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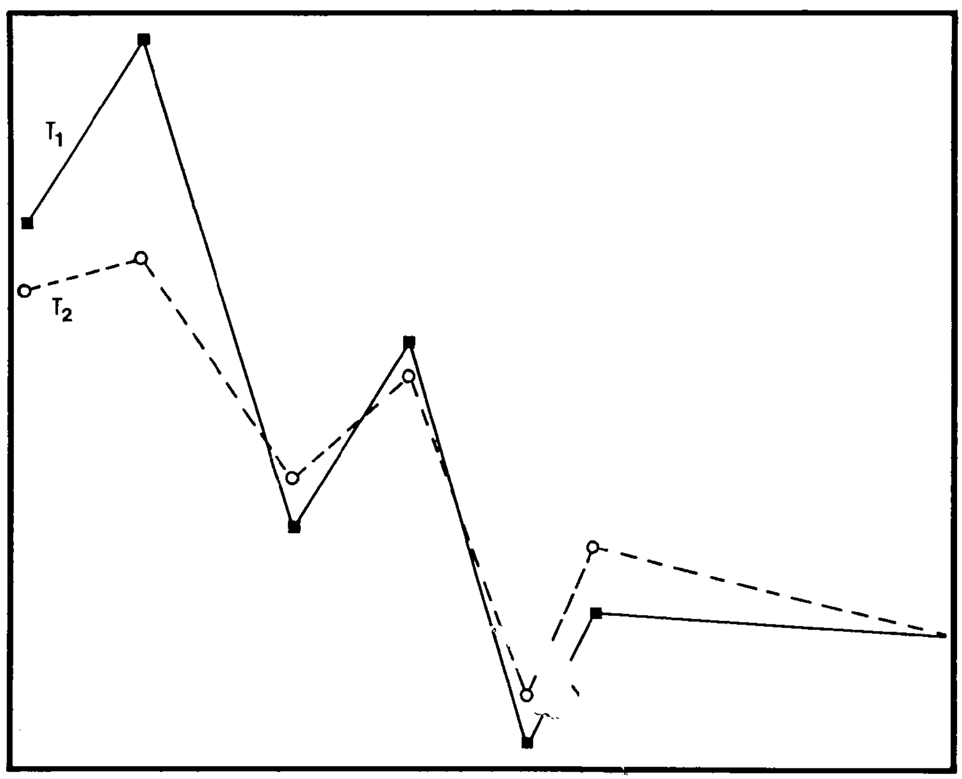
Temperature-Gradient Information for Several Boreholes Drilled in Oklahoma

William E. Harrison, Kenneth V. Luza



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TEMPERATURE-GRADIENT INFORMATION FOR SEVERAL BOREHOLES DRILLED IN OKLAHOMA

Prepared by

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Idaho Operations Office
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(ORIGINAL TITLE: Monitoring Temperature Conditions
in Recently Drilled Nonproductive Industry
Boreholes in Oklahoma)

Oklahoma Geological Survey
Charles J. Mankin, Director
The University of Oklahoma
Norman, Oklahoma

1986

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TEMPERATURE-GRADIENT INFORMATION FOR SEVERAL BOREHOLES DRILLED IN OKLAHOMA

William E. Harrison and Kenneth V. Luza

ABSTRACT

Temperature conditions were monitored in six industry wells (called holes-of-opportunity in this report) that were drilled in central and eastern Oklahoma. Five of these wells provided useful temperature information, and two wells were used to determine the length of time needed for the borehole-fluid temperature to achieve thermal equilibrium with the formation rocks. The Ward Petroleum 1 Boardman well in Cleveland County had a final equilibrated temperature of 66^{o}F at 776 ft about 65 days after the cessation of drilling. A temperature survey began in the TXO F-1 Henley well in Pittsburg County 107 days after drilling had stopped. The temperature measurements indicated that the fluids within the borehole probably had achieved thermal equilibrium prior to the first temperature survey.

Four wells were used to verify the validity of a geothermal-gradient map of Oklahoma (Cheung, 1978). Temperature surveys in two wells indicated a gradient lower than the predicted gradients on the geothermal-gradient map. When deep temperature data, between 5,000 and 13,000 ft, are adjusted for mud-circulation

effects, the adjusted gradients approximate the gradients on the geothermal-gradient map. Two boreholes that were surveyed showed the possible influence of ground water on the temperature gradient. In one hole the temperature gradient was lowered by movement of ground water, whereas the gradient was raised in the second well.

The temperature-confirmation program appears to substantiate the geographic distribution of the high- and low-thermal-gradient regimes in Oklahoma. Some variation in site-specific gradient conditions exists, however. Therefore, the map data should serve only as a guide for gradient information. Precise temperature measurements at specific depths are needed to assess a site for a potential geothermal application.

INTRODUCTION

In connection with activities performed under Contract DE-AS07-80ID12172 to evaluate the geothermal resources of Oklahoma, a number of peripheral investigations were conducted. These investigations are summarized in Prater and others (1981), Harrison and Luza (1982), Harrison and others (1983), and Luza and others (1984). During 1983-85, two additional studies were made. Both are important for a better understanding of the geothermal potential of Oklahoma and are subjects of topical reports.

This study concerns the program to monitor temperature conditions in six industry wells (called holes-of-opportunity in this report) that were drilled in central and eastern Oklahoma. By far the most abundant information on geothermal-gradient conditions in Oklahoma comes from geophysical logs that are used to evaluate the potential of wells drilled in search of petroleum. The drilling process affects the temperature of the rocks that are penetrated, and the temperature data that appear on logs usually do not reflect true (equilibrated) formation temperature.

A geothermal-gradient map of Oklahoma (Cheung, 1978) was constructed from temperature data given in industry geophysical logs. Although the temperature data were subjected to various adjustments (Cheung, 1978,1979), site-specific information concerning thermal equilibration after drilling generally is not available. In order to gain basic information on the variation between log-heading data and equilibrated thermal conditions, a portion of the activities of Contract DE-AS07-80ID12172 was directed toward monitoring temperature conditions in industry holes-of-opportunity. To implement this program, it was necessary to contact operators to work out a mutually suitable means for the Oklahoma Geological Survey (OGS) to assume responsibility for several matters pertaining to final plugging and site restoration of wells declared to be dry and abandoned (D&A).

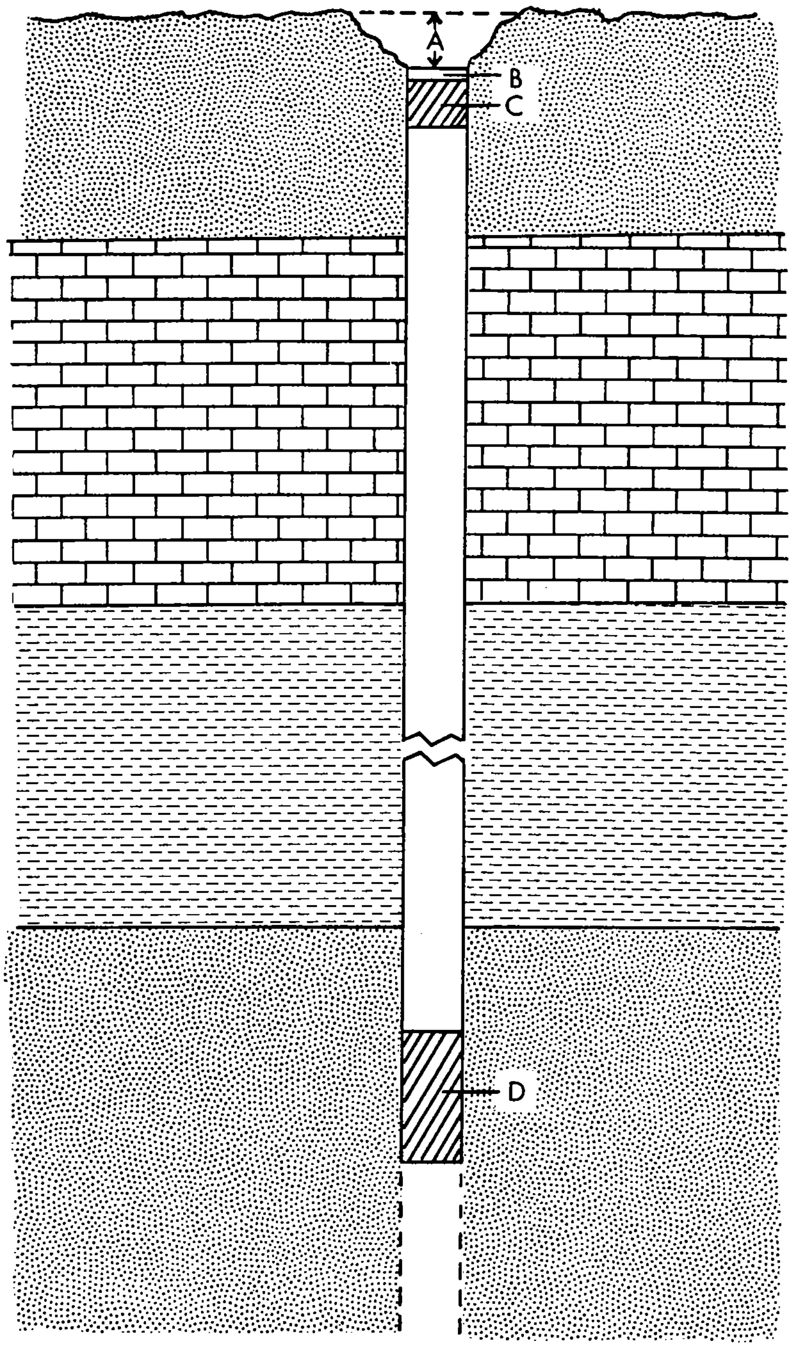
In Oklahoma, D&A wells must have a 100-ft cement plug at the bottom of the surface casing and a 30-ft plug at the top. The surface casing must be cut at least 36 in. below ground level, and a steel plate must be welded to the top of the casing. In the present program the operators were asked to set the 100-ft (bottom) plug and turn the well over to the OGS for research purposes. The OGS became responsible for (1) final plugging (30-ft surface plug), (2) cutting the surface casing off at the required depth, (3) welding the plate to the casing, and (4) backfilling the pit around the surface casing (Fig. 1).

The Oklahoma Corporation Commission, the regulatory agency for oil and gas operations within the state, permits open casing in abandoned wells for research purposes for up to 120 days. Holes-of-opportunity were difficult to obtain in the Pittsburg and Haskell County area, because almost all the activity is in-fill (development) drilling, and wells with relatively low initial potentials are routinely completed as productive wells or listed as shut-in wells. Thus the number (and location) of wells available for this part of the study were not ideal.

The results of this temperature-monitoring program are described in the next section.

ACKNOWLEDGMENTS

A critical part of this study involved the monitoring of temperature conditions in recently drilled oil and gas boreholes. To obtain these data, the Oklahoma Geological Survey solicited the cooperation of oil and gas companies in the use of wells which proved to be noncommercial. We thank Jumas Oil, Ward Petroleum, TXO Production Corp., and Tenneco Oil Co. for their cooperation on this project.



A -- minimum of 3 ft

B -- required plate welded to surface casing

C -- cement plug (30 ft) required at top of casing

D -- cement plug (100 ft) required at bottom of casing

Figure 1. Current plugging program required by the Oklahoma Corporation Commission for dry and abandoned boreholes. The distance between C and D is the vertical interval in which fresh-water-bearing formations might occur. These intervals vary in thickness and depend on geographic location.

INSTRUMENTATION

A precision micro-thermometer was constructed according to specifications provided to the OGS by S. T. Morrisey of St. Louis University. Figure 2 shows the circuit diagram of the micro-thermometers used in this investigation. Early attempts to monitor downhole temperature conditions using the micro-thermometer and conventional (7-conductor) logging cable were not successful. This resulted from the challenge of designing a tool that would be waterproof under the pressure conditions that exist at depths of a few thousand feet. After two downhole-tool designs failed after reaching total depth in well bores, a stainless-steel assembly was obtained from Log-Master Services, Inc. (Enid, Oklahoma). The interior of the assembly was milled out so that the micro-thermometer components could be accommodated, and threaded bar stock was added for weight (Fig. 3). The assembly was connected to a Log-Master Model LMH-30-POE hoist, which was fitted with 3,000 ft of 4-conductor cable. The resulting system was used successfully, and attempts to install sacrificial downhole sensing devices were abandoned.

The micro-thermometer circuitry provides for one sensor (T_1) to measure temperatures up to 60°C and another sensor (T_2) to measure temperatures greater than 60°C. The micro-thermometer was calibrated against a Class M mercury thermometer as shown in Table 1.

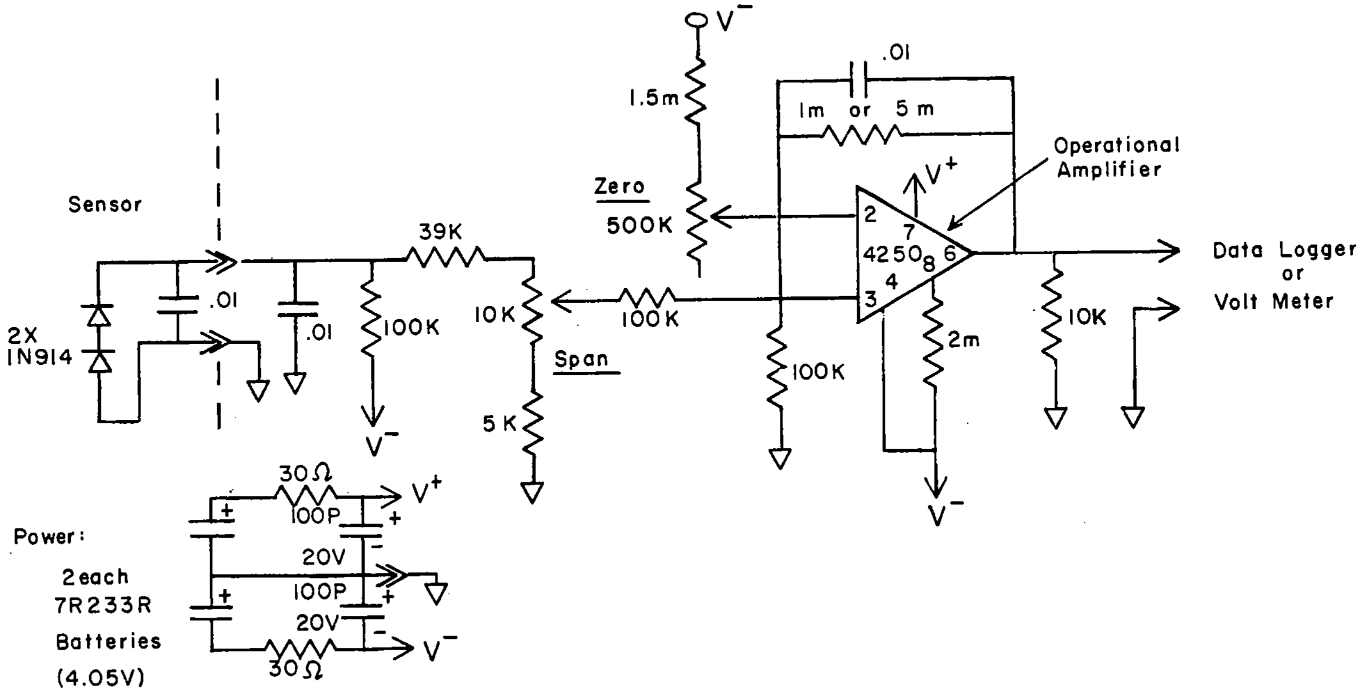


Figure 2. Circuit diagram for precision micro-thermometer.

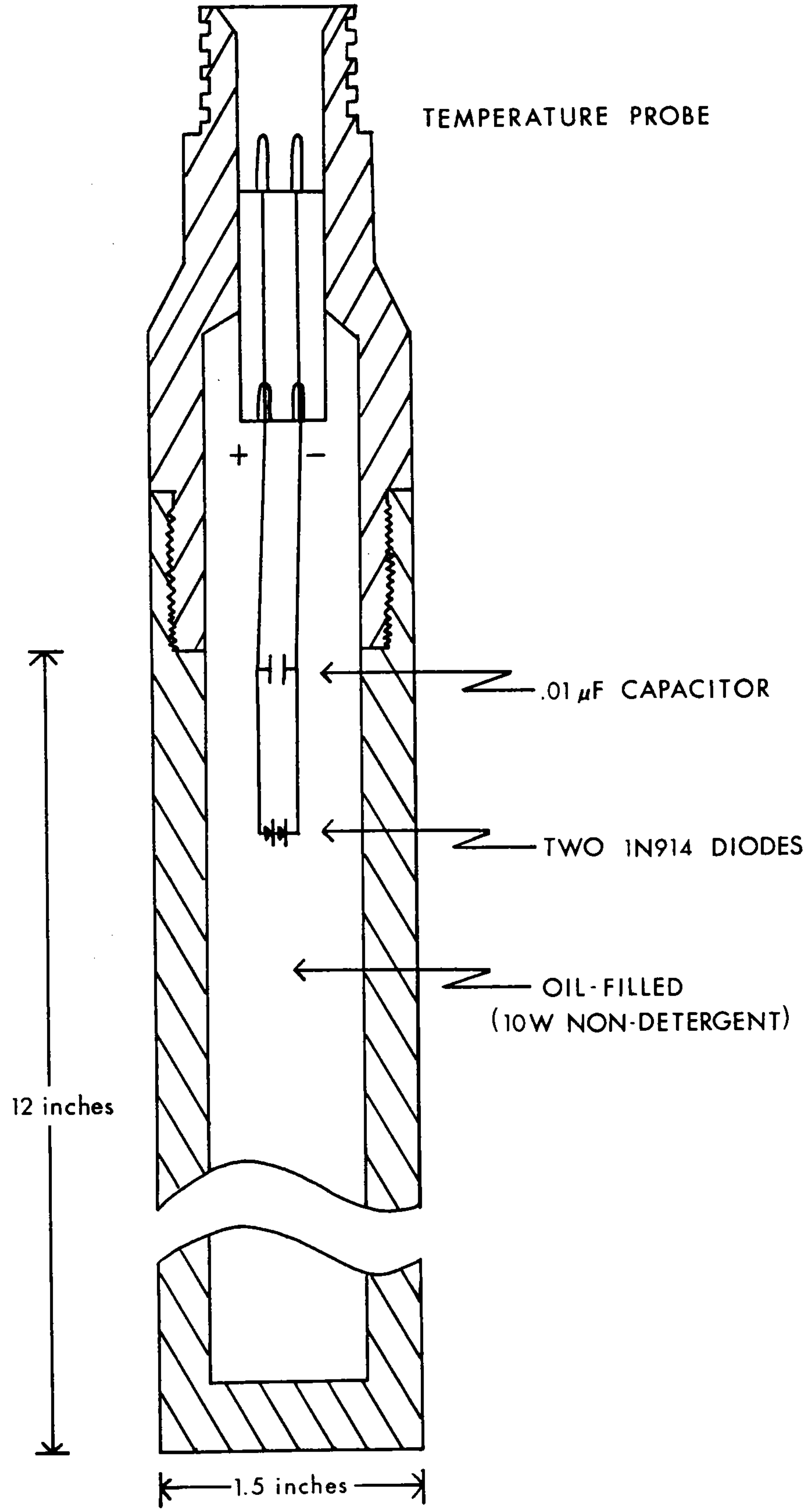


Figure 3. Schematic cross section of the temperature probe used in the downhole temperature surveys.

Table 1. Calibration data for micro-thermometer

Mercury thermometer		T_1		T_2	
^{o}C	^{o}F	^{o}C	^{o}F	^{o}C	^{o}F
21.6	70.88	22.6	72.68	22.2	71.96
29.2	84.56	30.6	87.08	30.8	87.44
43.3	109.94	44.2	111.56	44.9	112.82
43.8	110.84	44.8	112.64	45.4	113.72
61.8	143.24	63.6	146.43	65.7	150.26
65.6	150.08			69.6	157.28
70.0	158.00			73.5	164.30

The linear regression equations for T_1 and T_2 are:

$$T_1 = Y = -0.803 + 0.987(X),$$

$$T_2 = Y = 3.635 + 0.935(X),$$

where T_1 and T_2 are corrected temperatures in ^{o}F, and X values are uncorrected temperatures in ^{o}F.

Because of slightly greater sensitivity, and because most measurements were below 140^{o}F (60^{o}C), data from the T_1 circuit were used in this study. Also, in keeping with industry convention for temperature data, measurements resulting from this investigation are reported in ^{o}F.

TEMPERATURE-MONITORING PROGRAM

Jumas Oil 13 Oklahoma 2

This well, in sec. 5, T1S, R3E (Murray County), was involved in the first attempt at obtaining downhole temperature data (Fig. 4). Conventional 7-conductor logging cable was fitted with a temperature sensor that had been calibrated between 0 and 250°F. A digital voltmeter was used to indicate temperature at the sensor. The sensor and cable were lowered into the surface casing to a depth of approximately 900 ft. The sensor housing apparently was not waterproof at the pressure exerted by a 900-ft column of water, and the sensor failed after reaching the bottom of the hole. Thus, no useful temperature data were obtained.

Ward Petroleum 1 Boardman

This well, in sec. 19, T9N, R3W (Cleveland County), was the first well that provided useful temperature information (Fig. 5). The well had 888 ft of 8 5/8-in. surface casing, which was plugged back with cement to 795 ft when the borehole was declared noncommercial.

The first temperature measurement was made on January 25, 1984, at a depth of 795 ft 32 days after drilling had ceased. After several days the components of the drilling mud started settling to the bottom of the borehole, and over the 62-day monitoring period subsequent measurements were made at progressively shallower depths. The final measurement was made

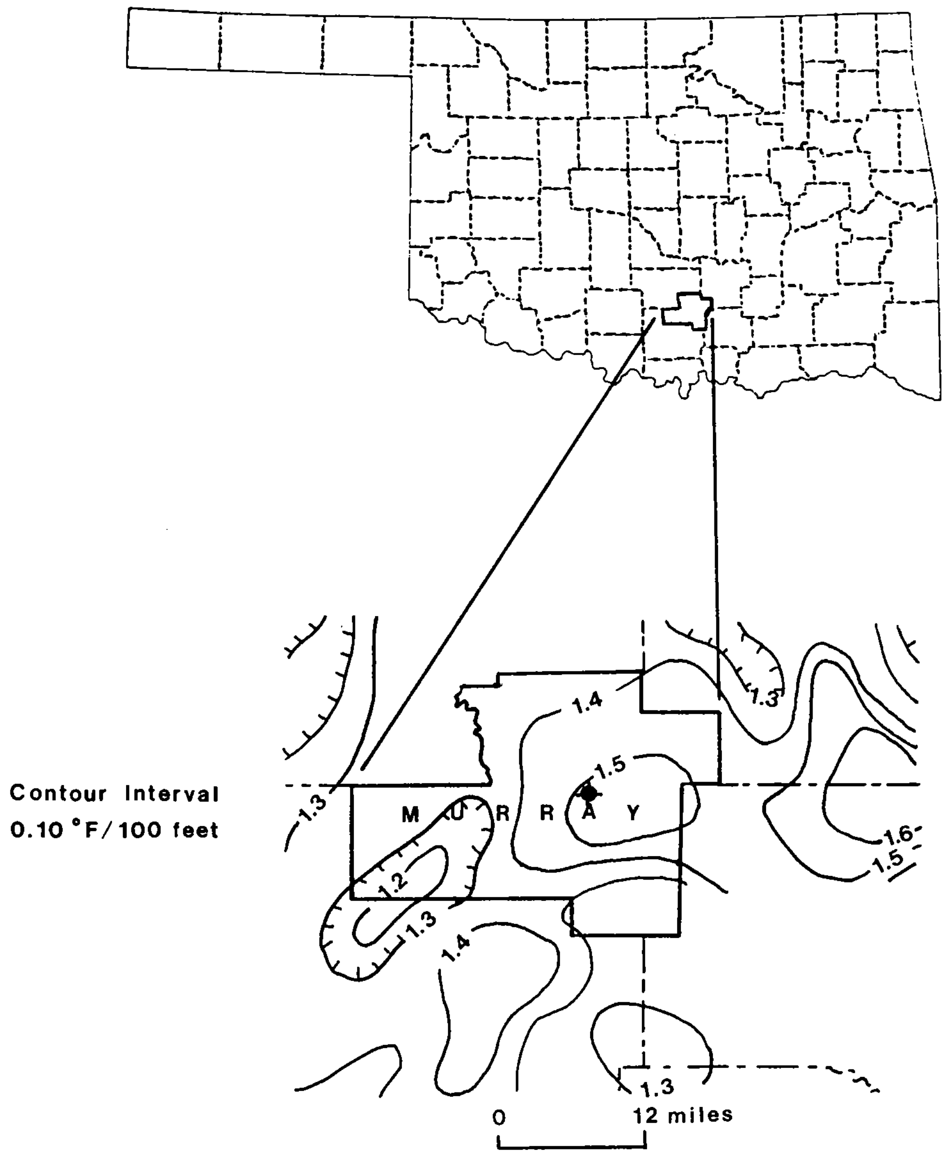


Figure 4. Location of the Jumas Oil 13 Oklahoma 2 well in Murray County and a portion of the geothermal gradient map (modified from Cheung, 1978). Mechanical problems with the sacrificial temperature sensor prevented the collection of reliable data.

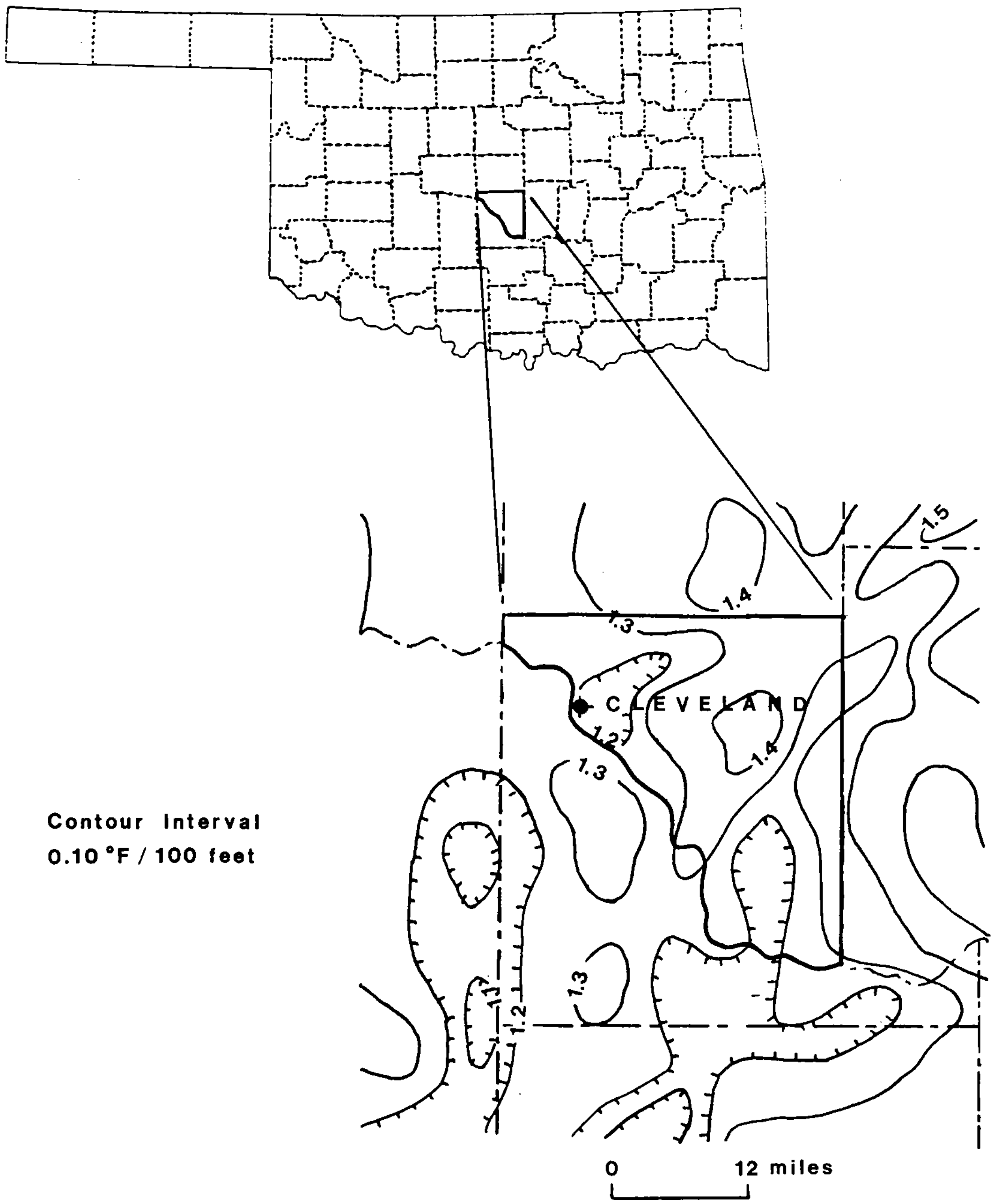


Figure 5. Location of the Ward Petroleum 1 Boardman well in Cleveland County and a portion of the geothermal gradient map (modified from Cheung, 1978). Temperature measurements over a 62-day interval confirm the presence of a relatively cool area in the northwestern part of the county.

at a depth of 776 ft. Figure 6 shows the variation in bottom-hole temperature as a function of time, following termination of drilling activity. The last two bottom-hole-temperature measurements indicate that the borehole achieved thermal equilibrium about 65 days after cessation of drilling.

The geothermal-gradient map of Oklahoma, a part of which appears in Figure 5, shows the Ward Petroleum 1 Boardman to be located in a relatively cool area. Using the criteria established by Cheung (1978), the temperature of the Boardman well should have been 71-72°F at 775 ft. The final equilibrated temperature was about 66°F at 776 ft and indicates that the area defined by the 1.2°F/100-ft gradient shown on the geothermal-gradient map (Fig. 5) is actually cooler than suggested by log-heading data. This example shows that there is some variation between site-specific gradient conditions, as interpreted from industry data, and equilibrated downhole measurements. Although certain features (i.e., the cool area in northwestern Cleveland County) shown on the geothermal-gradient map may be geographically correct, precise temperature measurements at specific depths should be obtained after thermal equilibration has occurred.

Oklahoma Geophysical Observatory Borehole

In 1961, Humble Research and Development Corp. drilled a borehole to a depth of 2,540 ft in sec. 35, T17N, R14E (Fig. 7). This hole, which was drilled for geophysical and petrophysical research purposes, was made available for the present study.

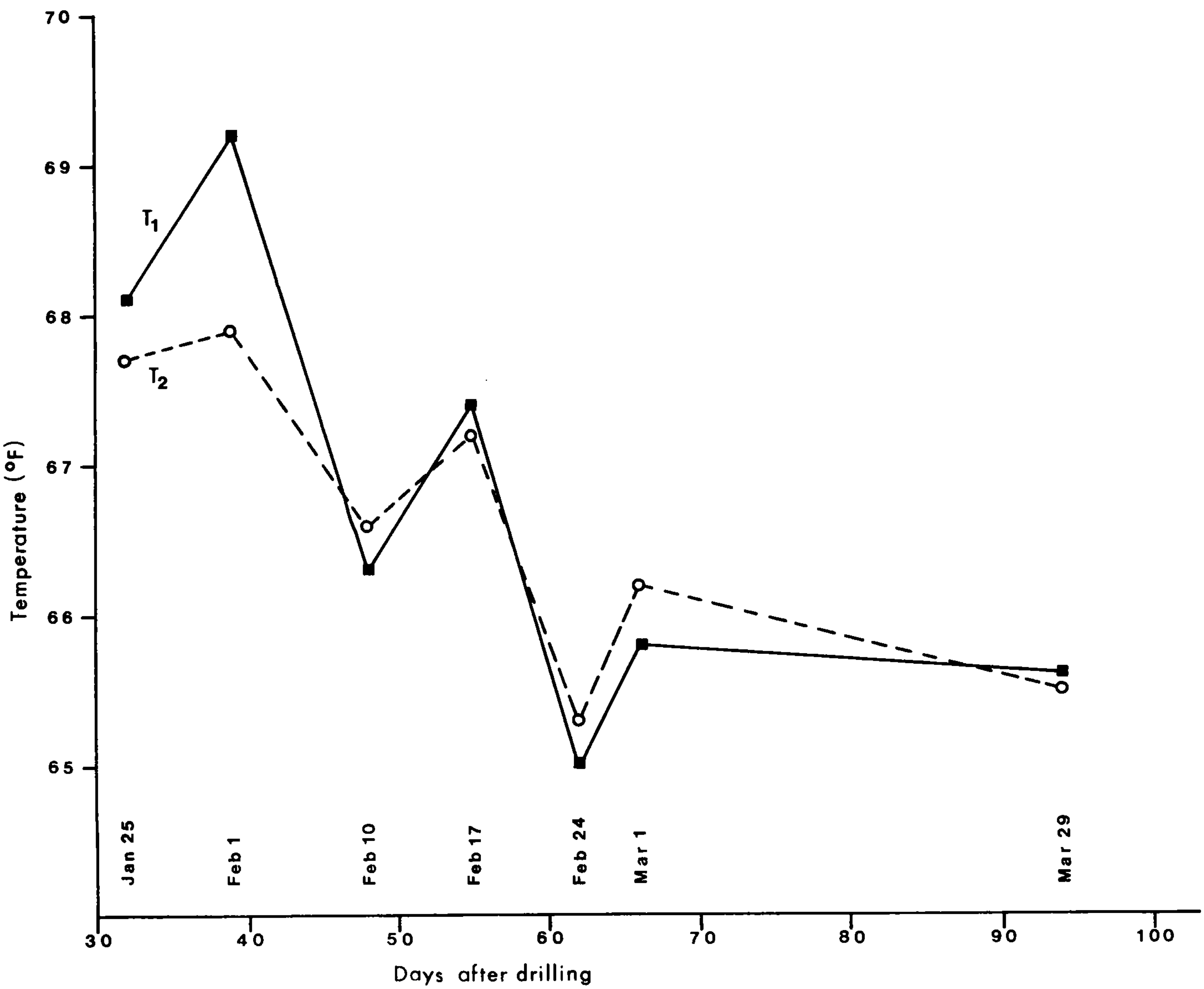


Figure 6. Relationship between borehole temperature and number of days since drilling was terminated for the Ward Petroleum 1 Boardman well (Cleveland County).

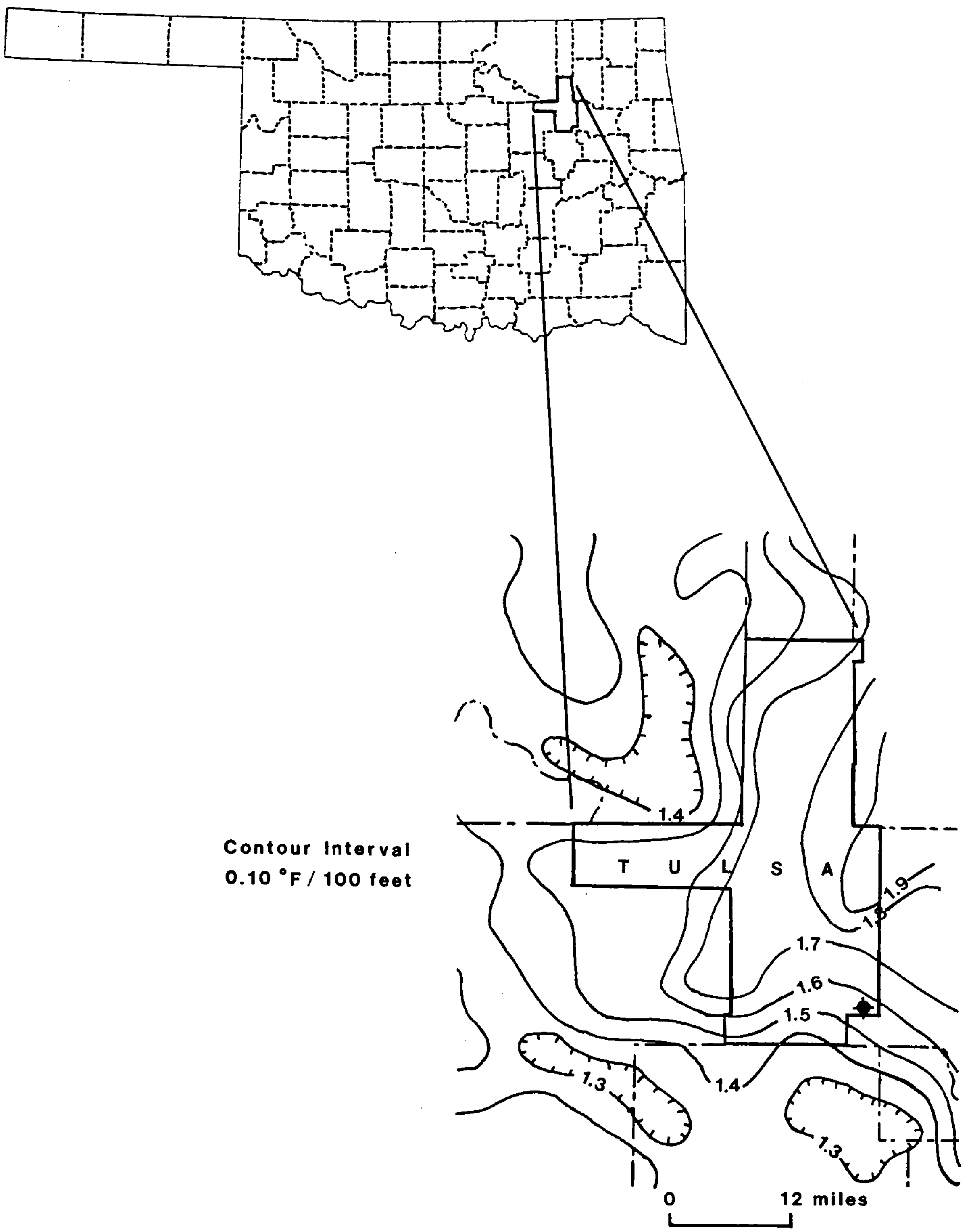


Figure 7. Location of the Oklahoma Geophysical Observatory borehole in Tulsa County and a portion of the geothermal gradient map (modified from Cheung, 1978).

The geothermal-gradient map indicates a gradient of about 1.55°F/100 ft for the area in which this borehole is located (Fig. 7). The temperature was recorded at depths of 2,539; 2,250; 2,000; 1,500; 1,000; and 500 ft (Table 2).

Table 2. Temperature data for the Oklahoma Geophysical Observatory borehole

Depth (ft)	Recorded temperature (°C)	Calculated temperature (°F)	Corrected temperature (°F)
500	20.8	69.4	67.7
1000	27.2	80.9	79.1
1500	33.4	92.1	90.1
2000	38.8	101.8	99.7
2250	40.8	105.4	103.2
2539	41.8	107.2	105.0

A graphical plot of the temperature-vs.-depth data is shown in Figure 8. A linear-regression fit of the data points produces a gradient of 1.9°F/100 ft. This value is much higher than anticipated. However, a straight-line fit drawn between the data points produces four separate slope changes and an overall decrease in temperature gradient with depth (Fig. 8). Between the 500 and 1,500-ft level, the calculated temperature gradient

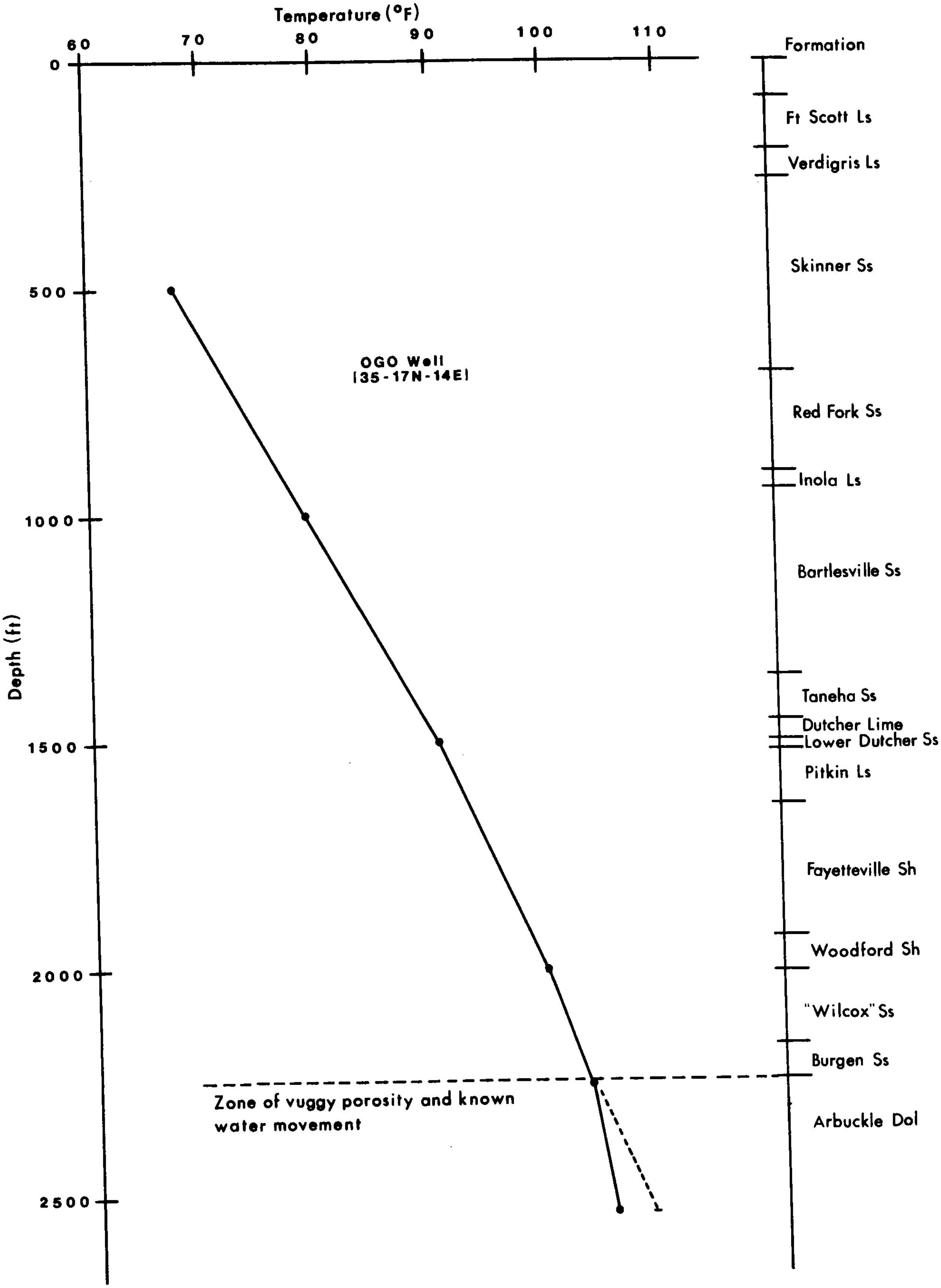


Figure 8. Depth-temperature curve for the Oklahoma Geophysical Observatory borehole (Tulsa County).

is 2.24°F/100 ft. The temperature gradient decreases to 1.92°F/100 ft between the 1,500 to 2,000-ft interval. Below the 2,000-ft level to 2,250 ft, the gradient is 1.4°F/100 ft. The interval between 2,250 and 2,539 ft shows a sharp decrease in gradient to 0.62°/100 ft. The steep reversal in gradient below 2,250 ft also corresponds to the Burgen Sandstone-Arbuckle Group contact.

The Arbuckle Group, which is composed mostly of dolomite, usually has vuggy porosity and is a zone of water movement in this area (Jorgensen and Signor, 1981). This movement probably inhibits thermal equilibrium and distorts static gradient conditions.

If the temperature information below 1,500 ft is grouped into a single data set, a graphical plot of the data would project a temperature value of 108°F at 2,539 ft (Fig. 8). This gives a calculated gradient of 1.66°F/100 ft. The calculated gradient is higher than the predicted value of 1.55°F/100 ft from the geothermal-gradient map.

The depth-temperature data obtained in the Oklahoma Geophysical Observatory borehole exhibits both very high and very low thermal gradients. Geothermal applications involving specific reservoirs should be designed on the basis of such local variations. Thus, in a situation like this one, a calculated gradient from a single borehole-temperature measurement could be highly misleading for most geothermal applications.

Eagle Picher Powerhouse Well

In 1929, Eagle Picher Mining and Smelting Co. drilled a water well to 1,229 ft in sec. 25, T29N, R22E, in Ottawa County (Fig. 9). The water was used in the operation of a nearby electrical-generation plant as well as for drinking and sanitation. This well, which was scheduled to be plugged in late October 1984, became available for a temperature survey.

Although little temperature-gradient information exists for northeastern Oklahoma, the temperature-gradient map suggests that the geothermal gradient increases toward this corner of the state (Cheung, 1978). Furthermore, a driller's log and a sample description were available for this well (Reed and others, 1955). Therefore, this well appeared to be ideally suited for a temperature survey.

The well had approximately 7 1/2-in. casing to a depth of 384 ft. Open-hole conditions existed below the 384-ft level to a total depth of 1,229 ft. On September 29, 1984, the powerhouse well was logged by the U.S. Geological Survey. The logs obtained from this survey include caliper, gamma, electric-log, gamma-gamma, neutron, flow meter, long-short normal resistivity, and fluid resistivity. The fluid level in the well was 151 ft below the surface.

The temperature survey was conducted on October 23, 1984. Between 500 ft and 1,200 ft, temperature measurements were taken at 100-ft intervals. Table 3 lists the temperatures recorded at each depth interval. The depth-temperature plot indicates an

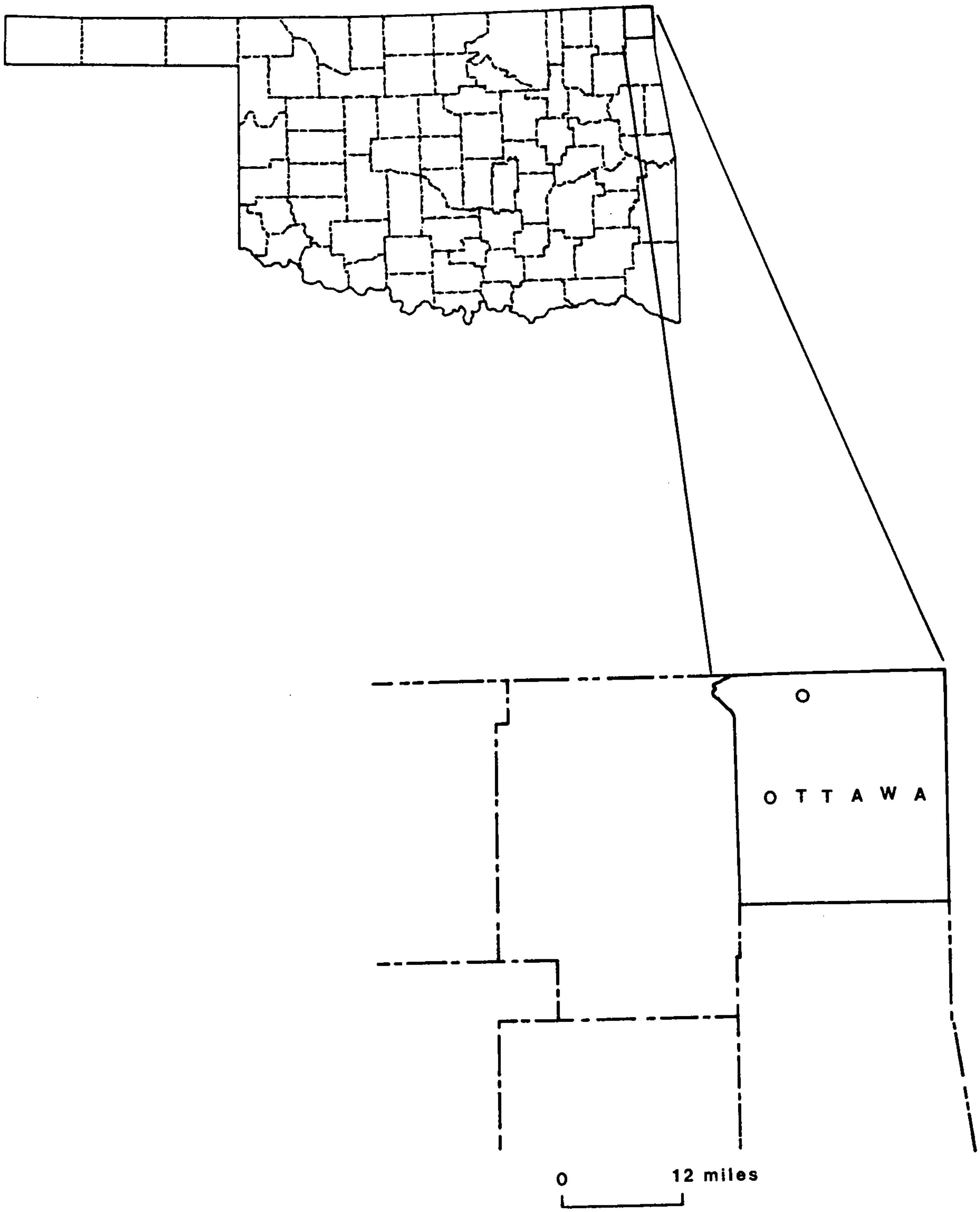


Figure 9. Location of Eagle Picher's powerhouse water well in Ottawa County.

abrupt change in gradient at about 1,000 ft (Fig. 10). Above 1,000 ft the gradient is approximately 0.47°F/100 ft. Below 1,000 ft the gradient increases to 1.47°F/100 ft.

Table 3. Temperature data for the Eagle Picher powerhouse well

Depth (ft)	Recorded temperature (°F)	Corrected temperature (°F)
300	65.7	64.0
500	66.7	65.0
600	67.3	65.6
700	67.8	66.1
800	68.0	66.3
900	68.7	67.0
1000	69.1	67.4
1100	70.5	68.9
1200	72.0	70.3

The very low temperature gradient above the 1,000-ft level in the borehole can be attributed to downward movement of ground water from the Boone Formation. The U.S. Geological Survey flowmeter measurements suggest that ground water, probably from the Boone Formation, was moving downward below the casing.

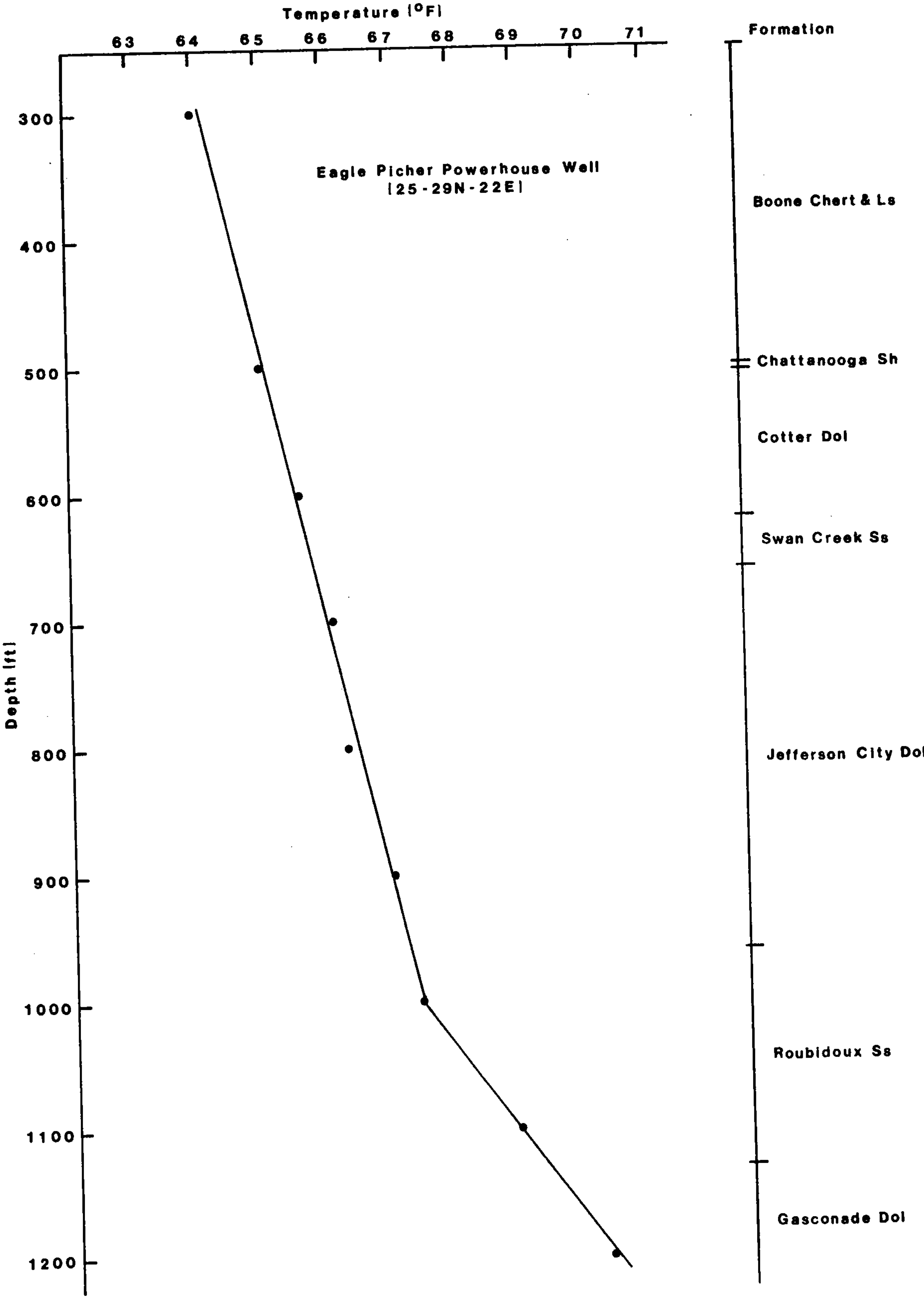


Figure 10. Depth-temperature curve for the Eagle Picher powerhouse well.

Perhaps the cooler Boone water, when mixed with water from deeper formations, causes the temperature gradient to be lower at this location.

Below the 1,000-ft level the abrupt change in gradient corresponds to a predominantly thick sandstone section in the Roubidoux Formation. The sample description for this well indicates that this sandstone interval occurs between 960 and 1,130 ft (Reed and others, 1955). Although the Roubidoux Formation is a major ground water aquifer in this region, it is not clear if a relationship exists between Roubidoux water and the gradient increase.

The well is about 1,000 ft or less west of the Miami Trough, which is a syncline and (or) graben that is up to 2,000 ft wide and has a maximum vertical displacement of about 300 ft (McKnight and Fischer, 1970). It is possible that water warmed in the deeper parts of the trough could move updip toward the west.

TXO F-1 Henley

A well drilled in Pittsburg County became available for a temperature survey after it was declared a dry hole in late October 1984. The well, in sec. 8, T3N, R16E, had a lower plug emplaced at the 4,685-ft level (Fig. 11). The casing program consisted of 1,628 ft of 11 3/4-in. and 4,685 ft of 8 5/8-in. pipe. Drilling had stopped on August 14, 1984.

The first temperature survey was made on November 29, 1984. Temperatures were measured at depths of 1,000; 1,500; 2,000; and 2,500 ft. Three additional temperature surveys were conducted on

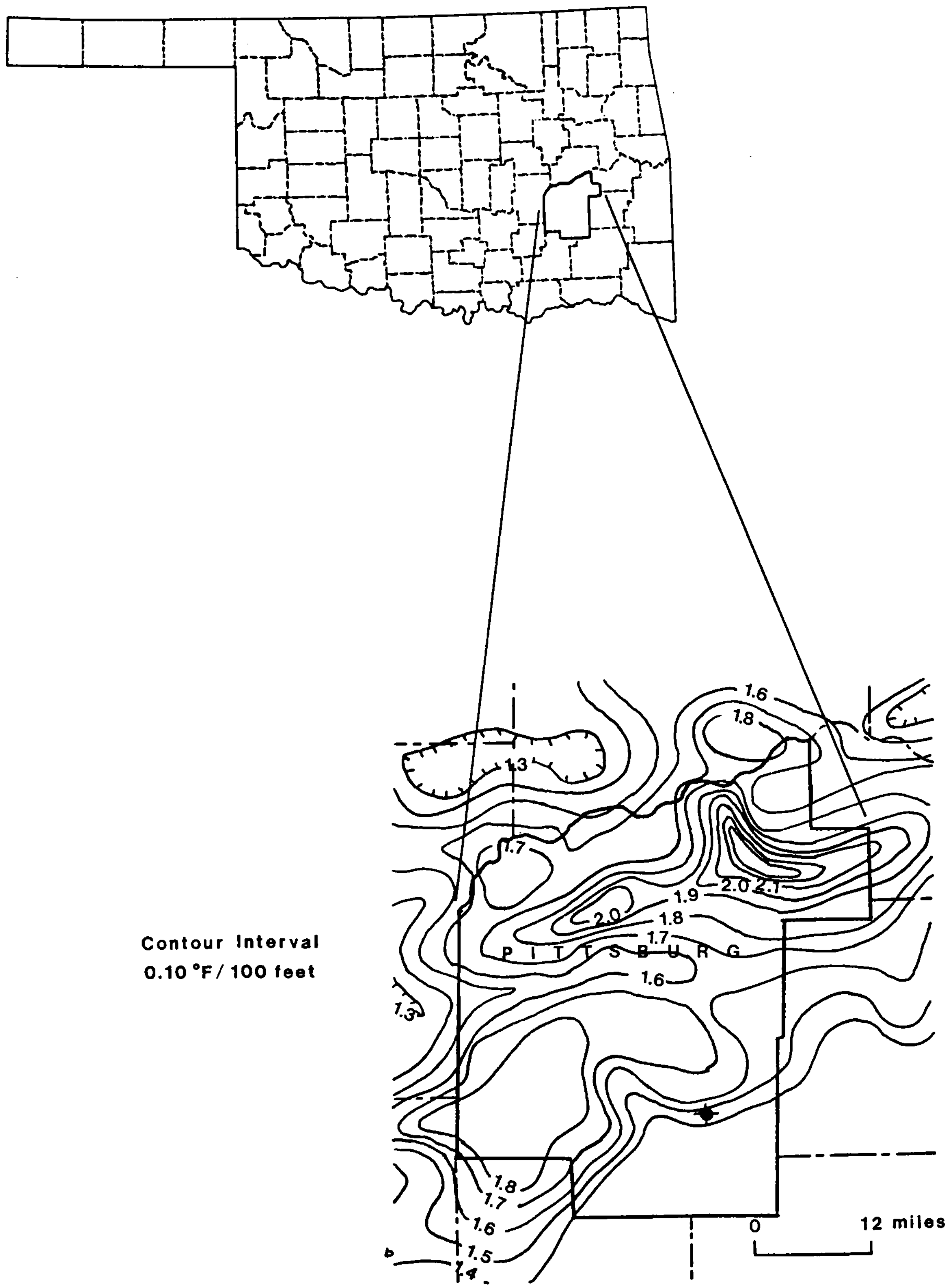


Figure 11. Location of the TXO F-1 Henley well in Pittsburg County and a portion of the geothermal gradient map (modified from Cheung, 1978).

December 18, 1984; January 16, 1985; and January 23, 1985. The T_1 temperature values recorded at the 1,500-ft level and the 2,500-ft level were plotted against time or days after drilling (Fig. 12). At the 1,500-ft level the December temperature was 1.8°F lower than the November reading. The temperature increased a few tenths of a degree in both January measurements. There was a decrease of 1.1°F between the November measurement and the last January measurement. At the 2,500-ft level the temperature increased 1.1°F in December and decreased in January. There was a decrease of 0.4°F between November and the last January measurement. The small fluctuation in temperature measurements is probably within instrumental and (or) operator error. Thus, the temperature data suggest that the fluids within the borehole probably achieved thermal equilibrium prior to the first temperature survey.

A temperature-vs.-depth plot of the January 23 data indicates a gradient of 1.1°F/100 ft (Table 4; Fig. 13). The geothermal-gradient map of Oklahoma indicates a gradient between 1.4° to 1.5°F/100 ft (Fig. 11). The discrepancy between the measured lower gradient and the geothermal-gradient map may be attributed to (1) an increase in gradient at depth and (or) (2) an error in the geothermal-gradient map of Oklahoma for this area.

No bottom-hole temperature was recorded for this well, but three nearby wells had temperatures recorded at different depths (Table 5). A temperature-vs.-depth plot for the nearby wells indicates a gradient of approximately 1.2°F/100 ft (Fig. 14).

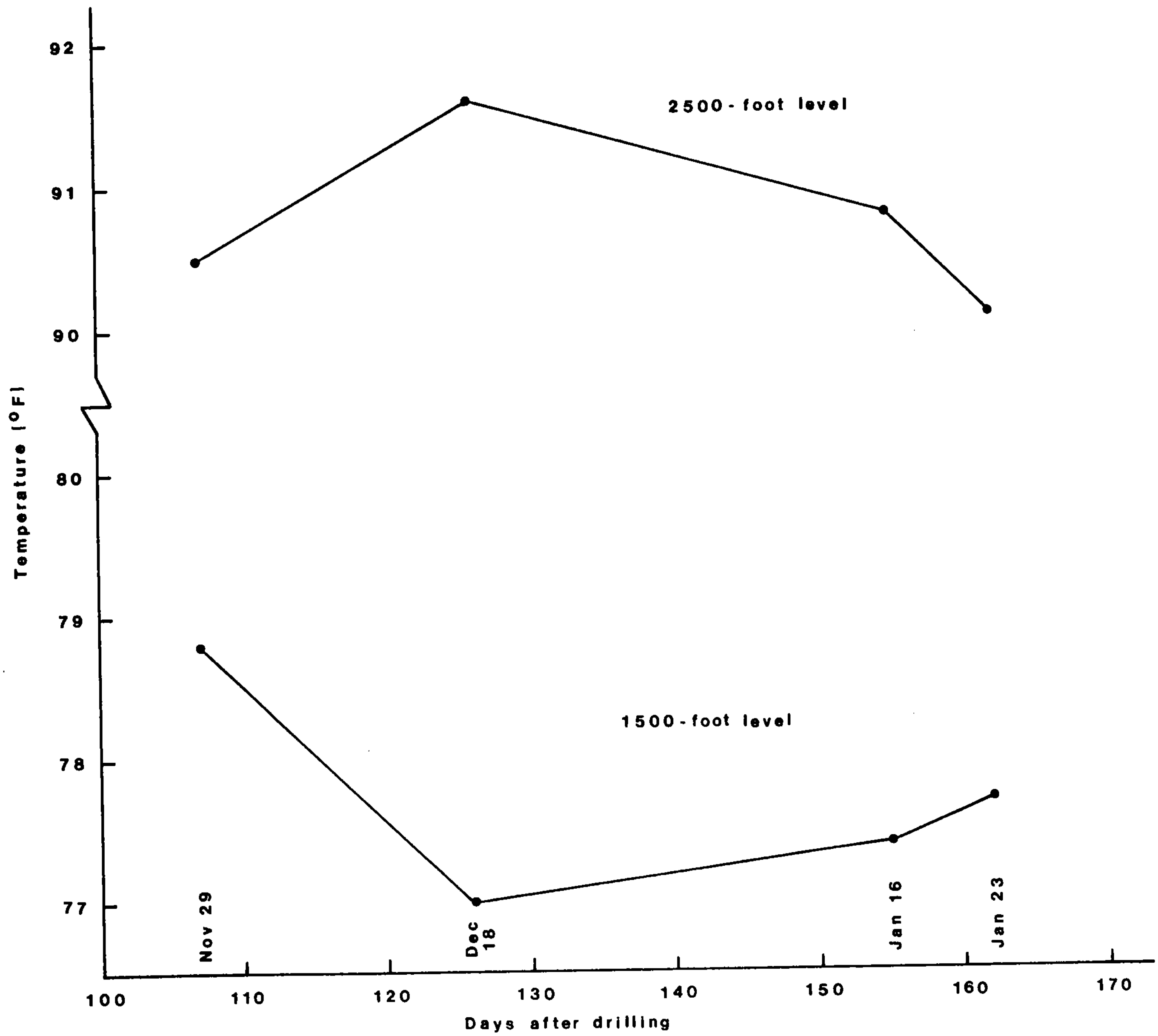


Figure 12. Relationship between borehole temperatures recorded at two levels and number of days following cessation of drilling for the TXO F-1 Henley well (Pittsburg County).

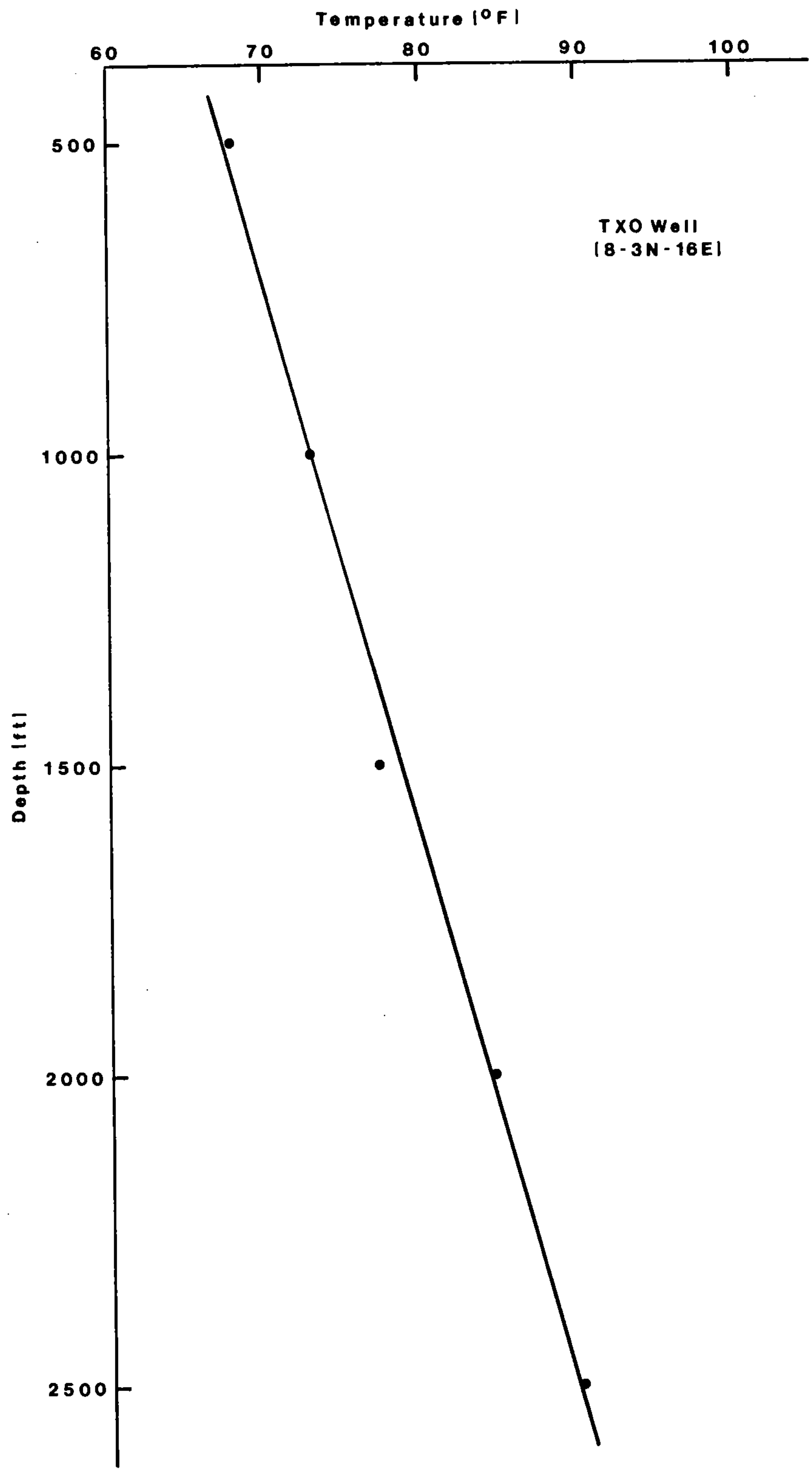


Figure 13. Depth-temperature plot for the TXO F-1 Henley well in Pittsburg County.

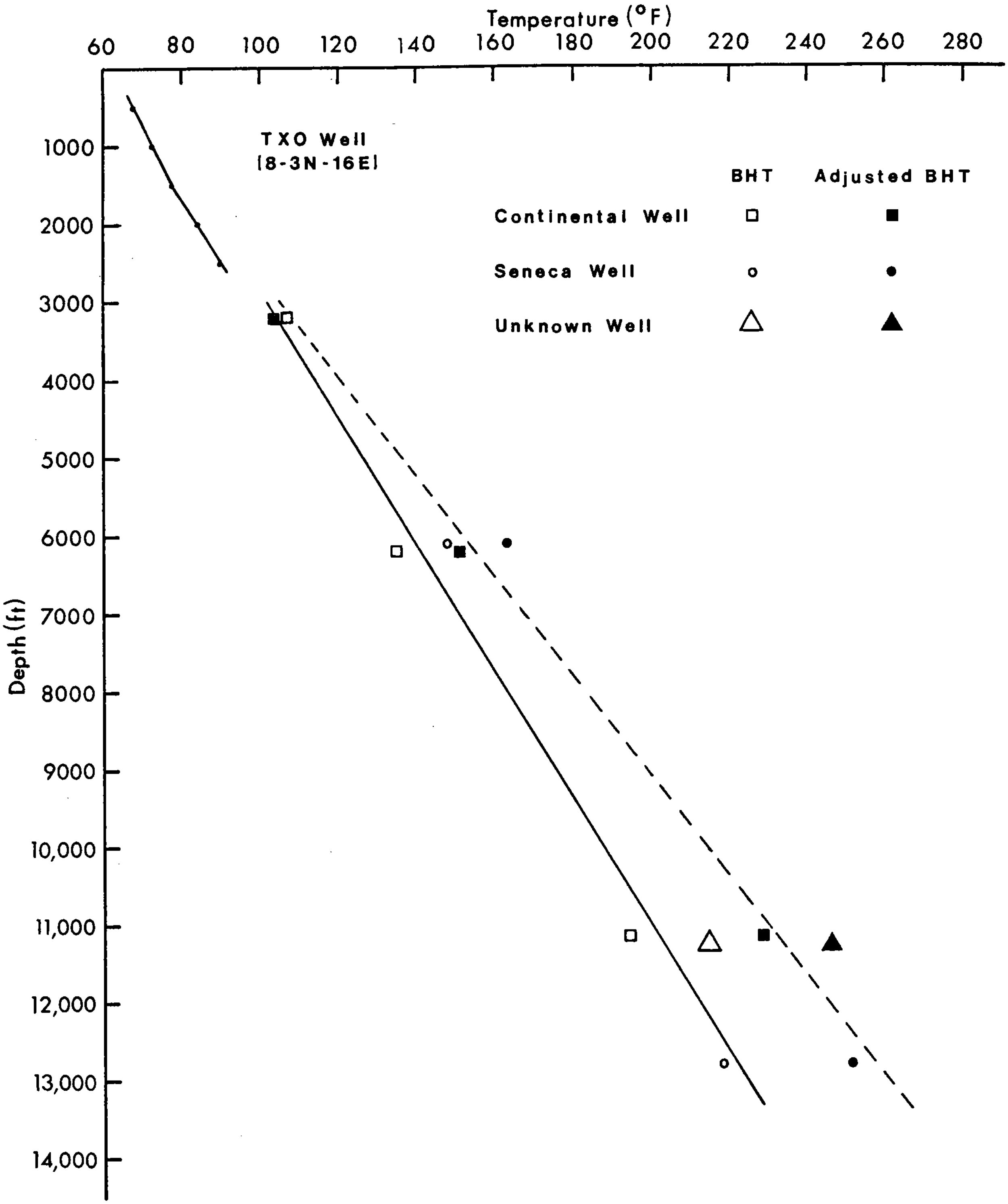


Figure 14. Depth-temperature curves for the TXO F-1 Henley well and three nearby wells. Dashed line drawn through adjusted borehole temperature data.

Table 4. Temperature data recorded on January 23, 1985, for the TXO F-1 Henley well

Depth (ft)	Recorded temperature (^{o}F)	Corrected temperature (^{o}F)
500	69.8	68.1
1000	74.8	73.0
1500	79.5	77.7
2000	86.4	84.5
2500	92.1	90.1

Borehole-temperature readings, which are taken shortly following cessation of drilling, are not usually in equilibrium with the rock-formation temperature. To remedy these discrepancies, Cheung (1978) developed a correction curve to adjust bottom-hole-temperature measurements (Fig. 15). This curve was obtained by comparing the differences between initial borehole-temperature readings and equilibrated temperature data as a function of depth. The adjusted temperatures, when plotted as a function of depth, are shown as a dashed line in Figure 14. The temperature gradient for the adjusted temperature data was approximately 1.56^{o}F/100 ft. This calculated gradient is higher than the value predicted by the geothermal-gradient map (Fig. 11). However, well-temperature data were not available for this

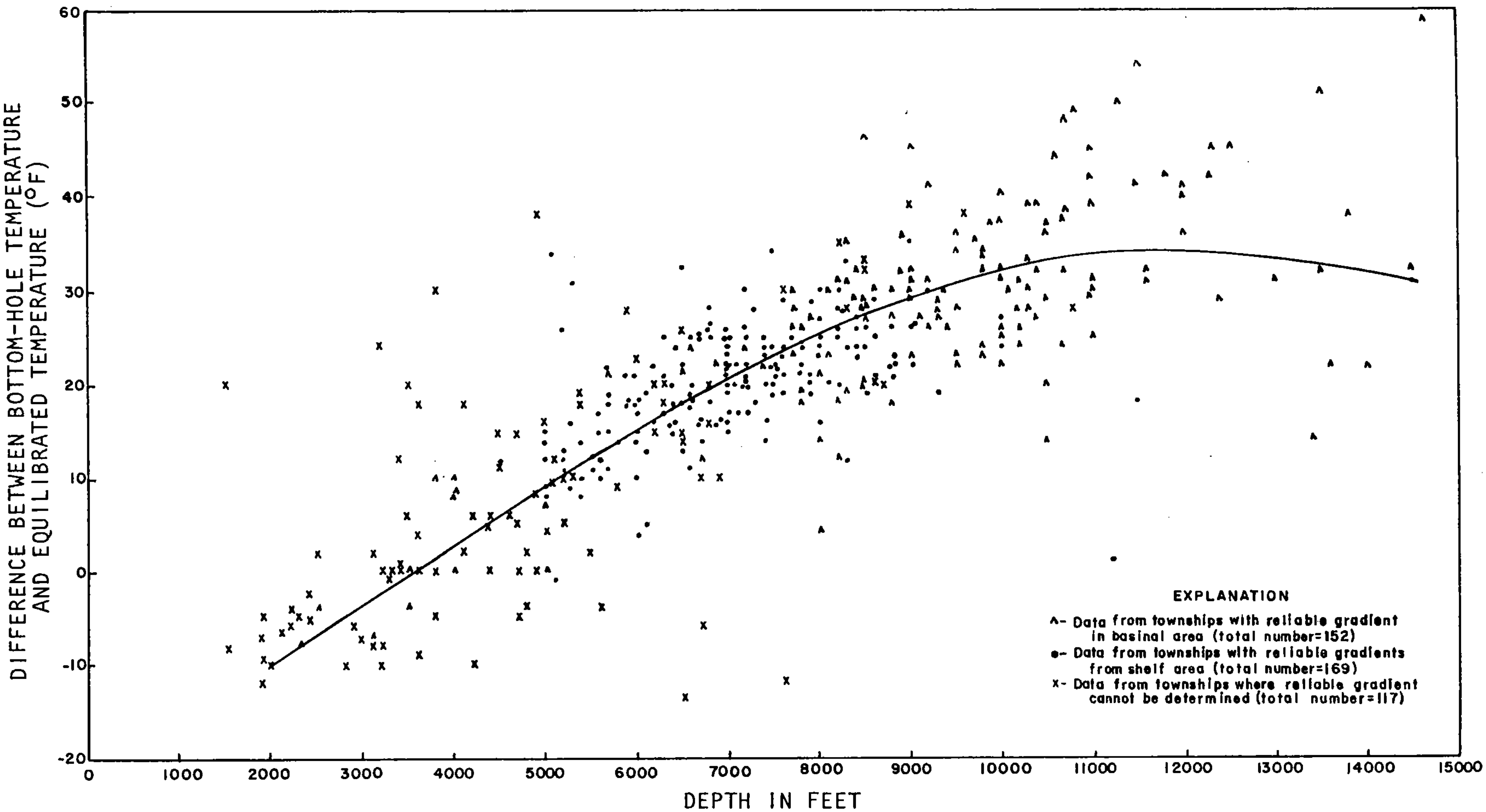


Figure 15. Correction curve for bottom-hole temperatures of wells in Oklahoma (modified from Cheung, 1978).

region when the temperature-gradient map was prepared in 1978, so the contour lines were extrapolated into this area. Therefore, it is reasonable to assume that the 1.56°F/100-ft gradient is a more accurate value for this area.

Table 5. Temperature information from wells near the TXO F-1 Henley well used to determine the temperature gradient at depth

Location[1]	Well name	Depth (ft)	Temperature ($^{\circ}$F)	Adjusted temperature[2] ($^{\circ}$F)
7-3N-15E	Seneca Oil Co.	6,100	148	163
	1-7 Williams	12,800	218	251
7-3N-15E	Continental Oil Co.	3,201	107	105
	1 Annie Jones	6,197	135	151
		11,130	194	228
17-3N-16E	Unknown	11,242	214	246

[1]Location given as section, township, and range.

[2]Correction curve used to adjust borehole temperatures (see Fig. 15).

Tenneco 1-24 Mixon

The Tenneco 1-24 Mixon well is in sec. 24, T7N, R21E, (Fig. 16). The Mixon well was a gas test drilled 12 mi south-southeast of the high-thermal area in Haskell County. The well was

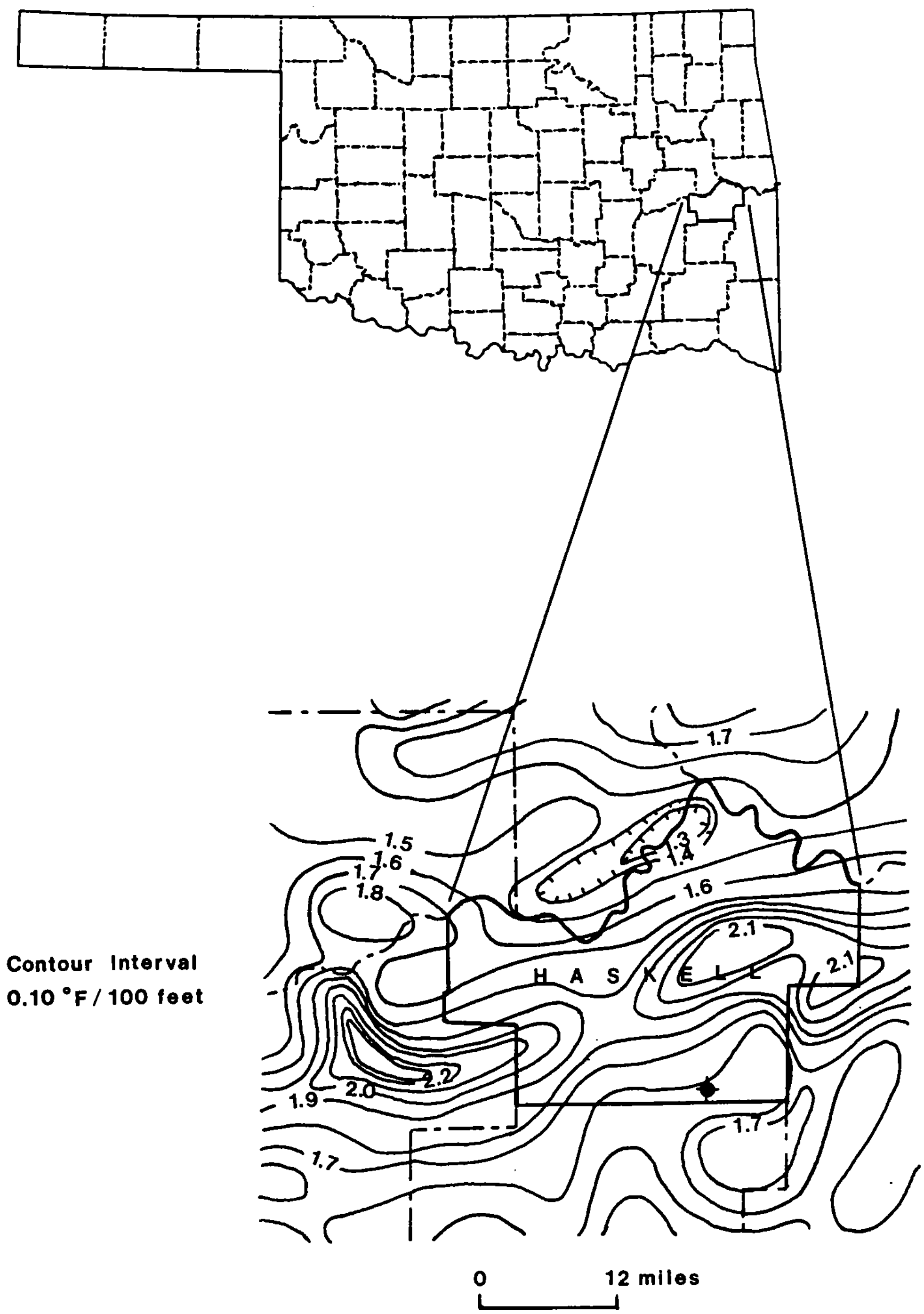


Figure 16. Location of the Tenneco 1-24 Mixon well in Haskell County and a portion of the geothermal gradient map (modified from Cheung, 1978).

abandoned in mid-January 1985 and was made available for a temperature survey. However, inclement weather and difficult site accessibility delayed our survey until April 8, 1985. A summary of the temperature data is listed in Table 6.

Table 6. Temperature data recorded on April 8, 1985, for the Tenneco 1-24 Mixon well

Depth (ft)	Recorded temperature (°F)	Corrected temperature (°F)
1000	81.0	79.1
1500	87.1	85.2
2000	91.8	89.8
2500	97.9	95.8

The geothermal-gradient map of Oklahoma, a part of which appears in Figure 16, shows the Tenneco 1-24 Mixon well to be in an area that has a gradient of approximately 1.6°F/100 ft. However, a temperature-depth plot of survey data indicates a gradient of 1.2°F/100 ft (Fig. 17). The much lower gradient can be attributed to (1) insufficient time for the temperature to equilibrate in the well bore, (2) an increase in temperature gradient with depth, and (or) (3) an error in the geothermal-gradient map of Oklahoma.

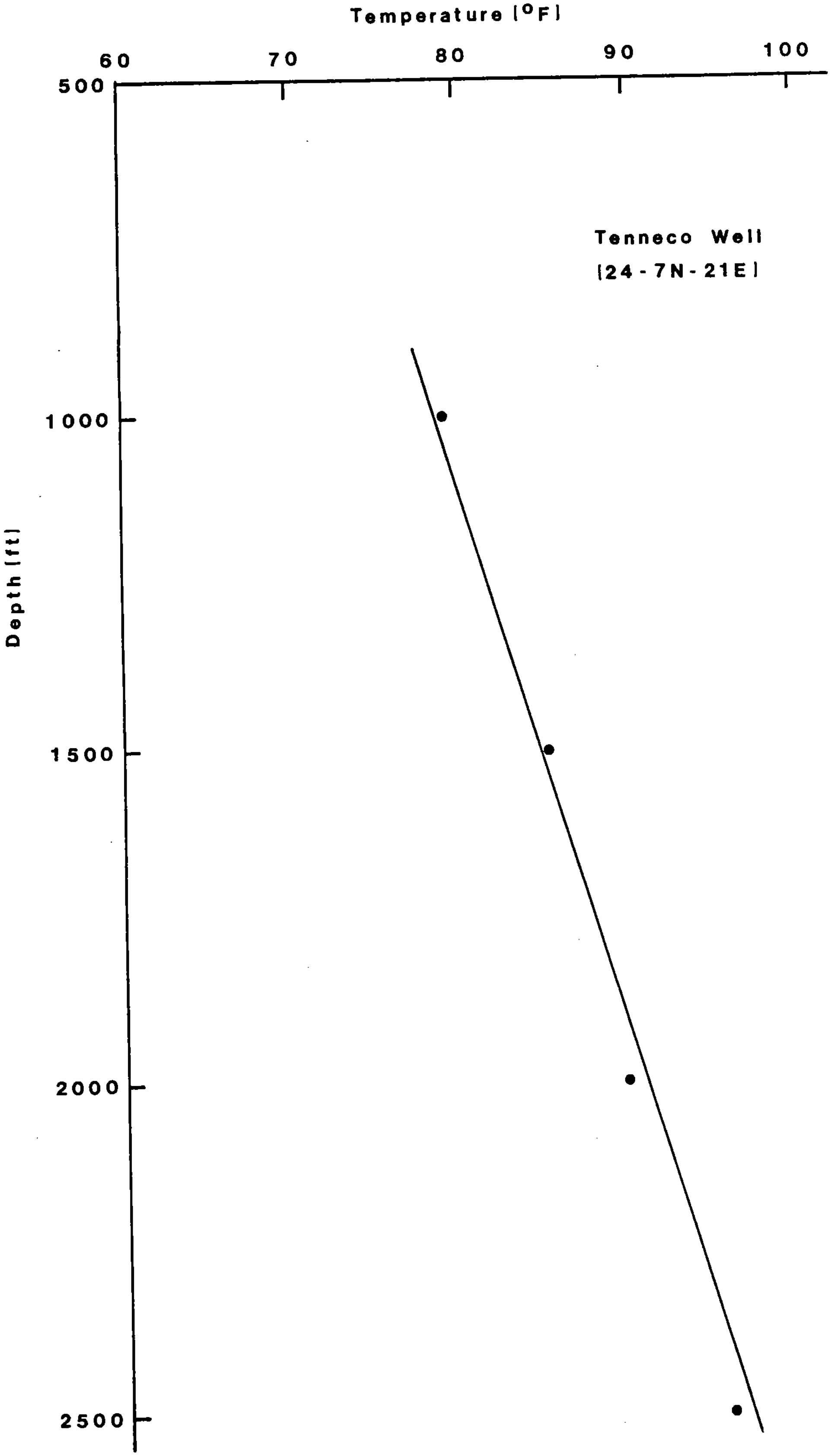


Figure 17. Depth-temperature plot for the Tenneco 1-24 Mixon well in Haskell County.

More than 200 days had lapsed since drilling had ceased at the well site. Time-temperature plots for the Ward Petroleum 1 Boardman and TXO F-1 Henley wells (Figs. 6, 12) suggest that fluid temperatures within the borehole achieve thermal equilibrium with the rock formations between 60 to 100 days after the termination of drilling. Therefore, the fluids within the borehole probably achieved thermal equilibrium before the temperature survey was conducted.

An attempt was made to verify the temperature gradient at depth. As no bottom-hole-temperature information was made available for the Mixon well, five nearby wells were selected to determine the temperature gradient between 2,500 and 13,500 ft for this region. The temperature information was taken from borehole geophysical records and is listed in Table 7.

The temperature-vs.-depth plot indicates a gradient of approximately 1.3°F/100 ft. Cheung's (1978) correction curve (Fig. 15) was used to adjust the borehole temperatures. The adjusted temperatures, plotted as a function of depth, are shown in Figure 18. The temperature gradient for the adjusted temperature data was approximately 1.6°F/100 ft. This calculated gradient of 1.6°F/100 ft is in excellent agreement with the contour values on the geothermal-gradient map (Fig. 16).

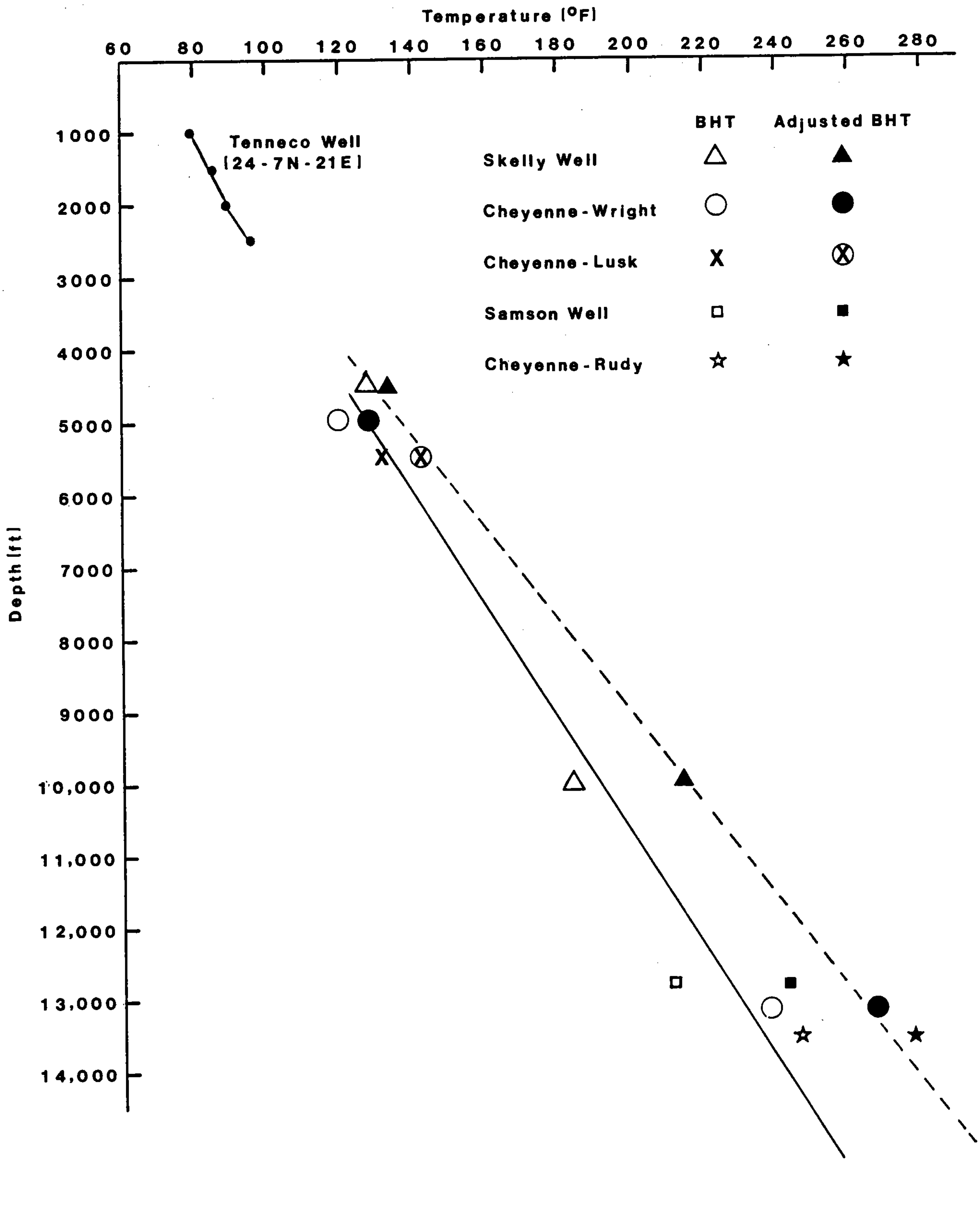


Figure 18. Depth-temperature curves for the Tenneco 1-24 Mixon well and five nearby wells. Dashed line drawn through adjusted borehole temperature data.

Table 7. Temperature information from wells near the Tenneco 1-24 Mixon well used to determine the temperature gradient at depth

Location[1]	Well name	Depth (ft)	Temperature (°F)	Adjusted temperature[2] (°F)
25-7N-21E	Skelly Oil Co. 1 Loretta Malone	4,448 9,997	127 183	132 213
21-7N-21E	Cheyenne Petroleum 1-21 Wright	4,999 13,176	119 236	127 266
26-7N-21E	Cheyenne Petroleum 1-26 Lusk	5,444	131	141
23-7N-21E	Samson Resources 1 Kirkwood	12,789	210	241
27-7N-21E	Cheyenne Petroleum 1-27 Rudy	13,567	245	275

[1]Location given as section, township, and range.

[2]Correction curve used to adjust borehole temperatures (see Fig. 15).

DISCUSSION

The principal goals of the temperature-monitoring program were (1) to determine the length of time needed for the fluid temperature in a recently drilled borehole to approach thermal equilibrium with the rocks penetrated and (2) to verify the validity of the geothermal-gradient map of Oklahoma, especially in the high-thermal-gradient regions of Pittsburg and Haskell Counties.

Two industry holes-of-opportunity were used to chart temperature variations over a number of days after drilling had ceased. The Ward Petroleum 1 Boardman well in Cleveland County provided the most useful temperature information. The first temperature reading was taken 32 days after drilling had stopped. Subsequent measurements over a 62-day period indicated that the borehole achieved thermal equilibrium in about 65 days after cessation of drilling. A temperature survey began in a second well, the TXO F-1 Henley, 107 days after drilling had ceased and continued for an additional 55 days. The temperature-time curve (Fig. 12) suggests that thermal equilibrium had been achieved prior to the temperature survey.

Many factors can affect the temperature-equilibrium process. Some of these factors include thermal conductivity of the rock formations, pore-fluid movement, and drilling conditions. Therefore, data from one well provide only an approximation for the time required for the temperature of the borehole fluids to reach equilibrium with the rock temperature.

Schoeppel and Gilarranz (1966), Edwardson and others (1962), Kehle and others (1971), and additional researchers have estimated the time needed for the well bore to attain the same temperature as the formation. For example, Gilarranz (1964) estimates that the well-bore temperature at 10,000 ft is approximately 96% of the undisturbed formation temperature 12 hours after cessation of circulation. Unfortunately, we were not able to monitor borehole-temperature conditions until the well was abandoned. In most cases, operators make repeated attempts to complete a well before the well is declared dry and abandoned. Post-drilling activities usually take several weeks to months after drilling has ceased.

The results of the temperature-verification program were mixed. After several failures of our sacrificial probes, that system was abandoned. Instead, a retrieval system with a depth limitation of 2,500 ft was successfully used to obtain downhole temperatures.

No holes-of-opportunity were made available in the high-thermal-anomaly areas. However, temperature surveys were conducted in areas adjacent to the Haskell and Pittsburg County anomalies. The surveys indicated a gradient lower than the predicted gradients on the temperature-gradient map (Cheung, 1978). When deep-temperature data, between 5,000 and 13,000 ft, are adjusted for mud-circulation effects, the adjusted gradients approximate the gradients on the geothermal-gradient map. The depth limitation of our equipment, as well as restriction to the cased portion of the borehole, produced severe constraints on the temperature-verification program.

The temperature surveys suggest that the temperature gradient at any site-specific locality is not a simple straight-line function. There is a definite change in the temperature-vs.-depth slope from near-surface measurements ($\leq$2,500 ft) and deep measurements (5,000 to 13,000 ft). Precise temperature measurements need to be made at greater depths to verify the variation in temperature gradient with depth.

Two surveyed boreholes showed the possible influence of ground water on the temperature gradient. The temperature surveys in the Oklahoma Geophysical Observatory well in Tulsa County and the powerhouse well in Ottawa County indicate the possible influence of water movement through an aquifer on the temperature gradient. At the Observatory well, water moves through rocks of the Arbuckle Group from a higher elevation to a lower elevation. Perhaps this inflow of cooler water inhibits thermal equilibrium and thus lowers the thermal gradient at this site. The opposite situation may exist at the powerhouse well. Water, which might be of a slightly warmer temperature in the structural depression east of the well, could be moving updip through the Roubidoux Formation. Thus the net result could cause the temperature gradient to increase near the formation contact. Therefore, variations in temperature gradients for selected reservoirs have a considerable impact on the use and design of geothermal systems.

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