04
303	21.40	2.65	6.50
305	21.45	2.65	6.22
308	21.52	2.64	8.57
309	21.54	2.61	7.31
314	21.64	2.41	11.31
318	21.73	2.32	13.07
320	21.77	2.32	12.38
325	21.88	2.20	12.07
344	22.47	2.68	7.10

OLSON #1 "G", REDFIELD, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
217	11.54	2.67	7.20
221	11.59	2.56	8.05
228	11.67	2.69	7.75
290	12.36	2.38	9.66
292	12.39	2.63	10.07
305	12.54	2.39	10.00
310	12.59	2.30	7.53
319	12.65	2.32	9.87
324	12.69	2.29	9.12
445	14.34	2.42	13.08
576	15.62	2.56	8.84
579	15.65	2.02	9.11
586	15.73	2.27	8.67
616	16.26	2.49	7.16
617	16.28	2.33	6.68
621	16.35	2.42	6.80

P. HUTCHINSON #2, CAIRO, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
227	15.72	2.43	7.08
238	15.92	2.43	8.71
240	15.96	2.63	10.11
247	16.11	2.40	6.97
250	16.20	2.58	6.81
252	16.25	2.66	7.58
255	16.31	2.65	7.93

PRICE #1, REDFIELD, IOWA

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
416	17.99	2.54	5.34
417	18.02	2.51	5.78
428	18.27	2.27	5.09
455	18.80	2.47	4.88

#972, MARION, MICHIGAN

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
463	21.07	2.38	10.28
465	21.09	2.21	9.12
466	21.10	2.23	9.22
467	21.12	2.08	8.68
469	21.13	2.34	9.37
470	21.15	2.22	9.11
471	21.15	2.30	10.20
472	21.16	2.26	10.62

#N-203, NORTHVILLE, MICHIGAN (ORIGINAL SET)

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
991	23.08	2.74	12.58
995	23.12	2.81	12.85
997	23.14	2.76	12.31
1001	23.18	2.83	12.17
1003	23.21	2.84	11.47
1016	23.35	2.78	12.29
1024	23.45	2.81	11.64
1030	23.52	2.81	12.57
1299	32.16	2.84	9.07
1300	32.20	2.83	9.70
1315	32.43	2.84	9.94
1316	32.44	2.82	10.02
1326	32.60	2.81	9.06
1350	33.03	2.83	10.49
1358	33.18	2.80	9.74
1361	33.22	2.85	9.62

#N-203, NORTHVILLE, MICHIGAN

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
989	23.04	2.82	12.04
991	23.08	2.74	12.58
993	23.10	2.77	13.21
995	23.12	2.81	12.85
997	23.14	2.76	12.31
1001	23.18	2.83	12.17
1003	23.21	2.84	11.47
1003	23.22	2.87	11.96
1006	23.24	2.83	12.29
1011	23.29	2.81	11.89
1014	23.33	2.89	14.02
1016	23.35	2.78	12.29
1020	23.40	2.77	10.84
1023	23.43	2.80	13.53
1024	23.45	2.81	11.64
1027	23.47	2.80	11.98
1028	23.50	2.80	9.55
1030	23.52	2.81	12.57
1031	23.53	2.76	11.70
1033	23.55	2.81	12.28
1286	31.72	2.82	10.06

#N-203, NORTHVILLE, MICHIGAN (con't.)

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
1289	31.85	2.82	10.03
1299	32.16	2.84	9.07
1300	32.20	2.83	9.70
1302	32.23	2.85	9.88
1305	32.28	2.84	9.95
1315	32.43	2.84	9.94
1316	32.44	2.82	10.02
1318	32.48	2.83	8.88
1323	32.56	2.83	10.69
1326	32.60	2.81	9.06
1328	32.63	2.82	9.53
1329	32.64	2.82	10.69
1344	32.90	2.82	10.39
1350	33.03	2.83	10.82
1354	33.10	2.82	11.33
1357	33.15	2.84	8.88
1358	33.18	2.80	9.74
1361	33.22	2.85	9.68

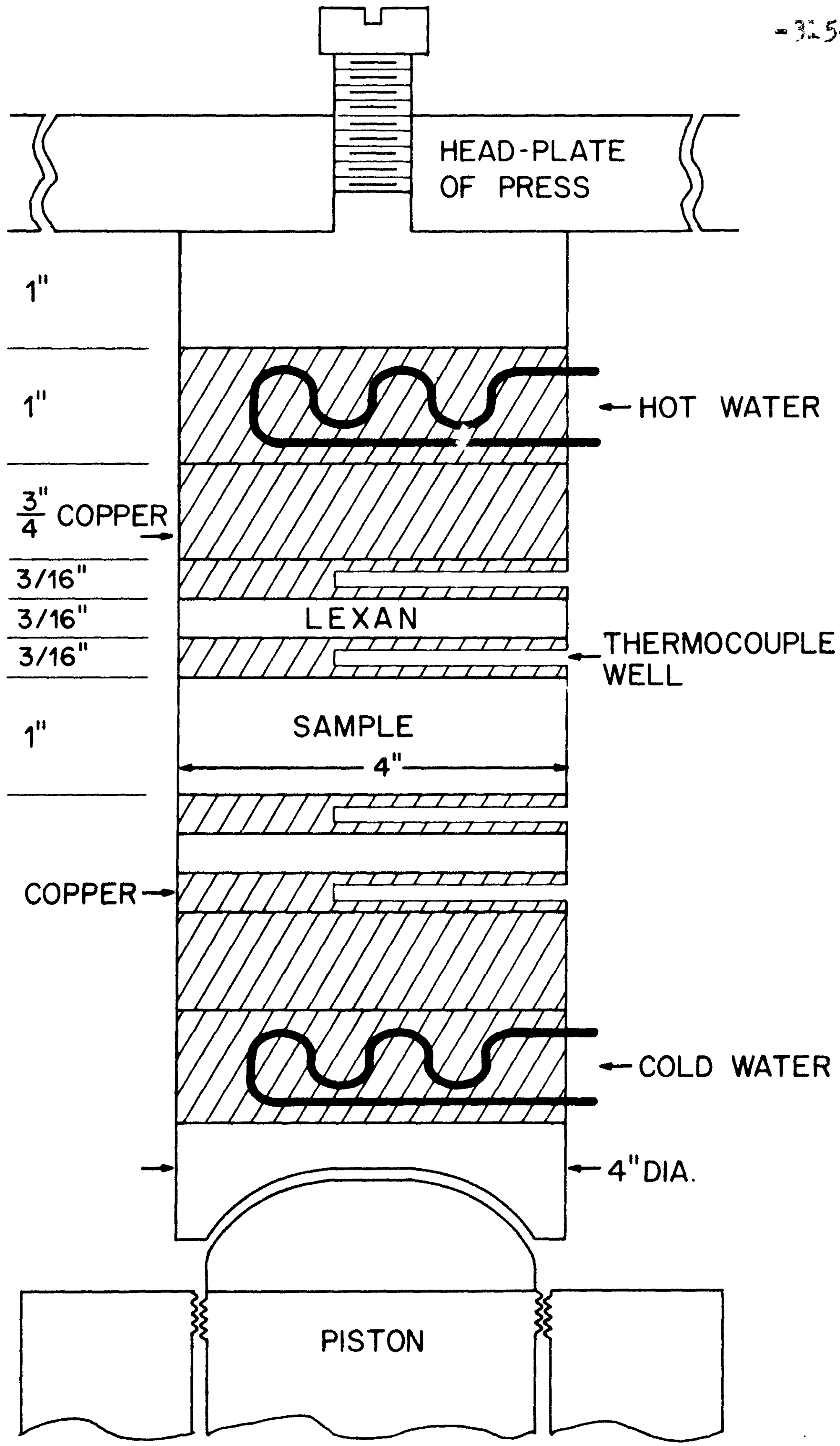
#S-503-E, BURNIPS, MICHIGAN

DEPTH	TEMPERATURE	DENSITY	CONDUCTIVITY
777	23.36	2.63	9.17
778	22.37	2.44	10.31
781	22.41	2.64	9.87
782	22.44	2.72	11.56
785	22.48	2.68	8.65
790	22.52	2.80	9.93
791	22.53	2.64	7.07
793	22.56	2.74	8.19
804	22.67	2.61	7.13
806	22.69	2.71	10.86

APPENDIX III

THERMAL CONDUCTIVITY APPARATUS

The divided-bar thermal conductivity apparatus (Figure III.1) consists of a stack of circular discs which was assembled in a hydraulic press, Ener Pac model RC-156, with a ten ton capacity. Two thermostatically controlled temperature baths, a Lab-line constant temperature circulating system model 3052 and a Lauda model NB constant temperature circulator, were used to produce a temperature difference across the sample and the reference elements. Since most of the in situ rock temperatures were approximately 20 °C, an Ebco Manufacturing Company model IW-10A In-a-wall air cooled refrigeration unit was used to cool the water for the Lauda constant temperature circulator. In order to reduce lateral heat losses, the stack was enclosed in polystyrene insulation, General Latex Vultafoam 15-L-206. Four thermocouples of number 28 copper-constant wire were used to measure the differences of temperature across the three poor conductors. Two of the poor conductors consisted of Lexan, a polycarbonate plastic, sandwiched between two copper discs and the third was the rock disc to be measured. The Lexan discs were cemented to the copper discs with Union Carbide Bakelite ERL-2795 epoxide plastic and ERL-2793 hardener in order to eliminate two-thirds of the variable contact resistances. Each thermocouple tip was covered with an insulating paint and immersed in Dow Corning 340 silicone heat sink compound in the wells drilled in the copper discs. The thermal emfs were measured with a Honeywell model 2784 potentiometer and a Keithley model 148 nanovoltmeter.


HEAD-PLATE OF PRESS
1"
1"
HOT WATER
3/4" COPPER
3/16"
3/16"
LEXAN
3/16"
THERMOCOUPLE WELL
1"
SAMPLE
4"
COPPER
COLD WATER
4" DIA.
PISTON

BIOGRAPHICAL NOTE

The author was born in Cordell, Oklahoma on July 15, 1942. He attended grammar school in Cordell and graduated from Cordell High School in June, 1960. In September, 1960, he entered Southern Methodist University in Dallas, Texas and graduated with a Bachelor of Science Degree in Mathematics and Geology in June, 1964. Upon receiving an NDEA Group IV fellowship, he remained at SMU for two additional years doing graduate work in physics, mathematics, and geophysics. The author entered the department of Geology and Geophysics (now Earth and Planetary Sciences) at the Massachusetts Institute of Technology in September, 1966. As a candidate for the degree of Doctor of Philosophy at MIT, he held a traineeship from the National Aeronautics and Space Administration.

In July, 1966, the author married Carolyn Lenoir Miller of Wilmette, Illinois; the couple have two children, Timothy Richmond and Andrew James.

The author is a member of the American Association for the Advancement of Science, Sigma Xi, and the American Geophysical Union. His previous scientific works include the following:

Combs, Jim, Automatic intersection analysis for three dimensional interpretation, Texas Instruments Co., Internal Publication, September, 1967.

Combs, Jim, and Gene Simmons, Heat flow measurements in Iowa, Trans. Am. Geophys. Union, 50, 316, 1969, abs.