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GEOTHERMAL RESOURCE ASSESSMENT IN OKLAHOMA

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INTRODUCTION

In September 1980, the Oklahoma Geological Survey in cooperation with the U.S. Department of Energy began a program to assess the geothermal potential of the State. The program, thus far, consists of (1) the preparation of a detailed geothermal-gradient map of Oklahoma at a scale of 1:500,000 and (2) site-specific investigations of gradient and sub-surface conditions in areas that appear to have geothermal potential.

Prior to this investigation, the best available geothermal-gradient map for Oklahoma was prepared by Cheung (1978) as part of his thesis investigation at Oklahoma State University. The American Association of Petroleum Geologists' (AAPG) North American Geothermal Project (1976) provided the data base for the Oklahoma State University work, although initially the Oklahoma Panhandle and northeastern and southeastern Oklahoma were excluded from Cheung's study. Several well-correction factors (e.g., maximum time since circulation, air-drilled versus mud-drilled, and geologic province) were applied to the raw data and to electric-log data in order to determine temperature gradient.

In 1981, Cheung expanded his geothermal-gradient program to include the unmapped areas of the State. The mapping for the Panhandle was completed in August 1981. Unfortunately, temperature data for the northeastern and southeastern parts of the State were not detailed enough to complete a temperature-gradient contour map.

Two areas where recent mapping has shown the high gradients (2.1°F/100 feet) were selected for detailed study. These areas are in (1) Haskell and (2) Pittsburg Counties and are subsequently referred to as the Haskell and Pittsburg anomalies. We estimated volume and deliverability of formation water potentially available from several sandstone units for geothermal applications. The Spiro and Cromwell sands were chosen for the Pittsburg anomaly. We hope similar investigations of subsurface formations can be expanded into other areas which have relatively 'high' geothermal gradients.

GEOTHERMAL-RESOURCE APPRAISAL

Introduction

A number of attempts have been made to map geothermal gradients in Oklahoma. McCutchin (1930) recognized a correlation between oil-bearing anticlinal structures and high geothermal gradients. Schoeppel and Gilarranz (1966) prepared a geothermal-gradient map of Oklahoma from corrected bottom-hole temperatures (fig. 1). Their study indicated that actual formation temperature could be determined from temperature measurements and the time since circulation in the well bore, provided that certain factors are known, such as (1) temperature of the drilling mud at the surface, (2) pipe size, (3) circulation rate, (4) size of annulus, and (5) heat capacities and thermal conductivities of the drilling fluid, drill pipe, and country rock. A comprehensive study sponsored by the AAPG was initiated in 1968 to map geothermal gradients in North America. That portion of the resulting map covering Oklahoma is shown in figure 2.

The best available geothermal-gradient map for Oklahoma was prepared by Cheung (1978, 1979). This map, which includes the 1981 mapping in the Oklahoma Panhandle, is shown on figure 3. Several correction factors were applied to the raw temperature data to reflect actual formation temperature more accurately. The procedures and methods used to develop this temperature map (fig. 3) are discussed below.

Temperature Data

The most reliable temperature data are derived from bottom-hole pressure tests. Temperature measurements taken from different tests during the production history of a particular well usually vary no more than 2^{o}F from the average. The average temperature measurement at a certain depth is considered to be the true formation

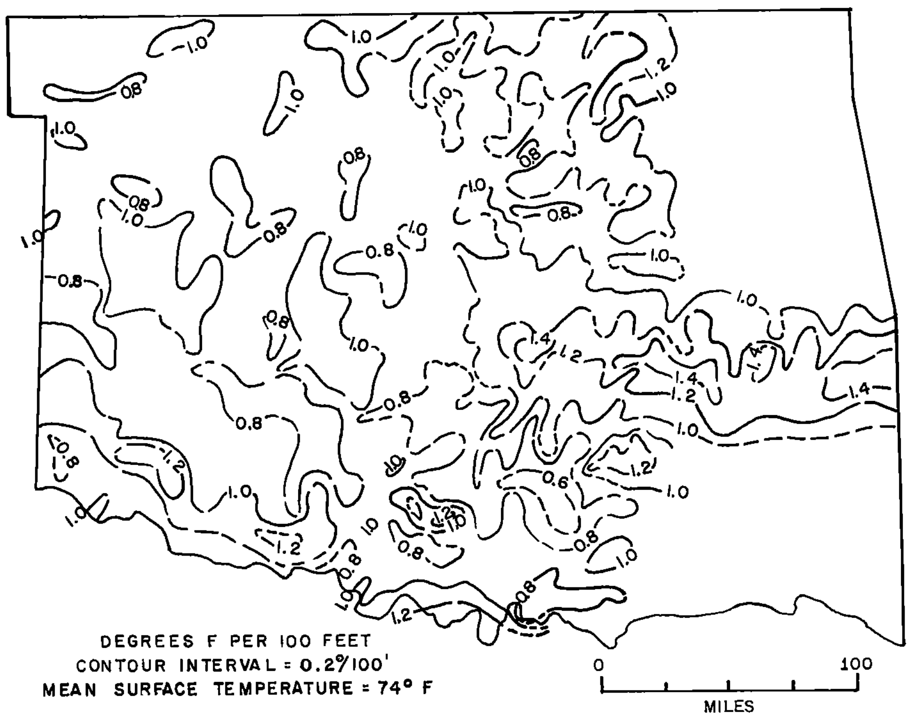

Fig. 1. Geothermal gradient map of Oklahoma (from Schoeppel and Gilarranz, 1966).

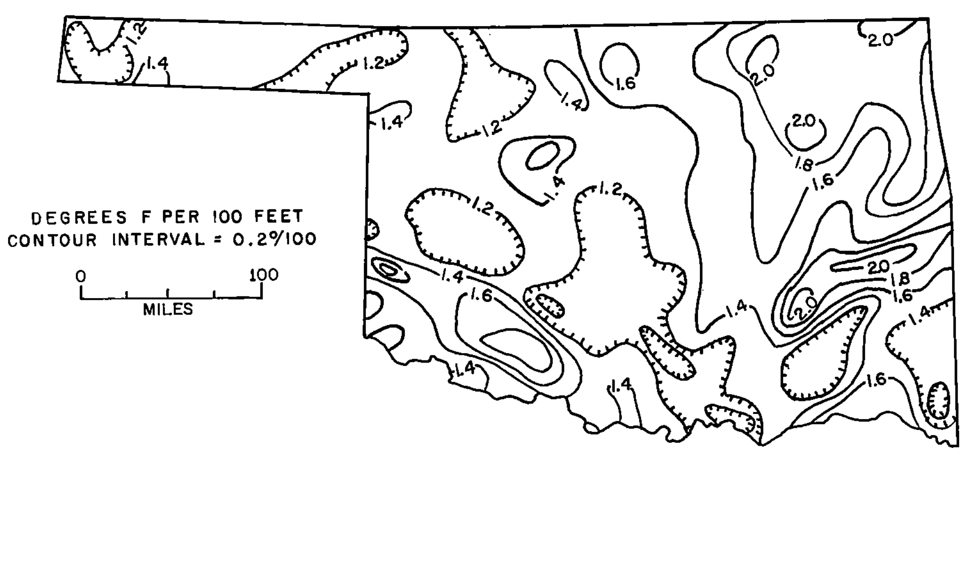

Fig. 2. Geothermal gradient map of Oklahoma (adapted from Geothermal Gradient Map of North America, 1976, see Shelton, 1976).

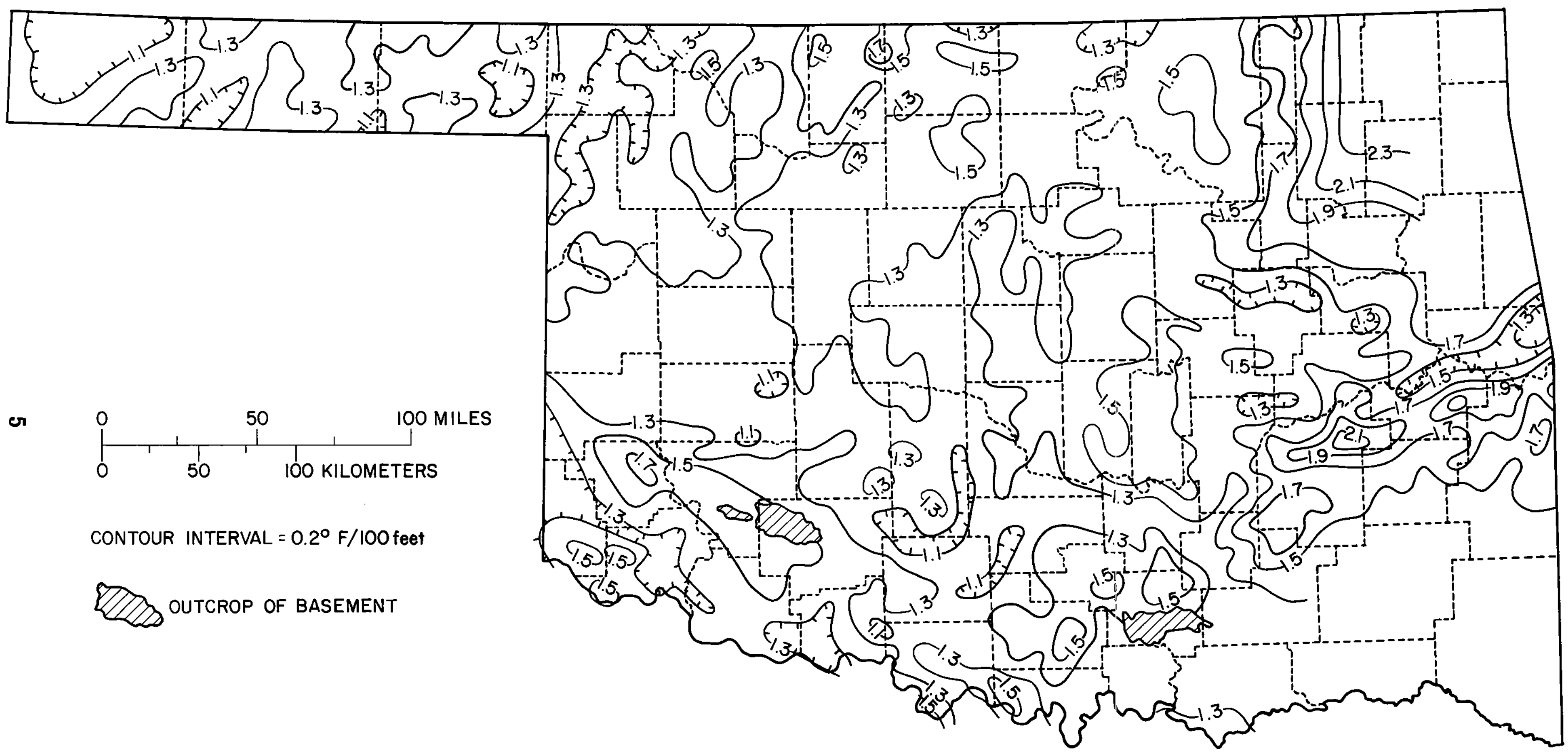

Fig. 3. Geothermal gradient map of Oklahoma (modified from Cheung, 1979).

temperature. However, these data from bottom-hole pressure tests are available only in areas of gas production.

Temperature logs and bottom-hole-temperature determination in air-drilled wells are considered to be reliable data. Temperature logs provide both continuous temperature measurements and temperature-gradient profiles. These two kinds of data are available only for the Arkoma Basin, however.

The most abundant and readily available temperature data are the bottom-hole temperatures measured in mud-drilled wells. But these data are unreliable, as they usually record temperatures lower than the true formation temperatures because of the cooling effect of the mud.

A temperature-depth plot was prepared for each township. Except for temperatures recorded within abnormally high pressure zones, all temperature measurements were used to determine the geothermal gradient for each township, the basic area for control-point spacing. Gradient determinations thus were made by one of these methods.

The first method for determining gradients, which is the most reliable, utilizes shut-in-gas-well temperature and (or) temperature logs. An example of this gradient determination is shown in figure 4. Gradient data from more than 125 townships were obtained using this method.

Where reliable temperature data are available only for one depth, a temperature measurement at a shallower depth is needed in order to determine the gradient. The mean annual surface temperature was not used as the control point because surface temperature is a function of a number of variables, such as soil type, moisture content, vegetation, climate, topography, and ground water. From the gradient plots of reliable temperatures, an average of 69^{O}F at 500 feet below the surface was established. This average was used as a control point for constructing a linear gradient where subsurface temperatures are available for a single depth.

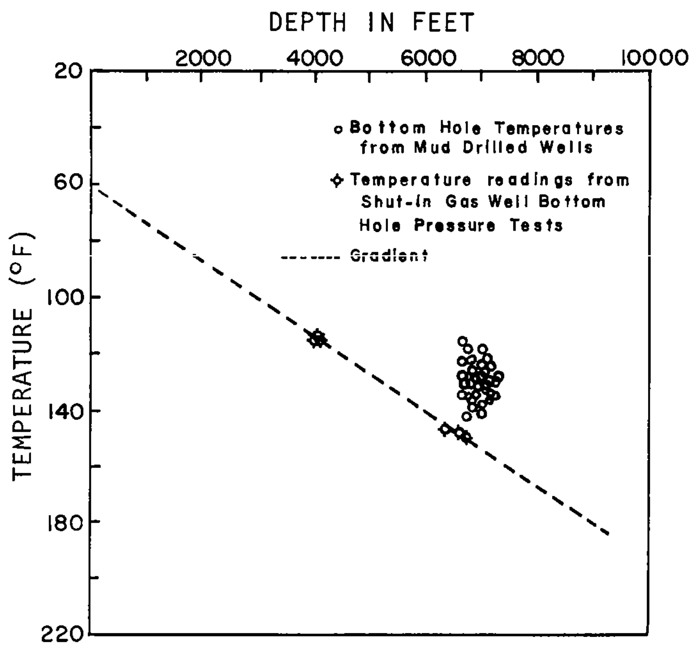

Fig. 4. Gradient determined by reliable temperature measurements at different depths in T. 27 N., R. 25 W.

In more than half of the townships within the State, bottom-hole-temperatures from electric logs constitute the only available data. A correction factor was applied to a calculated average bottom-hole-temperature at a specific depth to compensate for the cooling effect of the drilling mud. Within a township, a number of bottom-hole temperatures are needed to determine the average temperature at a certain depth. A township with only one or two wells does not provide sufficient data for the determination of a reliable average temperature gradient.

The correction factor used was determined by comparing the average of the bottom-hole temperatures to the reliable temperatures at the corresponding depths. The reliable temperatures were determined from temperature readings from pressure tests, temperature logs, and (or) interpolations from reliable temperature gradients. For this comparison, western and northwestern Oklahoma were divided into shelf and basin areas, and each of these areas was subdivided into four smaller areas. Differences between reliable temperatures and average bottom-hole temperatures, plotted according to depth for each small area, suggest a single population. Therefore, a correction curve for all the data was determined (fig. 5). This curve represents the deviation of bottom-hole temperatures from true formation temperature, and was used in this study to correct the temperatures from mud-drilled wells.

The correction curve suggests that at depths between 3,000 and 4,000 feet bottom-hole temperatures approximate formation temperatures and that differences between the two are as much as 32°F at a depth of 10,000 feet. Because of sparse reliable data at depths greater than 10,000 feet and the occurrence of abnormal pressures at those depths, the correction curve cannot be determined for depths greater than 10,000 feet. Correspondingly, the curve was used to correct bottom-hole temperatures for wells with depths of 3,000-10,000 feet.

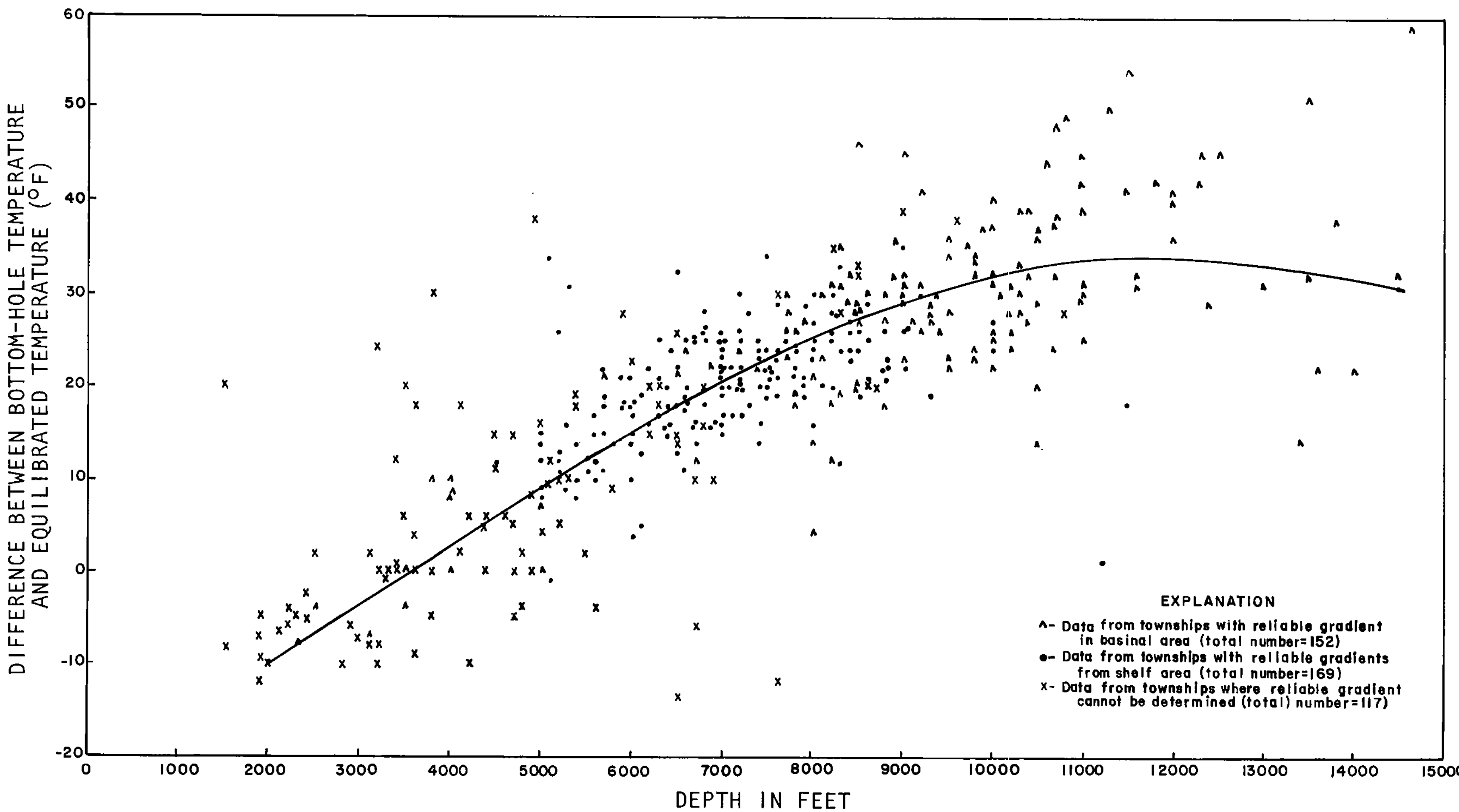

Fig. 5. Correction curve for bottom-hole temperatures of wells in Oklahoma.

The temperature gradient of a township is obtained from the assumed near-surface temperatures and the corrected temperatures at depth (fig. 6).

Geothermal-Gradient Map

Temperature-gradient information, derived from one of the previously discussed methods, was posted in the center of each township (where data are available). These data were used to construct a geothermal-gradient contour map for normally pressured formations in Oklahoma, using a contour interval of $0.10^{\circ}F/100$ feet (fig. 3).

The general tectonic framework of Oklahoma (fig. 7) is reflected quite well by the regional geothermal-gradient map. The deeper part of the Anadarko Basin is represented by lower-than-average values. The Ardmore Basin contains higher values than those of the Anadarko Basin, but generally lower than those of the Marietta and Hollis Basins. The Arkoma Basin is characterized by the highest values of any basin in the State.

The low geothermal gradients of the Anadarko Basin are probably caused by the thick sedimentary-rock section and the insulating effects of the abnormally pressured Morrow-Springer sands. The distribution of abnormal gradients corresponds generally to the areas of low gradients on the regional geothermal-gradient map (Cheung, 1979).

With the exception of the Arkoma Basin, the temperature gradient increases as depth of basement rock decreases. For example, the Northern Oklahoma Platform exhibits gradients approximately $0.20^{\circ}F/100$ feet higher than the gradients of the deeper part of the Anadarko Basin.

The Wichita Mountain Uplift is reflected by a prominent geothermal anomaly. The westernmost and southernmost parts of the Ozark Province are outlined by high gradients. The edge of the Ouachita Province is characterized by relatively low values, which define the southern edge of the Arkoma Basin. The high anomaly in Osage County apparently reflects the relief of the basement.

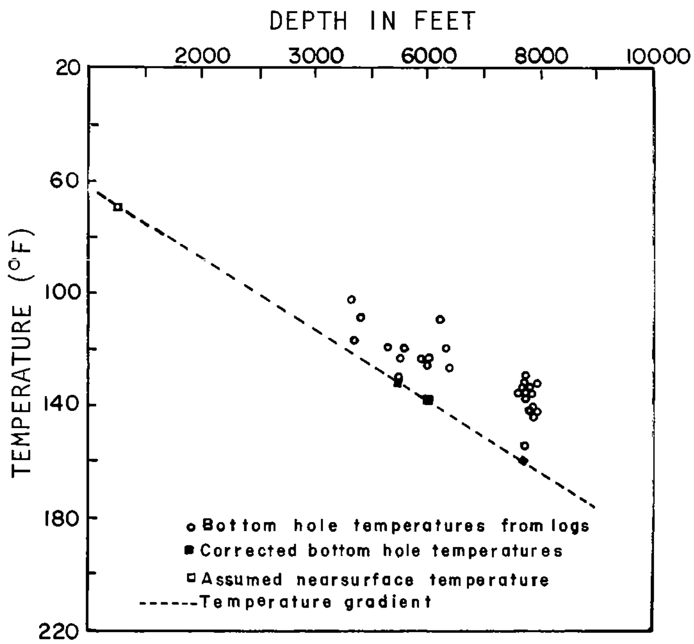

Fig. 6. Geothermal gradient from corrected bottom-hole temperatures, and assumed near surface temperatures, T. 28 N., R. 22 W.

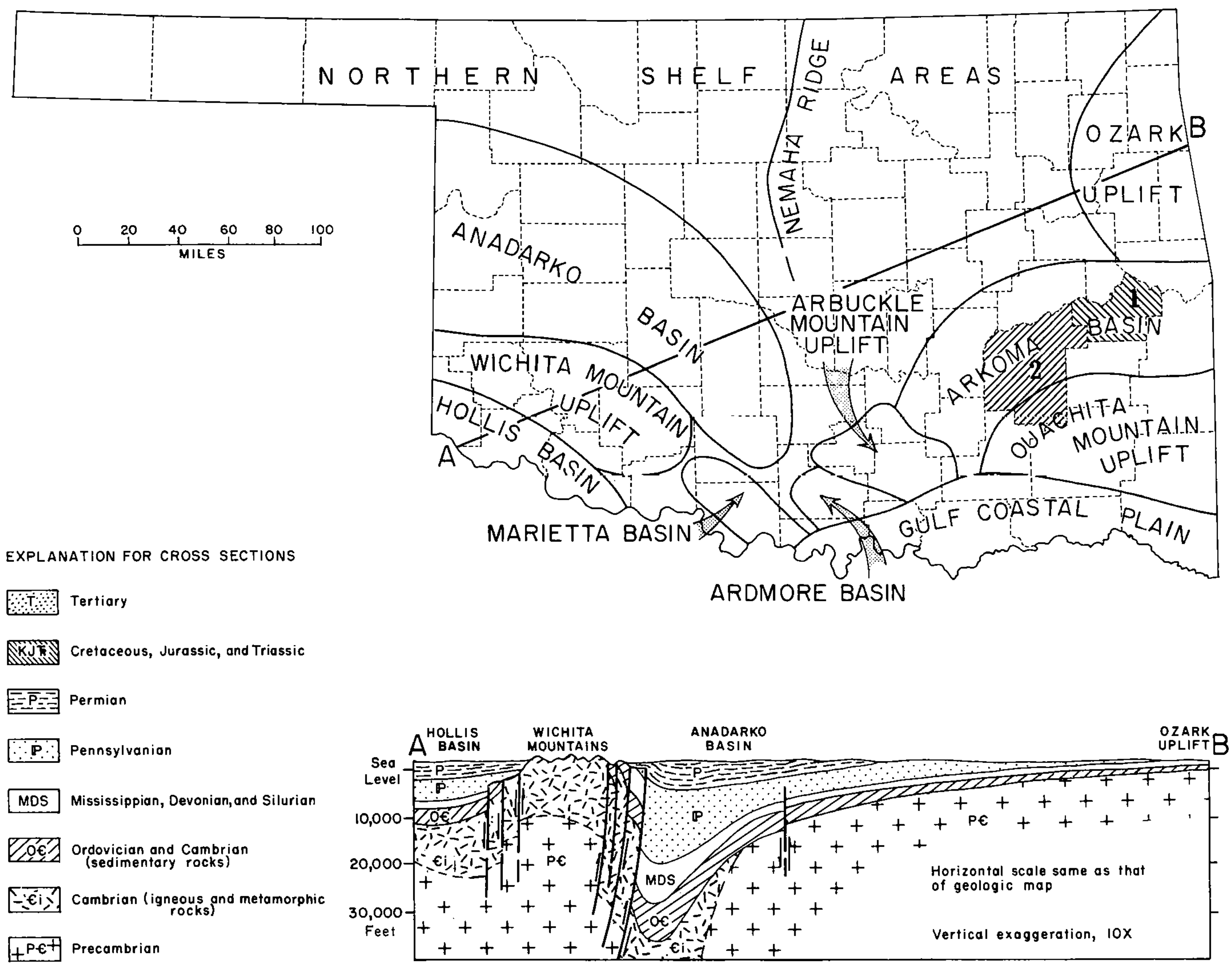

Fig. 7. Map and cross section showing major geologic and tectonic provinces of Oklahoma and locations of detailed investigations. Area 1 is the Haskell anomaly, and area 2 is the Pittsburg anomaly.

Conclusions

Several conclusions can be derived from the preparation and interpretation of the geothermal-gradient map of Oklahoma. For example, bottom-hole temperatures from well logs, if corrected properly, are useful in mapping geothermal gradients. Major tectonic-structural features of Oklahoma, such as basins, are generally reflected by the gradient anomalies and trends. In most cases, basin anomalies are a reflection of sediment thickness and structural complexities. In general, geothermal gradients in rocks overlying an abnormally pressured zone are anomalously low, possibly owing to restriction of heat flow by the abnormally pressured zone.

DETAILED INVESTIGATIONS

Introduction

Two areas in southeastern Oklahoma, where recent mapping has shown some of the highest gradients (2.1°F/100 feet), were chosen for detailed study (fig. 7). These areas are in (1) Haskell and (2) Pittsburg Counties, in the Arkoma Basin.

The Arkoma Basin is composed of a series of anticlines and synclines in Pennsylvanian clastic rocks, broken by thrust and (or) growth faults near the center of the basin (Fay, 1970; McQuillan, 1977). The resistant sandstones cap high ridges near the centers of the synclines, whereas shales occupy stream valleys along anticlinal axes.

Three sandstone units, the Spiro, Cromwell, and Hartshorne, were selected as potential sources of water for low-temperature geothermal applications. Completion cards were used to assist in determining the tops of these sandstone units on well logs. Each sand exhibits a characteristic pattern on the spontaneous-potential and (or) gamma-ray track as well as the resistivity track of the logs. Thickness and water saturation were then calculated from the log information.

These sandstone units were chosen because of their continuity over the anomalous areas. The Hartshorne was chosen for the Pittsburg anomaly (pl. 1), and the Spiro (pl. 2) and Cromwell (pl. 3) were chosen for the Haskell anomaly. All three sands are gas productive, so it is common for them to be penetrated and logged by drilling companies. The deeper Spiro and Cromwell sands have not yet been penetrated in the area of the Pittsburg anomaly, however.

Hartshorne Sandstone

The Hartshorne sandstone is an informal member of the Hartshorne Formation, which rests on the Atoka Formation and is conformably overlain by the McAlester Formation (fig. 8). Lithologically, the Hartshorne ranges from a fairly pure sandstone to

SYSTEM	SERIES	ARKOMA BASIN
PENNSYLVANIAN	VIRGILIAN	Vamoosa Formation
	MISSOURIAN	Hilltop Formation Bell City Formation Francis Formation Seminole Formation
	DESMOINESIAN	Holdenville Formation Wewoka Formation Wetumka Formation Calvin Sandstone Senora Formation Stuart Formation Thurman Sandstone
		Boggy Formation Savanna Formation McAlester Formation **Hartshorne Formation**
	ATOKAN	Atoka Formation **Spiro sandstone**
	MORROWAN	Wapanucka Limestone Union Valley Formation **Cromwell sandstone**
MISSISSIPPIAN	CHESTERIAN	Chester Formation Pitkin Limestone Fayetteville Formation
	MERAMECIAN	Moorefield Formation
	OSAGEAN	
	KINDERHOOKIAN	Woodford Shale Misener Sandstone
DEVONIAN		Hunton Group Frisco Chert Bois D'Arc Limestone Haragan Marl

Fig. 8. Generalized correlation chart for the Arkoma Basin (modified from Disney, 1960).

a sandstone interbedded with shale. In the study area, the Hartshorne varies from 20 to 120 feet in thickness (pl. 1, map B). The structure found in the study area consists of a series of northeast-southwest-trending anticlines and synclines (pl. 1, map A). The average temperature of the Hartshorne sandstone is 103^{O}F. This was determined by using bottom-hole temperatures and a calculated geothermal gradient. The estimated average porosity is 10 percent. The Hartshorne is found at an average depth of 2,558 feet in the study area, with an average thickness of 70 feet.

Spiro Sandstone

The Spiro sand is the name that is used for the basal sand unit of the Atoka Formation. It is also referred to as "basal Atokan sand," "Foster sand," and "Greenland sand." At several localities, the Spiro sand rests unconformably on the Wapanucka Limestone (fig. 8). At most places, the Spiro sand and Wapanucka Limestone are separated by a dark shale. The structure of the Spiro, somewhat similar to that of the Hartshorne sand, consists of a series of northeast-southwest-trending anticlines and synclines (pl. 2, map A). The Spiro sand is thought to be a blanket sand that was deposited during a major transgression. In the study area, the Spiro varies in thickness from 20 to 120 feet (pl. 2, map B). The thickest section occurs in the eastern part of the study area. The Spiro sand has an average temperature of 151^{O}F, and an average depth of 5,290 feet. The average thickness of the unit is 37 feet, and the average porosity was calculated at 14 percent.

Cromwell Sandstone

The Cromwell sand lies beneath the Union Valley Formation, which consists mainly of limestone. In some areas the two are separated by as much as 70 feet of dark shale.

The Cromwell lies unconformably on a shale of the Chesterian Series (fig. 8). The structure exhibited by the Cromwell, similar to that of the Spiro sand, is dominated by northeast-southwest-trending anticlines (pl. 3, map A). The thickness of the Cromwell varies from 20 to 120 feet in the study area (pl. 3, map B). The thickest areas are in the western and east-central parts of the Haskell anomaly. The average thickness is 43 feet, and the average porosity of the Cromwell is estimated to be 18 percent. The average temperature of the Cromwell is 158°F, with an average depth of 5,724 feet.

Water-Volume Estimate

An isovolume map was prepared for each formation. In this process, the thickness of water at each well location can be calculated. Because of the size of the area, one well per section was used in this study. The amount of water that can be produced from one well is estimated by the following equation:

$$V = AB\Sigma\ (h_i(Sw_i)\phi_i) \tag{1}$$

where
- A = area drained in acres
- B = 7,758 when V is in barrels
- h = thickness in feet
- i = 1, 2, etc., are layers of the reservoir having different properties
- ϕ = porosity

Because most reservoirs do not have a constant thickness or porosity, it is necessary to find the thickness of water at each well. After this has been done, an isovolume map is created by contouring the data. To determine the height of water at a well, equation (1), with A and B = 1, was used. This gives the equivalent height of water at that well for 100 percent porosity and water saturation.

On each isovolume map, the number beside the wells represents the vertical feet of water calculated by the above method. An example of this procedure can be shown by taking a well from plate 2, map C, in sec. 9, T. 8 N., R. 23 E. At this locality the Spiro sand is 20 feet thick (pl. 2, map B). The water saturation (Sw) was calculated to be 95 percent. Porosity was determined using porosity logs. The type of porosity log varied from well to well, but most were either density logs or neutron logs. The porosity of the example well was 14 percent. Using equation (1) and allowing A and B = 1, the following equation calculates the vertical feet of water for the example well:

$$V = 20(.95)\ (.14)$$

$$V = 2.66 \text{ vertical feet of water} \qquad (2)$$

After the vertical feet of water was calculated for each well, the map was contoured on a 1-foot interval. The area inside the contours was determined in acres by using the planimeter method. These areas are shown with the acreage on each isovolume map. The estimated minimum volume of water can be calculated using the following equation:

$$V = H(A_o + A_1 + A_2 + \ldots + A_n) \text{ X } 7{,}758 \text{ bbl/acre-ft} \qquad (3)$$

where V is the volume in barrels of water in place
H is the contour interval in feet
and A's are the areas, in acres, inside the zero (reservoir boundary), first, second, etc., contours.

Still using plate 2, map C, the areas inside the contour lines were determined. The acreage between the zero and 1 contours was 45,047. This was determined by adding the areas from domains 1, 9, 20, 24, 25, 32, 33, 34, 45, and 46 (pl. 2, map C). The areas between the other contour lines were added. The acreages then were inserted in equation (3). The results were as follows:

$$V = 1(45{,}047 + 35{,}904 + 8{,}562 + 3{,}388 + 2{,}002 + 1{,}953 + 1{,}522 + 598 + 393 + 106) \text{ X } 7{,}758 \text{ bbl/acre-ft}$$

$$V \cong 771{,}727{,}000 \text{ bbl of water in place for the Spiro sand.}$$

The same procedure was used to determine the minimum volume of water in place from the other isovolume maps. The results were 765,125,000 barrels of water in place for the Cromwell sandstone in the Haskell anomaly (pl. 3, map C) and 640,896,000 barrels of water in place for the Hartshorne sandstone in the Pittsburg anomaly (pl. 1, map C).

Flow Potential

By using Darcy's Law, which expresses radial liquid flow into a borehole in units of barrels of liquid per day, the open-flow potential of a well could be determined:

$$Q = \frac{7.07kh(P_e - P_w)}{\mu \ln(r_e/r_w)}$$

where Q = barrels per day
k = permeability in darcies
h = interval thickness in feet (20 feet)
P_e = 1 atmosphere in psi (14.7 psi)
P_w = formation pressure in psi
μ = viscosity (1.0)
r_e = distance from well bore (660 feet)
r_w = radius of well bore in feet (.42).

A nomograph (fig. 9) based on this equation was constructed for the wells in the study area. The interval thickness is set at 20 feet, P_e is equal to 1 atmosphere or 14.7 psi, viscosity is 1.0, and r_e is equal to 660 feet. The use of the latter value is standard procedure in similar types of petrophysical studies. The well-bore radius is set at 5 inches, since most of the wells in the study area have a well-bore diameter of about 10 inches.

The only variable remaining in the equation is permeability, which is dependent on the particular formation considered and the formation pressures which are functions of depth. Permeabilities can be estimated by using a chart of empirical petrophysical relationships developed by Gearhart Industries (fig. 10). The most accurate permeability determination that could be made would be from a laboratory analysis of a core. Especially in gas-producing zones, the chart's accuracy is decreased; but for a rough estimate of permeability the empirical chart is satisfactory. For an example, if the porosity was 25 percent, and water saturation was 35 percent, then an estimate of permeability would be 50 millidarcies.

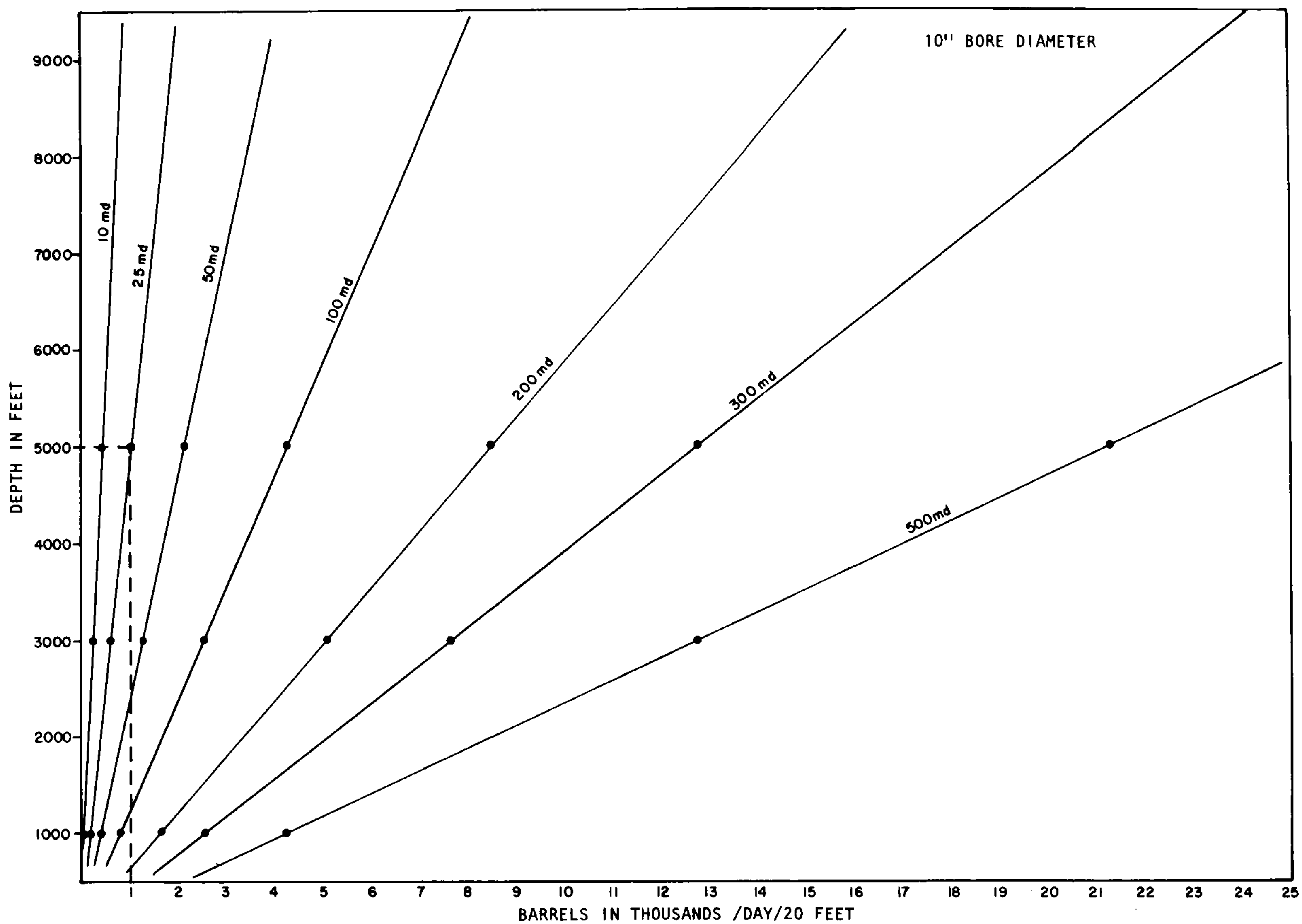

Fig. 9. Nomograph which relates permeability, depth, and barrels of liquid per day for 10-inch diameter well bore.

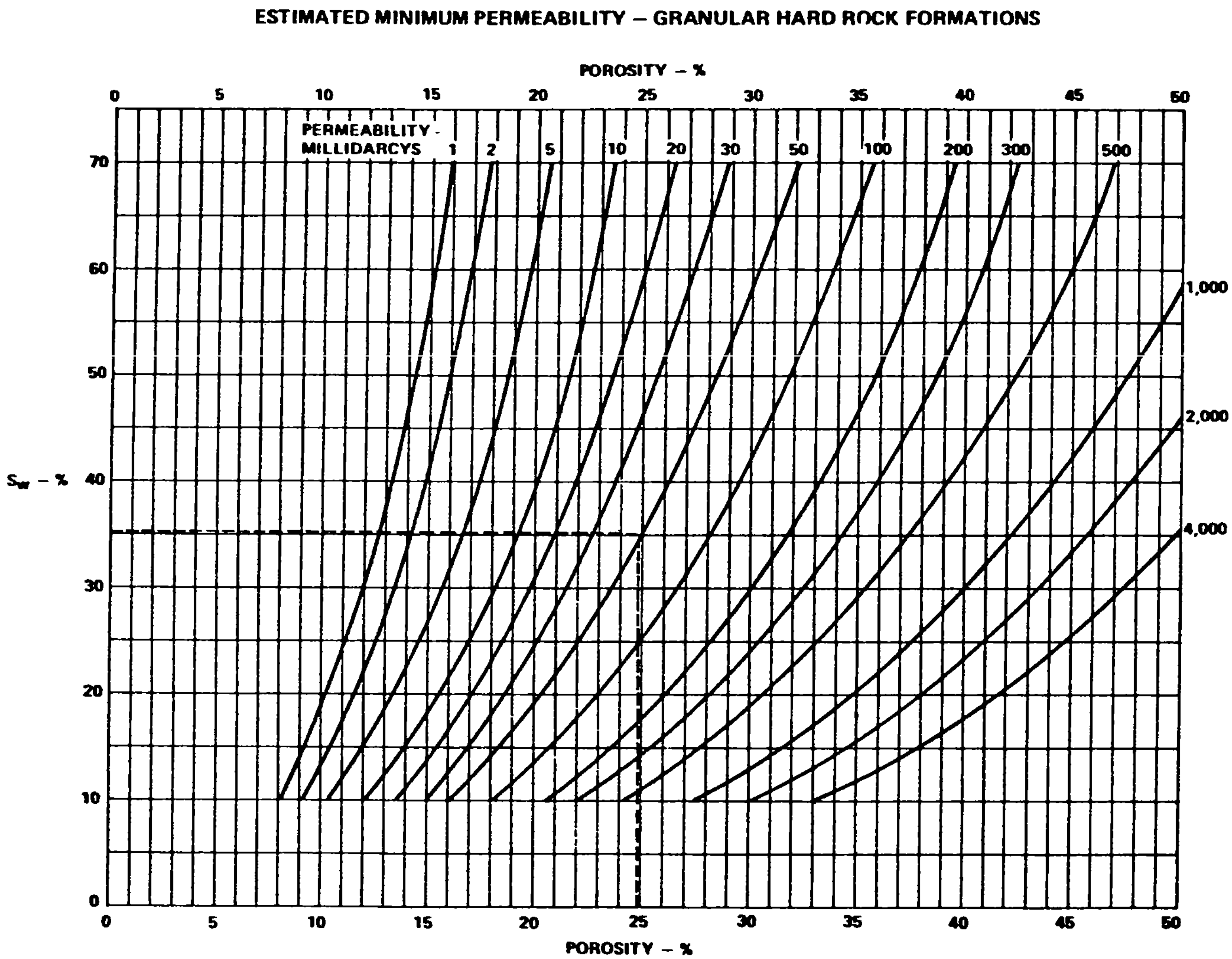

Fig. 10. Estimated minimum permeability for granular hard-rock formations (reprinted from Gearhart-Owen Formation Evaluation Data Handbook).

A normal hydrostatic gradient of 0.443 psi per foot was used for calculating the formation pressure. The pressures may be higher in some areas because of high salinities of the formation waters.

The nomograph can provide a good first approximation of initial flow. The depth of the formation, the permeability, and the thickness must be defined in order to use the nomograph, however. It can be seen on the nomograph that a formation 5,000 feet below the surface that has a 25-millidarcy permeability would initially flow 1,050 barrels of water per day from each 20 feet of the formation.

An example is given here of how to find the initial open-flow potential from a specific well in the study area. The well is in sec. 31, T. 9N, R. 21E. (pl. 2, map B). The Spiro sand at this locality is 104 feet thick, and the depth, taken from the electric log, is 4,442 feet. The water saturation was calculated to be 14 percent. The log-derived porosity was 14 percent. The permeability, taken from the chart, is 12 millidarcies. Enter the nomograph (fig. 9) at 4,442 feet and move right to approximately 12 millidarcies. This indicates an initial open-flow potential of about 500 barrels of water per day for each 20 feet of formation thickness. The total flow, then, would be

$$500 \times 104 \div 20 = 2{,}600 \text{ BW/D}$$

The estimated initial flow of water from the Spiro sand at this locality would be approximately 2,600 barrels per day. A similar exercise could be conducted for the Cromwell sandstone and the Hartshorne sandstone in their respective areas.

By using the isopach map, it is possible to calculate a rough estimate of water volume within a given area. In section 31, from the previous example, there is an average formation thickness of 60 feet of Spiro sand (pl. 2, map B). Assuming an average porosity of 14 percent for the Spiro sand, the total volume of reservoir water in this section would be:

$$60 \text{ feet} \times 640 \text{ acres} = 38{,}400 \text{ acre-feet}$$

of bulk formation volume. Then:

38,400 X .14 = 5,376 acre-feet

of water in the formation, assuming a 100 percent water saturation. Finally, converting acre-feet to barrels:

5,376 X 7,758 bbl/acre-ft $\cong$ 41,706,000 barrels of water

If the average water saturation is less than 100 percent, then the 41,706,000 barrels of water would be multiplied by the average water saturation. For the Spiro sand, the average water saturation is 26 percent, so this would result in the following:

41,706,000 X .26 = 10,844,000 barrels

This would indicate that the minimum quantity of water in place would be 10,844,000 barrels for the Spiro sand at this locality.

Summary

The minimum amount of water in a locality can be estimated by using the isovolume map. Furthermore, an estimate can be made over an area by using the isopach map along with average values for porosity and thickness. A summary of formation characteristics and minimum water-in-place estimates for the Hartshorne, Spiro, and Cromwell sandstones are listed in table 1.

The initial flow of water into the bore hole can be determined by using Darcy's Law. Values for the variables in the equation can be taken from appropriate maps (except for permeability). It is best to have a laboratory analysis for good permeability data. For a rough estimate, a chart of empirical petrophysical relationships can be used.

Because of the uncertainty involved in such calculations, site-specific areas which may be considered for geothermal applications should be subjected to detailed studies. Such studies would be in order so that an operator could estimate the productive lifetime of a given low-temperature geothermal resource. Estimates of in-place water volumes

Table 1. Summary of Formation Characteristics and Minimum Water-in-Place Estimates for Hartshorne, Spiro, and Cromwell Sandstones ***

FORMATION	AVERAGE DEPTH (ft)	AVERAGE THICKNESS (ft)	AVERAGE POROSITY (%)	WATER-SATURATION RANGE (%)	AVERAGE TEMPERATURE (°F)*	MINIMUM WATER IN PLACE (bbl)**
Hartshorne	2558	70	10	12-58	103	640,896,000
Spiro	5290	37	14	10-98	151	771,727,000
Cromwell	5724	43	18	5-39	158	761,424,000

* Calculated from uncorrected bottom-hole temperatures.

** Estimated from isovolume maps.

*** See appendix for detailed petrophysical data.

and deliverability calculated for the present study are regional in scope and are intended as order-of-magnitude assessments.

FUTURE INVESTIGATIONS

Temperature data from geophysical logs usually indicate geothermal gradients that are somewhat lower than measurements obtained after thermal equilibration. Therefore, a temperature-confirmation program will be initiated to determine the relationship between temperature data from geophysical logs and equilibration temperatures. Then we can ascertain (1) the magnitude of the variation and (2) whether the variation is systematic. If the difference between geophysical-log temperature and true temperature is systematic, it may be possible to make a standard correction to the geothermal-gradient map (fig. 3) in order to obtain an approximation of equilibration temperatures. Should the difference, however, vary with other characteristics, such as petrophysics or geologic province, correction factors will be somewhat more complicated.

A precision microthermometer was constructed according to specifications provided to us by Sean Thomas Morrisey of St. Louis University (fig. 11). The sensor consists of two 1N914 diodes wired in series and one 0.01 microfarad capacitor. A box-like compartment was built to house the operational amplifier and its components and the D.C.-power supply. A second system, which is less sensitive, was included within the component compartment. For this system, a 5-megaohm resistor was substituted for the 1-megaohm feedback resistor (see fig. 11) in order to record temperatures greater than $60^{o}C$. This circuit is referred to as T_2.

Ice water ($0^{o}C$) and hot water ($60^{o}C$) were used to calibrate the sensor. The zero potentiometer and span were adjusted until $50mV/^{o}C$ was attained. The T_2 circuit was calibrated in the same manner except signal response was $10mV/^{o}C$. This dual thermometer system permits very accurate temperature measurements ($\pm 0.5^{o}C$) up to $60^{o}C$ as well as the ability to record temperatures greater than $60^{o}C$, although the higher readings will not be as accurate ($\pm 1.0^{o}C$).

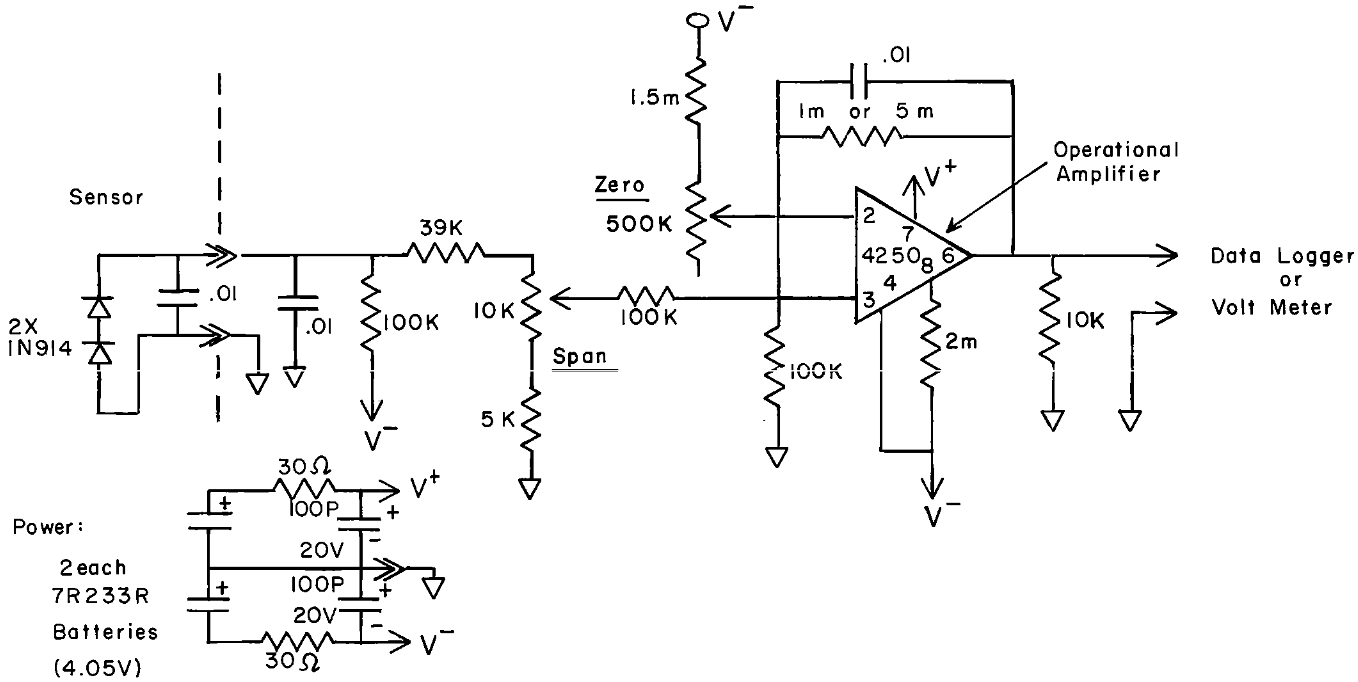

Fig. 11. Circuit diagram for precision micro-thermometer.

The temperature-confirmation program will consist of two systems, nonretrievable and retrievable. The first system involves the continuous recording of temperatures in recently abandoned oil and (or) gas test holes for a period of several months. A temperature sensor will be attached to a 7-conductor cable and lowered into an abandoned borehole to depths as great as 1,500 feet. A second cable and sensor will be placed into the same borehole to a depth of 500 feet. Concrete will be added to the top 30 feet of the borehole, thus making this installation somewhat permanent. A 10-channel analog data logger will continuously record the temperature data on a cassette tape. The tape will be retrieved once a month and processed at the Oklahoma Geophysical Observatory. Time-temperature data will be compared with temperature data obtained from geophysical logs. The difference between the two temperatures will enable us to assess equilibration variations. The Pittsburg and Haskell anomalies are the principal target areas. We plan to install several sensors in recently drilled abandoned oil and (or) gas wells drilled in the target areas. Thus far, almost every oil and gas well recently drilled in this region has been productive.

The second system will use a retrievable temperature probe to perform the temperature-assessment work. A temperature sensor will be attached to a 3,000-foot 4-conductor logging cable. A D.C.-powered hoist will be used to raise and (or) lower the temperature probe. A digital voltmeter can be used to measure voltage variations, which can be converted to temperature measurements.

This system will be used principally in abandoned boreholes drilled during the last 10 years. The surface plug, generally 30 to 50 feet thick, will be drilled out. Then the temperature probe will be lowered into the borehole to depths between 700 and 1200 feet. Generally the depth will depend upon the length of surface casing left in the hole.

We feel that both of these systems will provide temperature data that will give us even greater reliability in evaluating geophysical-log temperatures in Oklahoma.

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APPENDIX

Selected Petrophysical Data

1. Hartshorne sandstone
2. Spiro sandstone
3. Cromwell sandstone

FORMATION HARTSHORNE

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
1-7N-16E	3048-3100	108	-	0.075	25	10	51	65,000
2-7N-16E	2575-92	106	-	0.075	60	7	49	65,000
4-7N-16E	2765-74	117	-	0.075	25	10	52	60,000
12-7N-16E	3134-72	101	-	0.075	75	10	30	70,000
14-7N-16E	2570-2620	112	-95	0.08	80	10	28	55,000
21-7N-16E	3170-90	109	-	0.075	75	10	28	65,000
24-7N-16E	2662-2768	101	-	0.075	80	10	27	70,000
26-7N-16E	3050-3117	113	-	0.075	40	10	40	68,000
27-7N-16E	2990-3052	112	-	0.075	25	10	50	60,000
31-7N-16E	2022-66	87	-	0.075	50	10	35	82,000
35-7N-16E	2850-2914	104	-	0.1	50	10	42	68,000
36-7N-16E	2370-2442	102	-	0.075	45	10	37	69,000
3-7N-17E	2505-89	103	-	0.075	300	12	12	69,000
4-7N-17E	2750-84	106	-	0.075	250	11	15	65,000
5-7N-17E	2845-2929	107	-	0.075	90	10	26	65,000
6-7N-17E	2972-3100	108	-	0.075	80	10	60	65,000
8-7N-17E	2685-2795	109	-	0.075	100	10	25	64,000
9-7N-17E	2702-56	108	-	0.075	300	10	14	65,000
10-7N-17E	2960-3013	107	-	0.075	300	10	14	65,000
11-7N-17E	2382-2432	109	-	0.075	350	10	14	65,000
12-7N-17E	2442-2562	91	-75	0.075	150	10	22	80,000
13-7N-17E	2015-79	102	-	0.075	200	10	22	68,000
15-7N-17E	2500-36	102	-	0.075	350	10	15	69,000
16-7N-17E	2330-56	99	-	0.075	300	10	15	62,000
17-7N-17E	2944-3020	114	-	0.075	50	10	36	60,000
18-7N-17E	2570-2619	104	-	0.075	200	10	18	67,000
19-7N-17E	2565-2702	106	-	0.075	95	10	25	65,000
20-7N-17E	2464-2584	102	-	0.075	100	10	26	68,000
22-7N-17E	2160-2240	96	-40	0.075	100	10	26	72,050
23-7N-17E	2219-49	89	-40	0.075	100	10	26	86,000
24-7N-17E	2096-2124	94	-68	0.075	300	10	16	75,000
25-7N-17E	2584-2632	115	-	0.075	100	10	26	59,000
26-7N-17E	2610-40	97	-20	0.075	40	10	42	73,000
27-7N-17E	2672-2722	112	-	0.075	250	10	16	60,000

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
28-7N-17E	3010-68	109	-40	0.075	50	10	37	65,000
29-7N-17E	2615-65	98	-120	0.045	10	10	62	140,000
30-7N-17E	2920-3020	108	-	0.075	100	10	25	65,000
31-7N-17E	3070-3135	105	-	0.075	62	10	31	65,000
32-7N-17E	3260-3327	121	-	0.075	270	10	15	55,000
33-7N-17E	2764-2819	97	-	0.075	43	10	39	72,000
35-7N-17E	2570-2628	96	-	0.075	35	10	42	73,000
2-8N-16E	2340-2402	93	-	0.075	35	10	44	76,000
3-8N-16E	2414-34	119	-	0.075	100	10	25	58,000
4-8N-16E	2266-2282	96	-	0.075	40	10	40	73,000
5-8N-16E	2003-43	99	-	0.075	40	10	40	70,000
6-8N-16E	2203-37	112	-	0.075	35	10	42	60,000
8-8N-16E	2510-50	91	-	0.075	35	10	42	78,000
25-8N-16E	2552-84	104	-	0.075	30	10	46	66,000
32-8N-16E	3122-48	102	-	0.075	20	10	58	68,000
36-8N-16E	2590-2622	109	-	0.075	35	10	44	65,000
1-8N-17E	1963-2113	97	-	0.075	20	10	58	72,000
10-8N-17E	2206-2326	98	-	0.075	35	10	43	72,000
11-8N-17E	1985-2155	94	-	0.075	25	10	51	75,000
12-8N-17E	1950-2088	91	-	0.075	25	10	51	78,000
13-8N-17E	1910-2060	90	-	0.075	35	10	46	80,000
14-8N-17E	1967-2022	93	-	0.075	100	10	25	75,000
15-8N-17E	1947-2027	89	-	0.075	100	10	25	80,000
16-8N-17E	2270-2370	117	-	0.075	100	10	25	59,000
17-8N-17E	2502-2652	108	-	0.075	50	10	36	65,000
19-8N-17E	2960-3090	108	-	0.075	35	10	43	65,000
20-8N-17E	2760-2850	109	-	0.075	40	10	40	64,000
21-8N-17E	2918-53	106	-	0.075	150	10	21	66,000
22-8N-17E	2331-61	100	-	0.075	100	10	25	70,000
23-8N-17E	2084-2154	97	-	0.075	400	10	13	81,000
24-8N-17E	2101-2201	99	-	0.075	110	10	24	71,000
25-8N-17E	2465-2545	101	-	0.075	150	10	21	70,000
26-8N-17E	2502-2602	100	-	0.075	100	10	25	70,000

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
28-8N-17E	2611-81	104	-	0.075	400	10	13	68,000
29-8N-17E	2790-2820	98	-	0.075	225	10	17	72,000
31-8N-17E	2710-2810	96	-	0.075	100	10	25	74,000
32-8N-17E	2784-2904	106	-	0.075	75	10	29	65,000
33-8N-17E	2532-2612	103	-	0.075	150	10	21	68,000
34-8N-17E	2480-2580	103	-	0.075	100	10	25	68,000
35-8N-17E	2662-2752	96	-	0.075	100	10	25	70,000
36-8N-17E	2578-2648	104	-	0.075	150	10	21	68,000

FORMATION SPIRO sand

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
1-8N-23E	5172-5210	141	-10	0.5	400	14	21	6,000
2-8N-23E	5393-5425	141	-60	0.054	300	14	10	70,000
3-8N-23E	5443-95	147	-	0.06	60	14	27	60,000
5-8N-23E	5512-30	138	-13	0.55	45	14	65	5,500
6-8N-23E	5720-38	142	-38	0.3	200	14	25	7,500
7-8N-23E	5645-60	177	-	0.06	50	14	23	45,000
8-8N-23E	5473-5500	195	-	0.06	350	8	15	42,000
9-8N-23E	5185-5205	138	-21	0.26	17	14	95	12,000
11-8N-23E	5282-5325	162	-	0.28	400	12	12	10,000
12-8N-23E	5275-5300	137	-23	0.06	50	12	27	65,000
13-8N-23E	5024-5065	186	-	0.06	125	12	17	45,000
14-8N-23E	5149-65	151	-51	0.3	62	12	55	10,000
15-8N-23E	5470-5550	164	-	0.06	325	14	11	55,000
16-8N-23E	5505-45	172	-	0.06	125	12	17	48,000
18-8N-23E	5478-5508	171	-	0.06	160	12	15	50,000
19-8N-23E	5472-5500	135	-121	0.03	250	14	10	150,000
22-8N-23E	5245-80	139	-54	0.16	350	17	10	20,000
23-8N-23E	5100-35	138	-	0.35	75	12	50	9,500
24-8N-23E	5035-85	184	-	0.06	150	12	13	45,000
28-8N-23E	5249-80	122	-50	0.06	70	12	23	75,000
29-8N-23E	5312-75	149	-100	0.065	200	14	10	55,000
30-8N-23E	5680-5710	140	-120	0.045	300	14	10	90,000
31-8N-23E	5566-85	139	-90	0.058	150	14	13	70,000
32-8N-23E	5427-5545	161	-	0.06	32	12	32	55,000
9-9N-21E	4029-50	126	-60	0.04	30	21	16	120,000
10-9N-21E	4000-25	118	-85	0.04	24	20	18	140,000
11-9N-21E	3912-60	119	-100	0.04	40	14	21	135,000
11-9N-21E	3930-60	119	-100	0.04	2	14	91	135,000
15-9N-21E	4040-4100	120	-70	0.06	57	17	52	75,000
17-9N-21E	4088-4120	128	-	0.06	27	14	30	73,000
19-9N-21E	4011-32	127	-	0.06	300	14	10	70,000
20-9N-21E	4133-4157	123	-65	0.068	11	12	60	63,000
23-9N-21E	4754-66	119	-90	0.085	30	14	35	55,000
25-9N-21E	4834-66	130	-100	0.04	1.30	14	98	120,000

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
27-9N-21E	4247-83	134	-	0.06	50	14	23	65,000
29-9N-21E	3982-98	113	-80	0.075	12	14	51	68,000
30-9N-21E	4076-96	126	-	0.06	33	14	24	70,000
32-9N-21E	4040-80	-	-	0.06	10	14	50	-
34-9N-21E	4751-4800	145	-	0.06	250	14	10	60,000
36-9N-21E	4570-4600	134	-100	0.04	28	17	20	110,000
1-9N-22E	6262-70	164	-	0.05	25	14	30	65,000
9-9N-22E	5215-85	142	-	0.06	31	12	33	60,000
12-9N-22E	6050-90	145	-	0.06	50	14	23	60,000
13-9N-22E	5581-98	164	-	0.06	20	14	35	55,000
21-9N-22E	6033-45	170	-	0.06	60	14	21	50,000
22-9N-22E	6100-25	168	-	0.06	22	14	33	50,000
25-9N-22E	5461-74	148	-	0.06	35	14	27	60,000
26-9N-22E	5647-60	130	-90	0.07	42	14	26	58,000
28-9N-22E	6074-90	133	-	0.06	100	14	16	65,000
29-9N-22E	4845-4915	131	-70	0.044	150	14	10	110,000
30-9N-22E	4550-70	122	-120	0.16	100	14	25	21,000
31-9N-22E	4442-4546	117	-75	0.02	44	14	14	300,000
32-9N-22E	6292-6310	176	-	0.06	100	14	17	50,000
33-9N-22E	6248-82	160	-	0.04	45	14	17	55,000
34-9N-22E	5648-60	165	-	0.06	70	14	18	50,000
35-9N-22E	5662-74	138	-30	0.05	150	9	13	80,000
36-9N-22E	5847-76	196	-	0.06	100	14	16	42,000
1-9N-23E	6180-6218	138	-120	0.045	35	14	23	90,000
2-9N-23E	5416-42	145	-	0.78	100	14	55	4,000
4-9N-23E	5450-72	144	-140	0.012	2	14	47	300,000
6-9N-23E	6140-56	169	-	0.45	100	14	40	6,000
7-9N-23E	5910-28	172	-	0.06	250	14	10	50,000
8-9N-23E	5473-86	161	-	0.06	100	14	17	55,000
9-9N-23E	5385-5408	171	-	0.06	100	14	17	50,000
10-9N-23E	5336-80	137	-105	0.06	270	14	10	65,000
11-9N-23E	5290-5384	141	-60	0.11	142	14	17	32,000
12-9N-23E	5560-5626	175	-	0.06	200	14	12	50,000

* From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
13-9N-23E	5435-5522	136	-100	0.065	200	14	10	60,000
15-9N-23E	5378-5464	183	-	0.06	35	14	26	45,000
16-9N-23E	5378-5400	178	-	0.06	38	14	25	50,000
17-9N-23E	5456-86	150	-	0.06	50	14	23	58,000
18-9N-23E	5452-66	148	-	0.06	32	14	27	60,000
19-9N-23E	5382-5398	141	-75	0.14	35	22	26	-
20-9N-23E	5592-5620	180	-100	0.026	10	14	36	140,000
21-9N-23E	5573-88	158	-	0.06	37	11	32	55,000
22-9N-23E	5365-5400	135	-50	0.38	70	14	50	8,500
23-9N-23E	5361-5436	173	-	0.06	200	14	12	50,000
24-9N-23E	5253-87	144	-	0.06	200	14	10	60,000
25-9N-23E	5662-88	153	-	0.06	100	14	16	57,000
26-9N-23E	5653-86	174	-	0.06	50	14	23	50,000
27-9N-23E	5522-58	153	-	0.06	50	14	23	57,000
28-9N-23E	5578-5614	156	-	0.06	33	14	27	56,000
29-9N-23E	5735-66	161	-	0.1	43	14	31	30,000
31-9N-23E	5511-26	168	-	0.06	25	14	33	50,000
32-9N-23E	5476-86	181	-	0.06	7	14	60	45,000
33-9N-23E	5446-60	149	-50	0.04	60	14	17	95,000
34-9N-23E	5273-5300	136	-60	0.06	66	14	18	65,000
35-9N-23E	5280-5308	130	-80	0.05	120	10	18	82,000
36-9N-23E	5170-5184	133	-	0.05	50	18	13	80,000
1-9N-24E	5761-84	162	-	0.05	55	11	25	65,000
3-9N-24E	6138-94	191	-	0.06	40	14	24	-
4-9N-24E	6096-6142	187	-	0.05	75	11	22	55,000
6-9N-24E	6230-40	189	-	0.06	10	14	50	45,000
7-9N-24E	5634-84	158	-	0.06	250	14	10	55,000
8-9N-24E	5884-5910	184	-	0.06	150	14	15	45,000
9-9N-24E	5578-5616	161	-	0.06	200	14	12	53,000
10-9N-24E	5316-40	162	-50	0.06	83	14	17	52,000
11-9N-24E	5097-5146	174	-	0.06	200	14	12	47,000
12-9N-24E	5007-46	186	-	0.06	200	14	10	45,000
13-9N-24E	4712-64	123	-40	0.06	250	14	8	75,000
19-9N-24E	5750-5888	134	-120	0.024	15	14	23	200,000

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
24-9N-24E	4802-52	153	-70	0.05	250	14	8	70,000
25-9N-24E	5180-5214	160	-	0.06	200	14	12	55,000
26-9N-24E	4993-5030	139	-85	0.05	45	9	35	80,000
27-9N-24E	4890-4910	-	-40	0.06	100	14	14	-
28-9N-24E	5155-90	-	-80	0.06	250	14	10	-
29-9N-24E	4892-4946	-	-120	0.06	70	14	18	-
33-9N-24E	4898-4946	154	-	0.05	50	12	24	70,000
34-9N-24E	4908-33	152	-140	0.06	125	17	12	60,000
35-9N-24E	4782-4858	126	-50	0.09	125	14	17	43,000
36-9N-24E	4680-4710	148	-	0.04	150	9	17	95,000

FORMATION CROMWELL

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
1-8N-23E	5602-20	148	-20	0.3	110	14	33	9,500
2-8N-23E	5832-72	147	-	0.06	25	18	24	60,000
3-8N-23E	5860-74	153	-	0.06	30	18	22	56,000
5-8N-23E	5930-46	144	-	0.06	27	18	23	60,000
6-8N-23E	6128-68	147	-	0.06	45	18	17	59,000
9-8N-23E	5587-5603	144	-	0.06	150	18	10	80,000
10-8N-23E	5640-5760	148	-120	0.04	300	18	10	95,000
15-8N-23E	5820-36	171	-	0.06	60	18	16	50,000
16-8N-23E	5996-6028	183	-80	0.085	250	18	10	32,000
16-8N-23E	6057-69	183	-80	0.085	140	18	13	32,000
18-8N-23E	5890-5956	179	-	0.06	100	18	12	47,000
21-8N-23E	5720-62	176	-	0.06	300	18	10	48,000
22-8N-23E	5612-32	145	-	0.06	50	9	36	60,000
23-8N-23E	5674-5760	147	-	0.06	25	18	24	60,000
24-8N-23E	5620-46	198	-	0.06	35	18	20	42,000
29-8N-23E	5800-40	157	-40	0.06	300	18	10	55,000
9-9N-21E	4435-82	132	-	0.04	300	18	10	110,000
10-9N-21E	4305-46	122	-	0.04	50	18	14	122,000
11-9N-21E	4240-4310	125	-	0.04	60	18	13	120,000
15-9N-21E	4358-4460	125	-40	0.06	47	18	17	70,000
25-9N-21E	5116-5200	135	-20	0.06	250	18	10	65,000
29-9N-21E	4308-4490	117	-40	0.06	60	18	16	85,000
30-9N-21E	4390-4450	131	-	0.06	40	18	19	66,000
32-9N-21E	4450-4580	-	-40	0.06	50	18	17	-
36-9N-21E	4896-4964	139	-	0.06	70	18	14	65,000
1-9N-22E	6523-46	169	-	0.05	80	18	13	63,000
9-9N-22E	5532-50	147	-	0.06	10	18	39	60,000
13-9N-22E	5957-6045	170	-	0.06	50	18	17	45,000
21-9N-22E	6338-95	175	-	0.06	70	18	14	45,000
22-9N-22E	6378-6420	173	-	0.06	60	18	16	48,000
25-9N-22E	5790-5830	153	-	0.06	60	18	16	57,000
26-9N-22E	5967-6030	133	-	0.06	250	18	10	66,000
28-9N-22E	6395-6455	174	-	0.06	25	18	24	48,000
29-9N-22E	4845-4915	131	-70	0.044	150	14	10	110,000
31-9N-22E	4828-4900	122	-	0.06	200	18	10	75,000

*From SPE Reprints Series, "Survey of resistivities of water from subsurface formations in Oklahoma," March 1975.

**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
32-9N-22E	6670-6760	181	-	0.06	100	18	13	45,000
33-9N-22E	6615-6680	166	-120	0.04	25	11	34	82,000
34-9N-22E	6001-6045	172	-	0.06	200	6	27	50,000
35-9N-22E	5945-6022	141	-20	0.06	45	18	18	60,000
36-9N-22E	6147-90	203	-	0.06	45	18	17	41,000
1-9N-23E	6543-90	143	-	0.06	50	18	17	60,000
2-9N-23E	5799-5880	151	-	0.06	100	18	13	58,000
6-9N-23E	6447-80	174	-	0.06	300	18	10	48,000
7-9N-23E	6216-38	178	-	0.06	350	18	10	48,000
8-9N-23E	5893-5997	168	-	0.06	45	18	18	50,000
11-9N-23E	5668-5710	147	-	0.06	45	18	17	60,000
12-9N-23E	5825-35	180	-	0.06	43	18	18	46,000
12-9N-23E	5952-85	183	-	0.06	45	18	17	45,000
12-9N-23E	6040-6130	185	-	0.06	100	18	13	45,000
16-9N-23E	5738-54	185	-	0.06	100	18	13	45,000
17-9N-23E	5782-96	155	-	0.06	70	18	14	57,000
18-9N-23E	5740-60	152	-	0.06	40	18	19	57,000
19-9N-23E	5706-30	146	-20	0.06	45	18	16	60,000
20-9N-23E	5944-76	187	-	0.06	35	18	20	45,000
22-9N-23E	5750-80	141	-	0.06	35	18	20	62,000
25-9N-23E	6052-85	160	-	0.06	50	18	17	55,000
27-9N-23E	6040-60	162	-	0.06	100	18	13	53,000
28-9N-23E	5995-6010	163	-	0.06	40	18	19	52,000
29-9N-23E	6092-6133	168	-	0.06	200	18	8	50,000
30-9N-23E	5980-6005	164	-	0.06	45	18	17	51,000
31-9N-23E	5902-30	175	-	0.06	20	18	27	48,000
32-9N-23E	5767-93	187	-	0.06	50	18	17	45,000
35-9N-23E	5700-30	136	-	0.06	250	18	5	65,000
36-9N-23E	5585-5615	139	-	0.06	35	18	21	62,000
1-9N-24E	6149-74	168	-	0.05	30	18	21	70,000
5-9N-24E	6572-90	-	-	0.06	50	18	17	-
7-9N-24E	5985-6035	164	-	0.06	25	18	24	51,000
8-9N-24E	6261-92	192	-	0.06	150	18	10	43,000
9-9N-24E	5970-6007	168	-	0.06	35	18	20	50,000
10-9N-24E	5696-5726	169	-	0.06	60	18	16	50,000

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**From charts using Rw and T.

Location	Depth (ft)	Temperature (°F)	SP (mv)	*Rw (ohm-m)	Rt (ohm-m)	Ø (%)	Sw (%)	**Salinity (ppm)
13-9N-24E	5108-45	128	-40	0.06	45	18	18	70,000
18-9N-24E	5816-67	-	-	0.06	100	18	13	-
19-9N-24E	6197-6223	140	-70	0.06	45	18	18	62,000
27-9N-24E	5310-20	-	-80	0.06	90	18	13	-
33-9N-24E	5318-30	162	-	0.06	22	18	26	52,000
35-9N-24E	5218-32	132	-	0.06	50	18	17	68,000
36-9N-24E	5122-50	156	-	0.04	50	18	14	90,000