DOE/ID/12079-71
ESL-98

CONF-820491-Vol.1-12

GEOTHERMAL DIRECT HEAT PROGRAM
ROUNDUP TECHNICAL CONFERENCE PROCEEDINGS

VOLUME I

PAPERS PRESENTED

STATE COUPLED RESOURCE
ASSESSMENT PROGRAM

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Editor

July 1982

MASTER

Work performed under contract DE-AC07-80ID12079

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Salt Lake City, Utah

Prepared for
U.S. Department of Energy
Division of Geothermal Energy

GEOTHERMAL RESOURCE ASSESSMENT IN OKLAHOMA

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SUMMARY

In September 1980, the Oklahoma Geological Survey 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 subsurface 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 Haskell anomaly and the Hartshorne sandstone was 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 in 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 (figure 3) are discussed below.

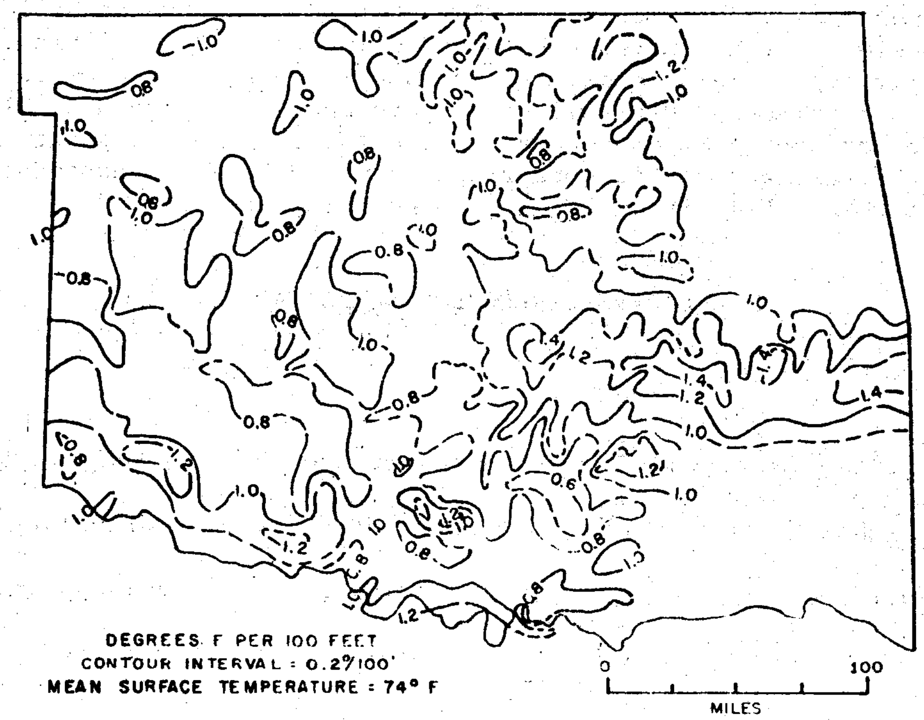

Fig. 1. Geothermal gradient map of Oklahoma (from Schoeppel and Gilarranz, 1966).

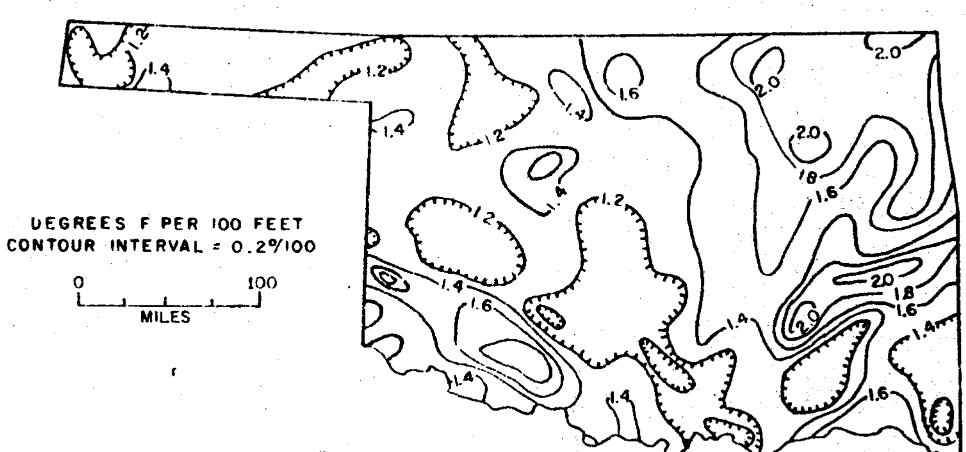

Fig. 2. Geothermal gradient map of Oklahoma (adapted from Geothermal Gradient Map of North America, 1976, see Shelton, 1976).

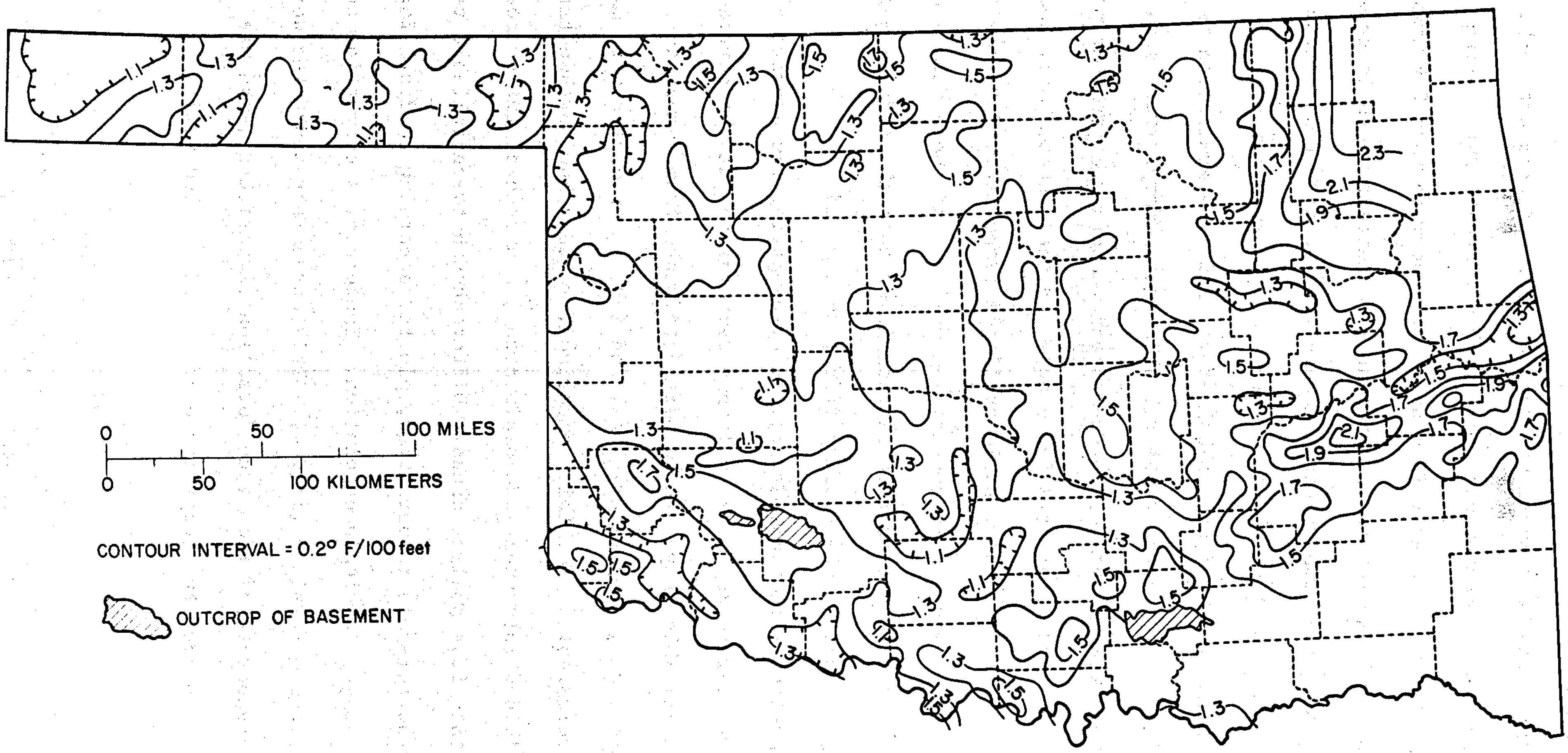

Fig. 3. Geothermal gradient map of Oklahoma (modified from Cheung, 1979).

Temperature 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°F from the average. The average temperature measurement at a certain depth is considered to be the true formation 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 correction factor 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. 4). This curve represents the deviation of bottom-hole temperatures from true formation temperatures, and was used in this study to correct the temperatures from mud-drilled wells.

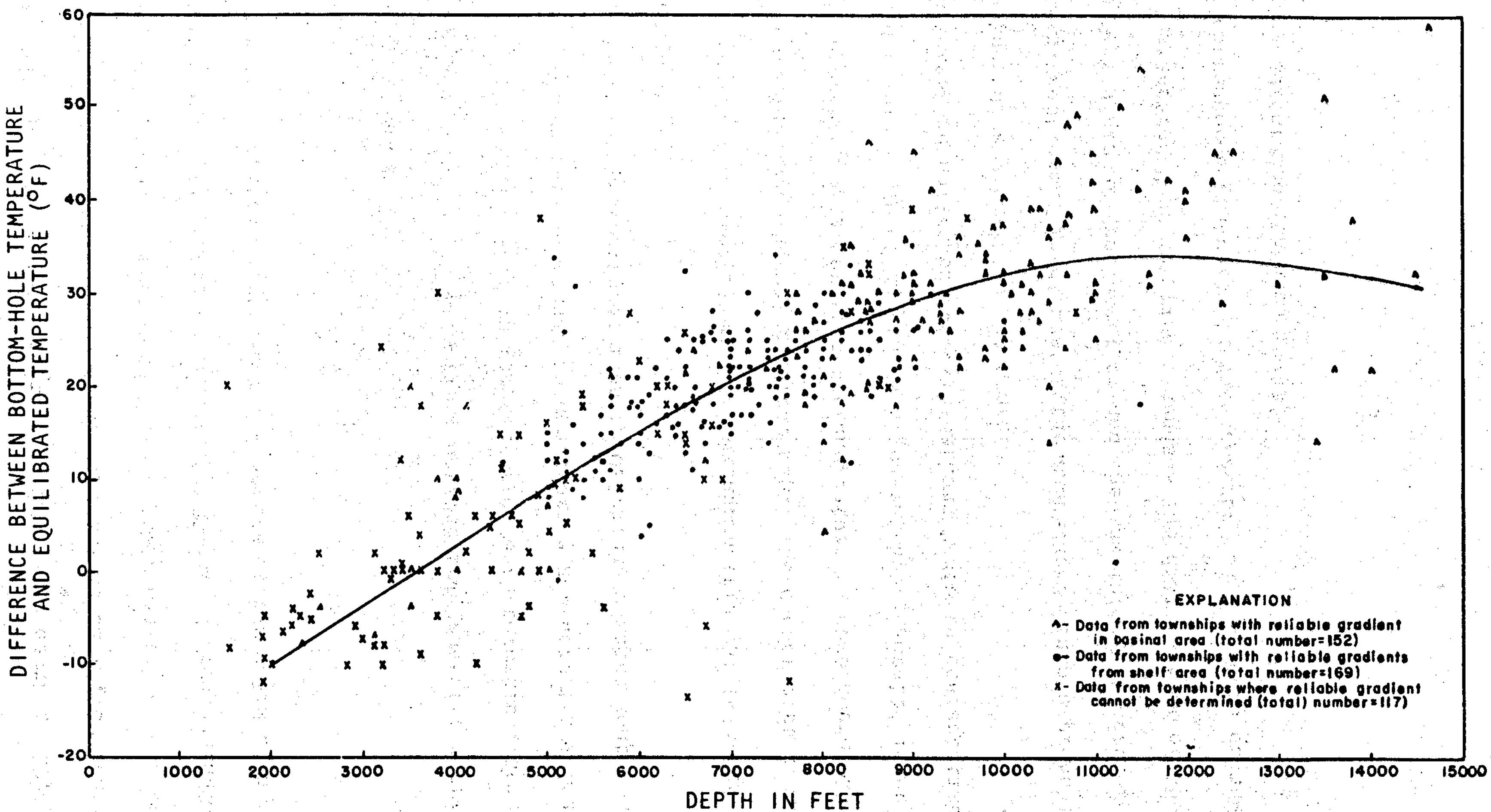

Fig. 4. Correction curve for bottom-hole temperatures of wells in Oklahoma.

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.

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°F/100 feet.

The general tectonic framework of Oklahoma (fig. 5) 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).

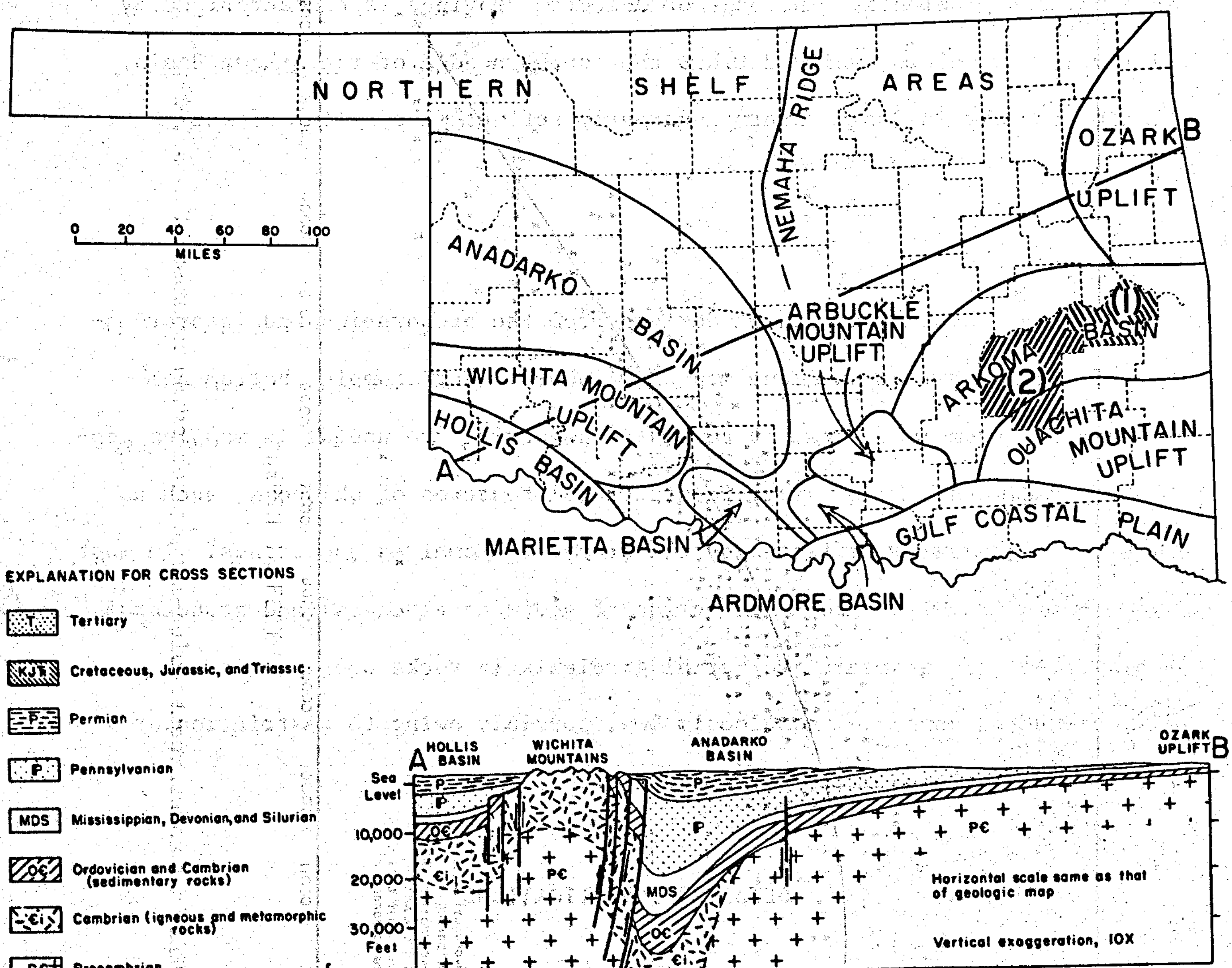

Fig. 5. Map and cross section showing major geologic and tectonic provinces of Oklahoma and locations of detailed investigations. Area 1 is the Haskell anomaly, and area 2 is the Pittsburg anomaly.

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°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 Ouachita Province is characterized by relatively low values, which defines the southern edge of the Arkoma Basin. The high anomaly in Osage County apparently reflects the relief of the basement.

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. 5). 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 (fig. 6). 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, and the Spiro and Cromwell 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.

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:

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 MC ALESTER 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. 6. Generalized correlation chart for the Arkoma Basin (modified from Disney, 1960).

$$V = AB\Sigma(h_i[Sw_i]\phi_i) \quad (1)$$

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. Porosity (ϕ) and water saturation (Sw) were determined from bore-hole geophysical logs.

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:

$$V = H(A_0 + A_1 + A_2 + \cdots + A_n) \times 7{,}758 \text{ bbl/acre-ft} \quad (2)$$

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.

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:

$$Q = \frac{7.07kh(P_e - P_w)}{\mu \ln(r_e/r_w)} \quad (3)$$

where Q = barrels per day (42 gallons/barrel)
k = permeability in darcies
h = interval thickness in feet
P_e = 1 atmosphere in 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

A nomagraph (fig. 7) based on equation (3) 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. 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.

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 of the formation 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.

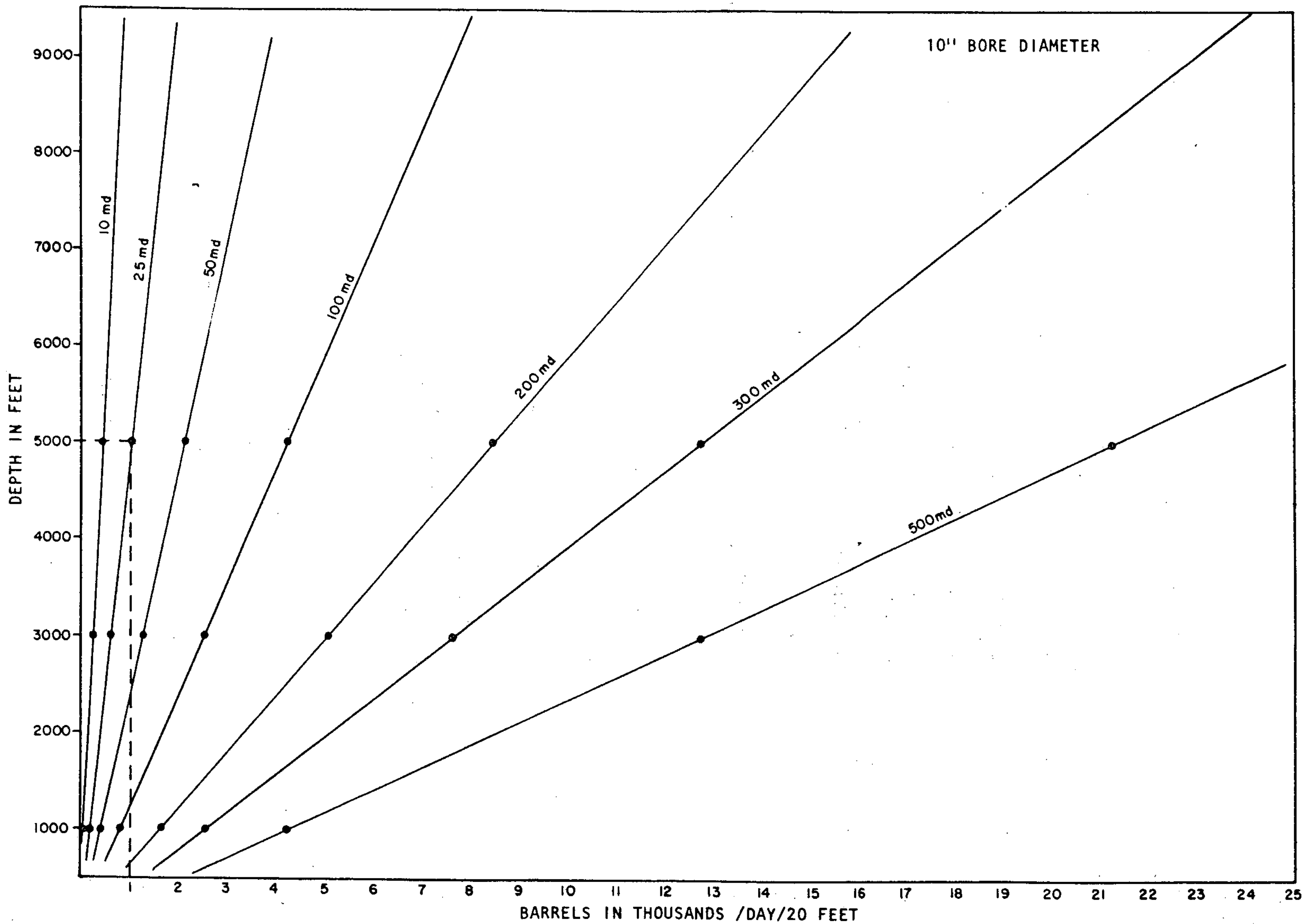

Fig. 7. Nomograph which relates permeability, depth, and barrels of liquid per day for a 10-inch diameter well bore.

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 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.

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	2,258	70	10	12-58	103	640,896,000
Spiro	5,290	37	14	10-98	151	771,727,000
Cromwell	5,724	43	18	5-39	158	761,424,000

*Calculated from uncorrected bottom-hole temperatures.

**Estimated from isovolume maps.

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 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.

The temperature-confirmation program will consist of two systems, non-retrievable 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 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 ditigal 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 1,200 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 bore-hole geophysical-log temperatures in Oklahoma.

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