THE GEOTHERMAL GRADIENT IN SEDIMENTARY ROCKS IN OKLAHOMA

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Scope and Method of Study: The main objective of this study was to construct a geothermal gradient map of Oklahoma, exclusive of the Panhandle, and the Ozark and Ouachita provinces. Subsurface temperature data from oil and gas operations were used to determine the geothermal gradient. Most of the temperature data were bottom-hole temperatures from well logs, and they do not represent true formation temperatures. A correction scheme was developed for these data by comparing the differences between bottom-hole temperatures and equilibrated temperatures as a function of depth. Nearsurface temperature was established as a control point for constructing a linear gradient where temperature data are available only for a single depth. The nearsurface temperature was determined by extrapolation of reliable temperatures at depth. Temperature gradients within an abnormally pressured zone were mapped separately. Mud-weight changes served as the indicators for abnormal pressure. A regional geothermal gradient map and an abnormal temperature gradient map were constructed from the values determined for each township with control. Correlations were made between features of these maps and knwon geologic and geophysical features.

Findings and Conclusions: Bottom-hole temperatures, after correction, are useful in mapping geothermal gradients. Anadarko and Ardmore basins show low thermal gradients, whereas the Arkoma basin shows high gradients. The gradients appear to be related primarily to basement configuration and fluid migration for areas outside the Arkoma basin. Features of the geothermal gradient maps correlate well with tectonic-structural features. A number of geothermal-gradient anomalies correlate with oil and gas accumulations; the best correlations involve abnormal gradients. Presence of an abnormally pressured zone at depth may result in lower gradients in overlying strata due to an insulating effect. Also, geothermal anomalies correlate quite well with geophysical anomalies.

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PREFACE

This thesis is a study of the geothermal gradient in the sedimentary-rock column in Oklahoma, exclusive of the Panhandle and the southeasternmost and the northeasternmost parts. Data used are temperature measurements in boreholes drilled for oil and gas. Maps prepared portray the temperature gradients in the normally pressured formations for the State of Oklahoma and the temperature gradients in the abnormally pressured strata in the Anadarko and Ardmore basins. These maps are thought to provide useful information of the subsurface temperature conditions in Oklahoma.

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ABSTRACT

Most subsurface temperature data available for this study of the geothermal regime of Oklahoma are non-equilibrium temperatures represented by bottom-hole temperatures from mud-drilled wells. Equilibrated temperatures including temperature logs, temperatures from shut-in gas well pressure tests, and from air-drilled wells are available in less than half of the study area. A correction factor used to correct the bottom-hole temperatures was obtained by comparing the differences between bottom-hole temperatures and equilibrated temperatures as a function of depth.

Because surface ground temperatures are often different from mean annual temperature, a nearsurface temperature, determined by extrapolation of reliable temperature at depth, was used as a control point for constructing a linear gradient where subsurface temperatures are available for a single depth.

Two maps were constructed. One shows the geothermal gradients of normally pressured formations in Oklahoma. The other shows the temperature gradients within the abnormally pressured Lower Pennsylvanian-Upper Mississippian rocks in the deep part of the Anadarko and Ardmore basins. Temperature gradients change abruptly as pore pressure becomes abnormal.

The gradient maps correlate well with major tectonic-structural features. The low gradients of Anadarko and Ardmore basins reflect their thick sedimentary rock section, and presence of abnormally pressured formations at depth resulted in restriction of upward heat flow. The high gradients of Arkoma basin suggest that the origin of the basin may be associated with a continental margin or rift zone. For areas outside the Arkoma basin, geothermal gradients appear to be related primarily to basement configuration and fluid migration. A number of geothermal-gradient anomalies correlate well with oil and gas accumulations; the best correlations involve gradients within the abnormally pressured formation. Correlations with geophysical features further suggest the geothermal gradients of Oklahoma are generally related to basement relief.

CHAPTER II

INTRODUCTION

The knowledge of subsurface temperature is of fundamental importance to a better understanding of the geological, geophysical, and geochemical processes of the earth. The thermal regime within sedimentary rocks reflects a number of factors which in many cases are related to major geologic features. Maturation and migration of hydrocarbons, coalification, cementation, certain porosity changes, and formation and stabilization of various minerals are sedimentary processes which are temperature dependent, at least in part. Geothermal gradient maps may be useful in delineating areas of source-rock maturation, locating abnormally pressured formations, differentiating various types of basins, mapping ground-water movements, and locating various types of deep-seated structures.

This study focuses on the geothermal gradient within the sedimentary rocks of Oklahoma (Fig. 1). Subsurface information from oil and gas operations represent the data base for mapping the geothermal gradients.

Mapping of Geothermal Gradient

The geothermal gradient is commonly expressed as changes in temperature in degrees Fahrenheit per 100 feet of depth. The gradient varies slightly with different rock types, and in general, it increases

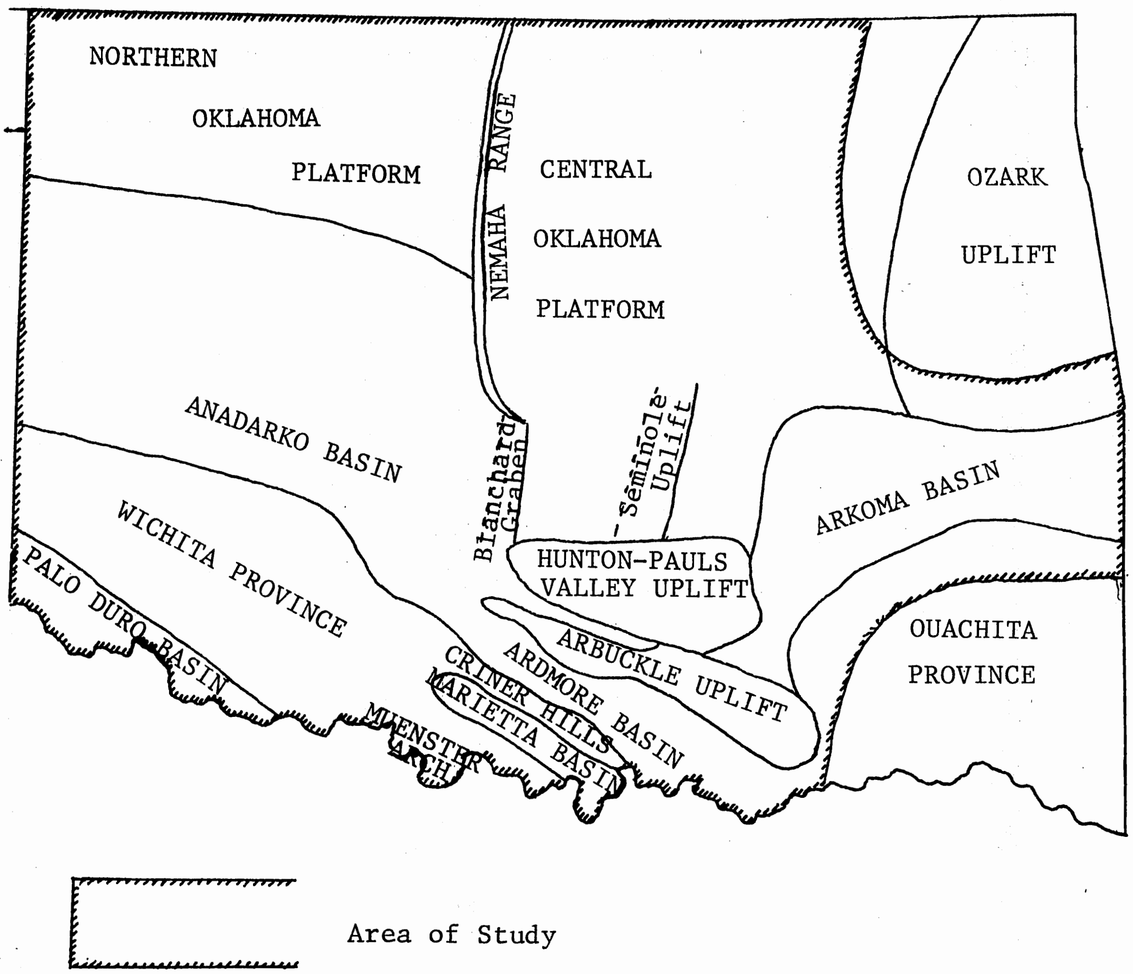

Fig. 1.-Index map showing the area of study and the major structural elements of Oklahoma (after Jordan, 1964)

slightly with depth due to changes in the thermal conductivity of the rocks (Levorson, 1967). In determining gradients for mapping purposes, they are considered to be linear, and the above-mentioned variations are ignored. However, abrupt changes in gradients have been observed to coincide with significant increases in fluid pressure. In this study, temperature gradients within an abnormally pressured zone are mapped separately.

Previous Investigations

An early attempt to map the geothermal gradient of Oklahoma was made by McCutchin (1930), who noted that among the 21 oil fields he studied there was a good correlation between oil-bearing anticlinal structures and high geothermal gradients. Bottom-hole temperatures from logs were excluded in most of the earlier works because it was thought that temperatures measured after circulation of drilling fluid would not be representative of true formation temperatures. Temperature readings from bottom-hole shut-in pressure tests were the only data used by Nichols (1947) and Moses (1961) in their studies.

In 1966, Schoeppel and Gilarranz mathematically analyzed heat-exchange processes associated with drilling and prepared a geothermal gradient map of Oklahoma (Fig. 2) from corrected bottom-hole temperatures. Their analysis showed that deviation of the measured bottom-hole temperature from the true formation temperature could be determined from the measured temperature and the time since circulation, provided factors such as the temperature of the drilling mud at surface, pipe size, circulation rate, size of annulus, and heat capacities and thermal conductivities of the drilling fluid, drill pipe, and country

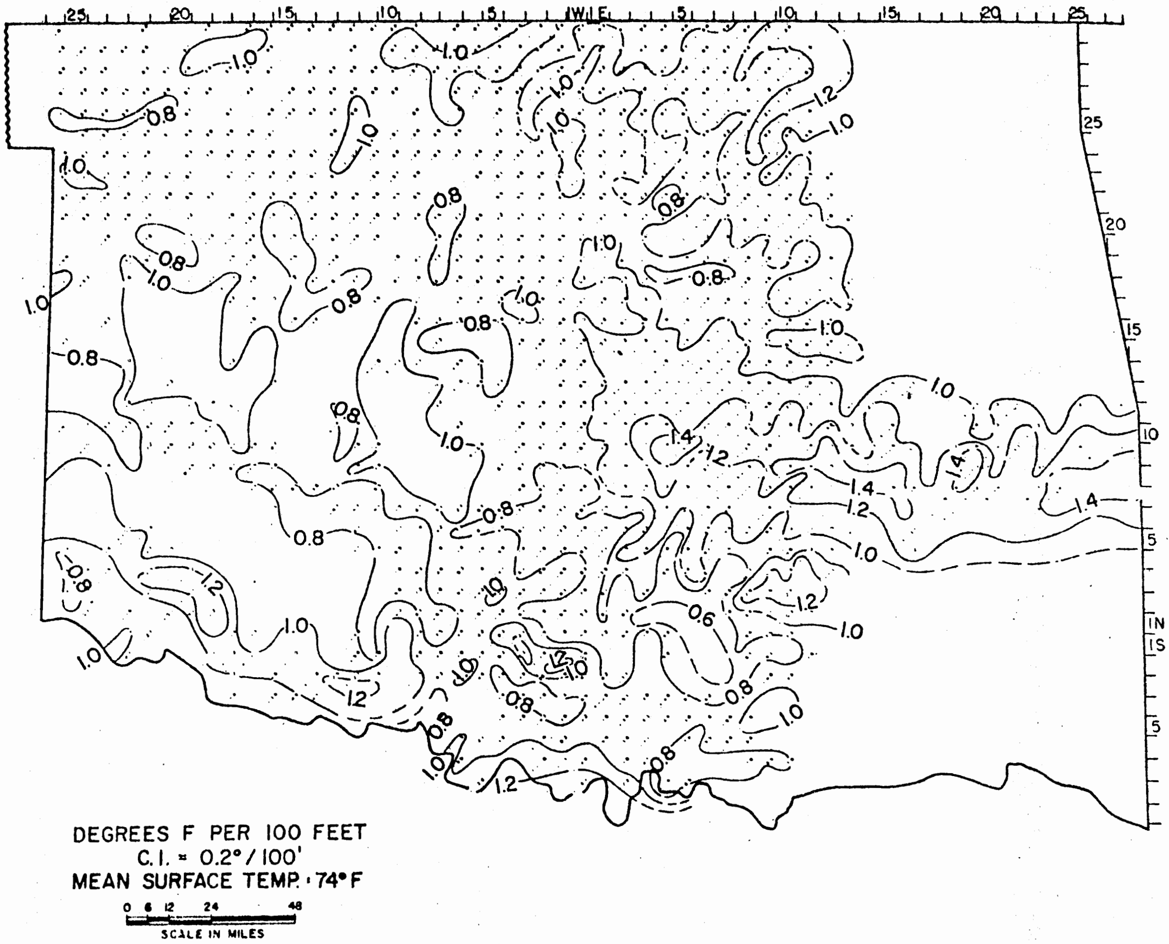

Fig. 2.-Geothermal gradient map of Oklahoma (from Schoeppel and Gilarranz, 1966)

rock are known.

In 1968, a project sponsored by the American Association of Petroleum Geologists was initiated to map the geothermal gradients in North America from all available temperature data from wells drilled for oil and gas, for water, and for heat-flow studies. The Geothermal Survey of North America made corrections for bottom-hole temperatures after a study of those temperatures and corresponding equilibrated temperatures in 336 wells in South Louisiana and 266 wells in West Texas. The differences in values between the two temperatures plotted according to depth provided correction curves for the two areas. A combined curve was used as the correction factor for other areas in North America (Kehle, 1971). As a part of that project, the geothermal regime of Oklahoma is portrayed by a computer-drawn gradient map. Features of Oklahoma are, of course, shown on the two maps of the project, the Geothermal Map of North America (1976) (Fig. 3) and Subsurface Temperature Map of North America (1976).

There have been a number of geothermal gradient studies outside of Oklahoma. Kumar (1977) in a study of Bayou Carlin-Lake Sand area in South Louisiana used the correction factor of Kehle (1971); Jam, Dickey, and Tryggvason (1969), in their study of temperature gradients in South Louisiana, used the temperature obtained during the bottom-hole pressure tests and compared them to conventional bottom-hole temperatures from well logs (Fig. 4). Griffin and Reel (1969), Harper (1971), and Grisafi (1973) used only the bottom-hole temperatures from logs, in their studies.

Schoeppel and Gilarranz's analysis is theoretically sound, but due to the complexity of the variables involved in drilling, application of

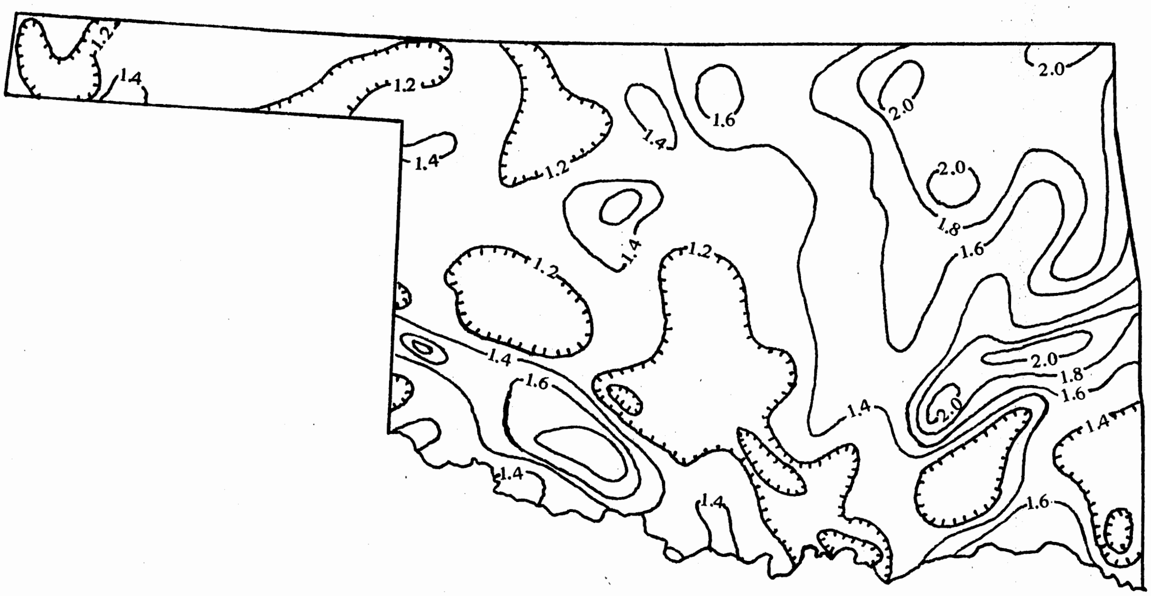

Fig. 3.-Geothermal gradient map of Oklahoma (adapted from Geothermal Gradient Map of North America, 1976)

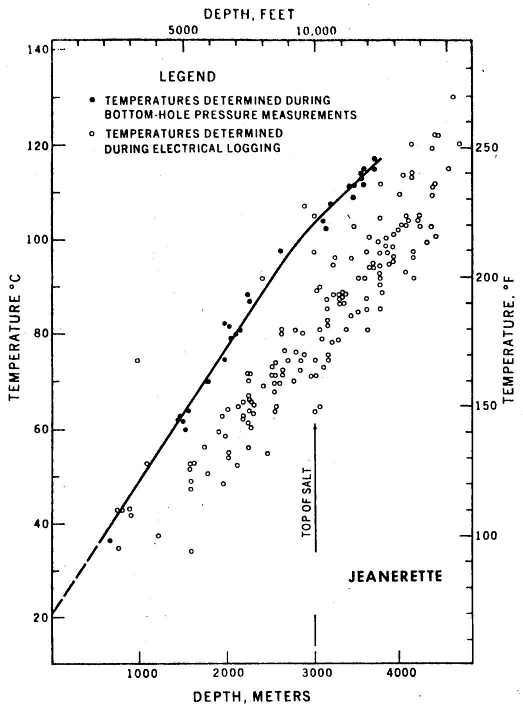

Fig. 4.-Comparison of temperature data from pressure tests and temperature data from logs at Jeanerette gas field, South Louisiana. Data from the pressure tests show 3°C scatter, whereas the bottom-hole temperatures show 10°C scatter. Temperatures measured during loggings average 15°C lower than those measured during pressure tests (from Jam, Dickey, and Tryggvason, 1969)

it generally is not feasible. The method used by the Geothermal Survey of North America, as a statistical analysis of differences in the two types of temperature data, is a direct approach to the reliability of bottom-hole temperatures. However, the average correction factor, which was used to adjust Oklahoma values, is not so reliable as one derived from Oklahoma data. Such a correction factor was used in this study.

Abnormal temperature-gradient profiles within Lower Pennsylvanian strata were noted by Breeze (1971) in his study of abnormal pressure. However, those temperature gradients were not mapped by him.

Objectives and Scope

The objective of this study is to prepare a geothermal gradient map of Oklahoma, excluding the Panhandle, and a geothermal gradient map within the abnormally pressured section in the Anadarko and Ardmore basins. The section coincides with the Pennsylvanian Morrowan Series and the Mississippian Springer Group. Because of the extensive data base utilized in this study, these maps provide the most reliable and accurate subsurface temperatures of Oklahoma which are available. The corrections scheme developed for correcting the bottom-hole temperatures resulted in improved quality of the data.

Interpretations of a number of geothermal gradient features are given. These anomalies are correlated with other regional and subregional geologic and geophysical features.

CHAPTER III

RELATED CONCEPTS

Sources of Heat Energy

Heat generated from depths greater than 600 miles beneath the earth's surface apparently has not, under existing geothermal gradients, reached the upper part of the crust by heat conduction alone. Igneous intrusion and volcanism represent means of upward mass transfer of heat from deep in the crust or upper mantle. They apparently are responsible for many of the geothermal anomalies expressed on the earth's surface (Jones, 1970). The major source of heat energy of the upper few miles of the crust is probably the outward flow of heat from disintegration of radioactive isotypes in the upper two hundred miles of the earth. From the knowledge of the crustal material, theoretical calculations show that the portions of terrestrial heat produced are 70% in acidic rocks, 20% in basic rocks, and 10% in ultramafic rocks. Also, the calculated portions of terrestrial heat produced are 50% in the upper 55 miles, 25% between depths of 55 and 110 miles, 15% between depths of 110 and 165 miles, and 10% from depths greater than 165 miles (Keppelmeyer and Haenel, 1974).

Heat sources of minor importance include exothermal chemical reactions, and frictional heat from diastrophism and earth tides (Gruntfest and Shaw, 1969). Solar energy is greater than the terrestrial heat flow by a number of orders of magnitude, but it affects only the upper few tens of feet of the earth's surface (Chang, 1958).

Factors Related to the Geothermal Gradient

Climate

Periodic fluctuation of temperature at the surface of the earth affects shallow geothermal gradients; its depth of influence is a function of the amplitude and the frequency of the fluctuation. Diurnal and annual temperature changes on the surface of the earth cause changes in temperature gradient to depths of less than 3 feet and 50 feet, respectively (Chang, 1958). Long periods of temperature changes affect geothermal gradients to greater depths. Kappelmeyer and Haenel (1974) have calculated that the Pleistocene glacial stages caused a 10% change in regional geothermal gradients to depths as much as 3,000 feet.

Thermal Conductivities

According to Fourier's law of heat conduction, temperature gradient is inversely proportional to thermal conductivity, which is also a function of pressure and temperature. The low values of pressure and temperature within the upper crust, however, have insignificant effects on the thermal conductivities of the rocks.

The thermal conductivity of a rock is inversely related to its porosity and clay content (Zierfuss, 1969). Evaporites, due to their crystal structures and low porosities, are good conductors; dolomite conducts heat better than calcite; sandstones and limestones have wide ranges in conductivity; and shale usually conducts heat poorly. Borehole correlation generally is good between changes of temperature gradient and changes of lithology (Levorson, 1967). However, data with sufficient accuracy for that type of correlation are not available for most wells.

Abnormal Pore Pressure

Temperature gradients increase abruptly in abnormally pressured formations. Lewis and Rose (1969), and Jones (1969) have proposed that water in an overpressured zone is responsible for its high geothermal gradient, because the conductivity of water is 4 to 5 times lower than that of mineral grains. The overpressured zone acts as a thermal barrier or as an insulator to the normal upward heat flow through the sedimentary rocks.

Migrating Fluid

The importance of migrating fluids in transferring heat within the sedimentary rock strata has been recognized in recent years. George (1970) has related temperature gradients to the migration of water made available by conversion of montmorillonite to illite. Water desorbed from montmorillonite normally flows upward during compaction and transfers heat upward through the sediments. A restriction in flow, such as in an abnormally pressured zone, causes heat to accumulate.

Water movement may also be restricted by oil accumulation. Permeability to water in an oil-bearing rock is inversely related to oil-saturation and thickness of the oil column. A number of oil fields have higher temperatures than surrounding areas (Loversen, 1967).

Another possible explanation for higher temperature in oil fields is the upward migration of oil to the trap.

Water movements may also be caused by osmotic pressure. Osmotic pressure possibly develops between two reservoirs containing pore fluid of different salinities, and the clay-bearing strata between the reservoirs may act as a semipermeable membrane in filtering dissolved solids and allowing only water particles to move across the bedding into the reservoir with lower salinities.

Convection of heated water through thick porous rocks is identified as the cause for many hot spots in geothermal areas (Elder, 1965). Thick rock sections with good vertical permeabilities, such as the thick carbonate sequences with vuggy porosities in Florida and Bahama Islands, allow convection of the pore water. However, migration of water by convection in Oklahoma is thought to be minor.

Movement of meteroic ground water from a recharge source to a discharge area modifies the temperature gradient of the rocks through which the water moves. Temperature gradient is increased by ascending fluids, and decreased by descending fluid (Cartwright, 1970; Schneider, 1964).

Tectonics

In recent years faults have been recognized as fluid barriers in many normally pressured zones, but hydraulic conduits for the upward migration of fluid in abnormally pressured zones (Price, 1976). Anomalous hot spots associated with deep-seated faults may be explained by the migration of fluid. George (1970) suggests that subsurface temperatures change very slowly except under the influence of moving water. He proposes the following:

(1) The downthrown block of a gravity fault and the downwarped steep flank of a basin exhibit lower than normal gradients; the upper plate of an overthrust, a horst, and crest of a fold exhibit higher than normal gradients. The shift in gradient is proportional to the vertical displacement of the structure.

(2) A shift to higher gradients is present under an angular unconformity due to uplift, provided invasion by meteoric water is minimal.

Klemme (1975), upon examination of geothermal gradient profiles of various basins, concludes that:

(1) The various types of basins show different characteristic geothermal gradients.

(2) The geothermal gradients of basins are related to regional heat flow.

(3) Some basins may lose part of their heat by convective processes during basinal development, and some basins may show lower gradients due to the insulating effect of overpressured formations at depth.

Distribution of Radioactive Isotopes

Disintegration of the radioactive isotopes is the major heat source for terrestrial heat flow. Fig. 5 shows the concentration of radioactive elements and the average heat productions of various types of rocks. Calculation of the heat released indicates that temperature gradients may reflect basement rock types, but they are rarely

Rock	Average concentration in parts per million				Average total heat production		Density	Thickness (km) of layer producing $1.6 \cdot 10^{-6}$
	U	K	Th	K/U	$[10^{-8}$ cal g^{-1} year$^{-1}]$	$[10^{-11}$ cal g^{-1} $s^{-1}]$	$[g\ cm^{-3}]$	$[cal\ cm^{-2}\ s^{-1}]$
Sediments	3.00	20000	5.0	$6.7 \cdot 10^4$	373.0	11.8	2.3	59
Granite	4.75	37900	18.5	$8.0 \cdot 10^3$	818.0	25.8	2.7	22
Intermediate	2.00	18000		$9.0 \cdot 10^3$	340.0	10.8	2.75	54
Basalt	0.60	8400	2.7	$1.4 \cdot 10^4$	120.5	3.8	3.0	140
Eclogite								
low uranium	0.048	360	0.18	$7.5 \cdot 10^3$	8.1	0.26	3.2	1920
high uranium	0.250	2,600	0.45	$1.0 \cdot 10^4$	34.3	1.09	3.2	460
Peridotite	0.015	63	0.05	$4.2 \cdot 10^3$	2.26	0.072	3.2	6950
Dunite	0.008	8	0.023	$1.0 \cdot 10^3$	1.07	0.034	3.3	14270
Chondrites	0.012	845	0.04	$7.0 \cdot 10^4$	3.95	0.125	3.6	3560

Fig. 5.-Concentration of radioactive elements and heat production in various types of rocks (from Keppelmeyer and Haenel, 1974)

affected by uranium deposits.

Abnormal Pressure in Morrow-Springer Strata

The Morrow Formation on the northern edge of the deep Anadarko basin trough consists of a south-thickening wedge of sandstone and shale. The pore-pressure conditions within the Morrow Formation change in a southerly direction from subnormal through normal to abnormal, corresponding to increases in thickness and overburden. Subnormal pressure is reported in Harper County, and the occurrence of abnormal pressure is roughly south of T18N, where the Morrow section is generally over 1,000 feet thick and is present at depths greater than 9,000 feet.

Abnormal gradients are essentially coincident with the abnormally pressured sections. The temperature gradients in the normally and subnormally pressured sections apparently are normal.

Mechanisms that are responsible for development of pore pressure other than normal are compaction, artesian conditions, osmotic-pressure, aquathermal-pressuring, capillary-pressure, and removal of overburden.

Different mechanisms have been proposed to account for the pressure conditions in the Morrow-Springer rocks. The primary cause of abnormal pressure appears to be compaction. The rapid deposition of the shale-sand sequence, especially in the deeper part of the trough, prevented pore water from escaping normally. Furthermore, desorption of water during conversion of montmorillonite to illite probably contributed excess water. Permeable connection between the individual lenticular sands generally is not present (Dickey and Cox, 1977). This condition favors the operation of aquathermal pressuring which probably further increases the pore pressure.

CHAPTER IV

METHODOLOGY

Available temperature data used in this study are temperature measurements obtained during bottom-hole pressure tests in shut-in gas wells, temperature logs of wells, and bottom-hole temperature measurements on well logs. One control point per township was used in preparation of the maps. In many townships the control points were selected from a number of wells. Other control points represent single wells or scattered wells within townships.

Data Reliability and Availability

Bottom-Hole Pressure Tests in Shut-in Gas Wells

The maximum temperature of a tested zone recorded during a bottom-hole pressure test after a shut-in period of at least 72 hours, or weeks in some cases, represents sufficient time for the temperature in the borehole to approach thermal equilibrium with the surrounding rocks. Temperature measurements taken from different tests during the production history of a particular well usually range no more than 2°F from the average. Because of the possibility of error in individual temperature readings, more than one measurement at a given depth is needed before the true formation temperature can be determined with confidence. The average temperature measurement at a certain depth is considered to be the true formation temperature. These are the most reliable data; however, they are available only in areas of gas production, and generally available only to participating companies.

Temperature Logs

Temperature logs provide both reliable continuous temperature measurements and temperature-gradient profiles. Almost all the temperature logs are from air-drilled wells in the Arkoma basin. There is little cooling effect of the borehole by the circulating air due to the low thermal conductivity and the very low permeability of the thick shale sections opposite which most measurements have been made, and of course, there is no drilling-fluid invasion. Because the specific heat of air is much lower than that of water, the time required for air in the borehole to come into equilibrium with the formation is much less than that required in a mud-drilled well. Data from gas wells with both temperature logs and pressure tests further support the reliability of the former type of data. However, because some temperature logs are not accurately calibrated, the temperature gradient based on only one log should be considered tentative. Gas entering the borehole affects the temperature gradient profile (Fig. 6). In accordance with the Ideal Gas Law, the pressure drop as gas enters the borehole results in a decrease in temperature. As the gas ascends, however, it causes a measurable increase in the borehole temperature (Keppelmeyer and Haenel, 1974). In Fig. 6, the well from section 1 without gas entry records a lower borehole temperature than the gas wells in sections 4 and 34.

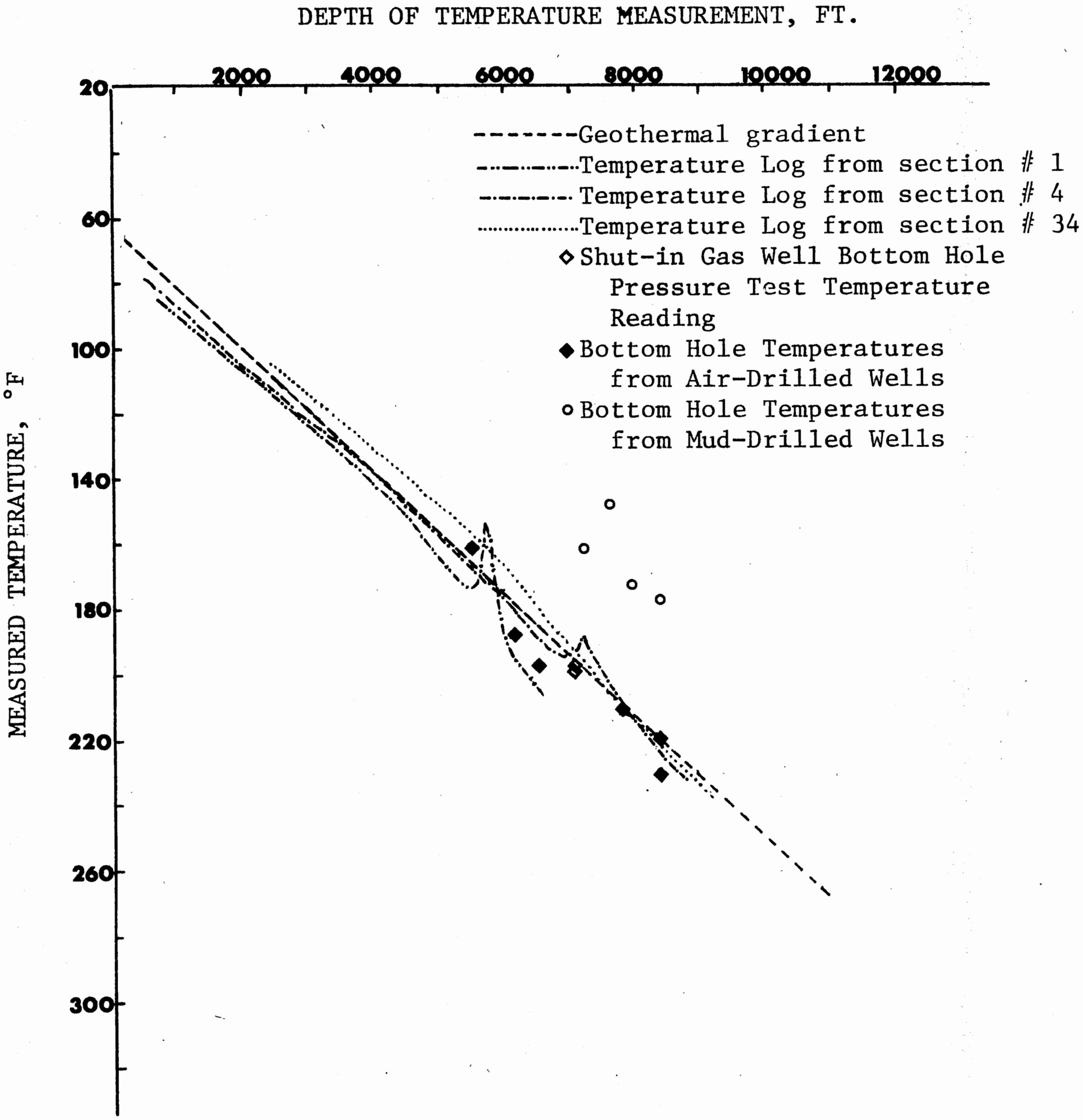

Fig. 6.-Temperature data in T9N, R25E include temperature logs, temperature readings from pressure tests, bottom-hole temperatures from both air-drilled wells and mud-drilled wells. Geothermal gradient coincides with temperature logs.

Temperature logs are available only from the Arkoma basin where many wells are air-drilled. Upon release, these data are available generally in log libraries.

Bottom-Hole Temperature Measurements on Wireline Logs

Mud-Drilled Wells

Bottom-hole temperature readings are not in equilibrium with the formation due to cooling of the borehole by the drilling mud and insufficient time between cessation of drilling and measurement of temperature for the fluid to be in equilibrium with the formation. Edwardson (1962), Jaeger (1961), Schoeppel and Gilarranz (1966), and Kehle (1971), for example, have estimated the effects of drilling and the time required for equilibration of the borehole and rock temperature. Jam and others (1969) in their study of gradients in South Louisiana showed borehole temperatures to be 15°C lower than those from pressure tests (Fig. 4). When plotted against depth, bottom-hole temperatures commonly form large clusters, indicating lack of precision of the data (Fig. 7).

This type of data is most abundant and readily available on wells in almost the entire state.

Air-Drilled Wells

Temperature data obtained during logging of air-drilled wells in the Arkoma basin approximate true formation temperatures. Each measurement, in effect, is the maximum value on a temperature log and is

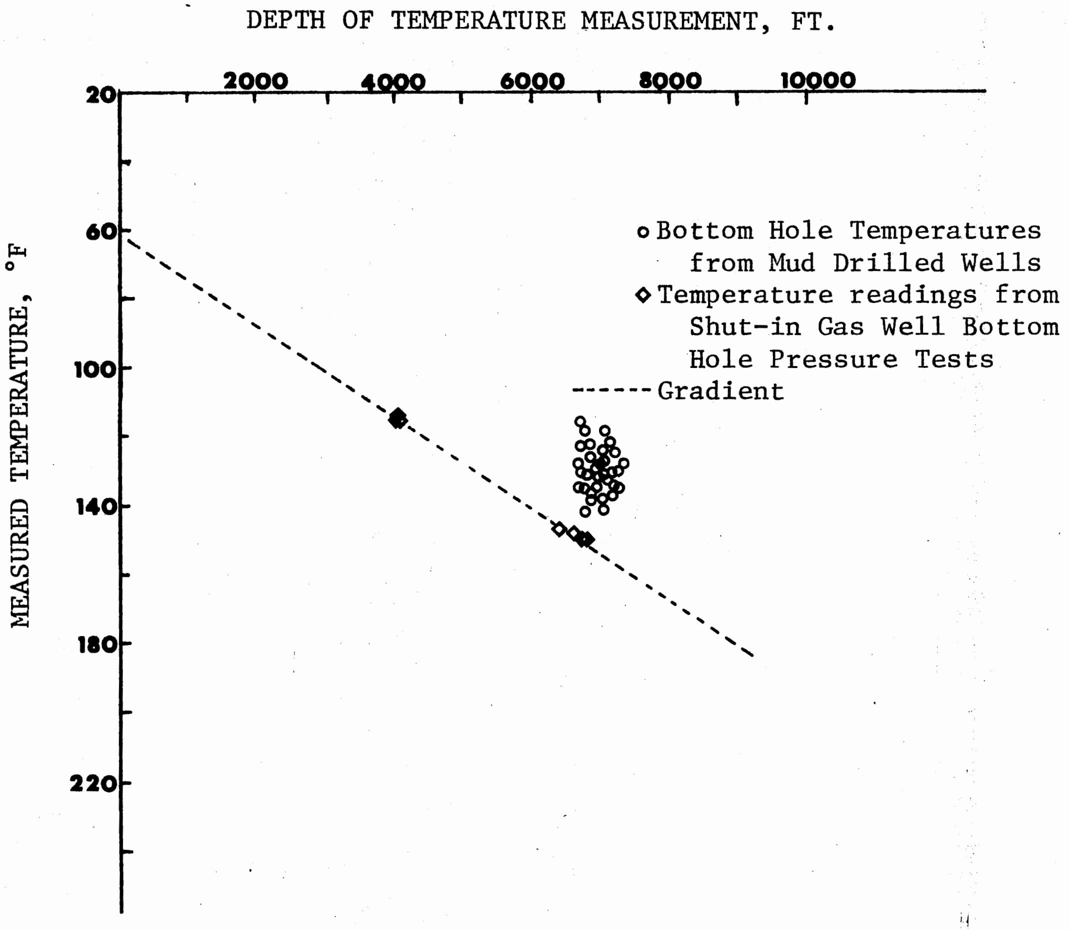

Fig. 7.-Bottom-hole temperatures of mud-drilled wells in T27N, R25W, show the imprecision of the measurements. The geothermal gradient is obtained by using temperature data from shut-in gas well pressure tests

analogous to the temperature of a shut-in gas well (Fig. 6). However, individual readings should be used with reservation due to possible problems in calibration of equipment.

Formation Pressure

Formation pressure can be estimated from drilling-mud weights. Although the optimal mud weight results in borehole pressure which slightly exceeds the actual formation pressure, in a few wells mud weights were substantially higher than those required to offset formation pressures. In this study, pressure corresponding to mud weights of eleven pounds per gallon or less is considered to be normal or not appreciably abnormal. Significant high pressure in the Pennsylvanian-Mississippian Morrow-Springer section of the Anadarko basin is indicated by mud weights of more than eleven pounds per gallon.

Mud-weight data are available on wireline logs. These data are used in this study, with some degree of reservation, to reflect the formation pressure.

Data Procurement

Shut-in gas well temperature readings were obtained from company files of Texas Oil and Gas Corporation and McBride Engineering Company, Oklahoma City. The latter has made bottom-hole pressure tests for the majority of gas wells in Oklahoma. Data are available for 528 townships.

Temperature logs were obtained from the Oklahoma City Geological Library. They are available for 38 townships.

Bottom-hole temperature data through 1969 were collected by the A.A.P.G.-sponsored Geothermal Survey of North America. These data were updated during this study by adding the bottom-hole temperatures from wells drilled between 1970 and 1977. Logs from wells in some 1500 and more townships are available at the Oklahoma City Geological Society Log Library.

Mud weights and depths of mud-weight changes are given on headings of wireline well logs. They were obtained from logs at the Oklahoma City Log Library. These data were used in preparing a gradient map for the area and stratigraphic section with abnormal fluid pressure.

Data Processing

Geothermal Gradient Map of Oklahoma

A temperature-depth plot was prepared for well data from each township. Except for temperatures recorded within the abnormally pressured zones, all temperature measurements were used to determine the geothermal gradient for any township, the basic area for control-point spacing. Depending on the availability of the types of data, the gradient was determined by one of the following methods:

1. Reliable temperature data at two or more depths
2. Reliable temperature data at a given depth and an assumed nearsurface temperature
3. Corrected bottom-hole temperature and an assumed nearsurface temperature.

Gradient From Reliable Temperature Data at Different Depths

Where shut-in gas well temperatures are available at two or more significantly different depths, the geothermal gradient is portrayed by a straight line through the temperature values plotted according to depths (Fig. 7). Where temperature logs are available, the gradient is represented by a straight line approximately coincident with the temperature profiles on the logs (Fig. 6). Gradients from 130 townships were obtained using this method.

Gradient From One Reliable Value at Depth and Assumed Nearsurface Temperature

Where reliable temperature data are available only for essentially one depth, the temperature gradient is given by a straight line through the points representing that reliable temperature at depth and the assumed nearsurface temperature.

Determination of the nearsurface temperature. Mean annual surface temperature is used in some temperature-gradient studies as the control point at the surface. Because surface temperature is a function of soil type, moisture content, vegetation, climate, topography, and surface water, it has been shown by various workers (for example, Chang, 1958), that it may be different from the mean air temperature. For this reason temperature at some specified depth below the influence of climate and soil type is used in this study as a control point.

The temperatures at 500 feet below the surface were determined from the gradient plots of reliable temperatures noted heretofore

(Fig. 8). These data indicate an average temperature of 69°F at 500 feet below the surface for the Anadarko basin and shelf area to the north and an average of 76°F at depth of 500 feet for the Arkoma basin area. As shown in Fig. 7 and explained previously, the higher nearsurface temperature is caused by warming of the borehole by ascending gas. Therefore, temperature of 69°F at depth of 500 feet is assumed to be a correct nearsurface temperature for the Arkoma basin.

Ground water may affect surface temperature to significant depths (Schneider, 1964; Cartwright, 1970). Ground water moving downward will decrease the rock temperature, whereas upward moving water will increase the rock temperature. These effects must be taken into account when one tries to estimate the nearsurface temperatures. The map of the base of fresh ground water prepared by Hart (1966) (Fig. 8) may be used to infer both the area of active recharge and the vertical movement of ground water. Areas with the fresh water at depths exceeding 500 feet should have temperatures of 69°F at depths greater than 500 feet. Correspondingly, adjustments, with acceptable limits of error, were applied to the nearsurface temperature readings for areas with thick columns of fresh ground water. The nearsurface temperature is assumed to change gradationally from shallow to deep aquifers.

Gradient From Corrected Bottom-Hole Temperatures and Assumed Nearsurface Temperature

In more than half of the townships within the study area, bottom-hole temperatures are the only available data. In some other townships, single values from shut-in gas wells or air-drilled wells supplement and calibrate to some extent bottom-hole temperatures.

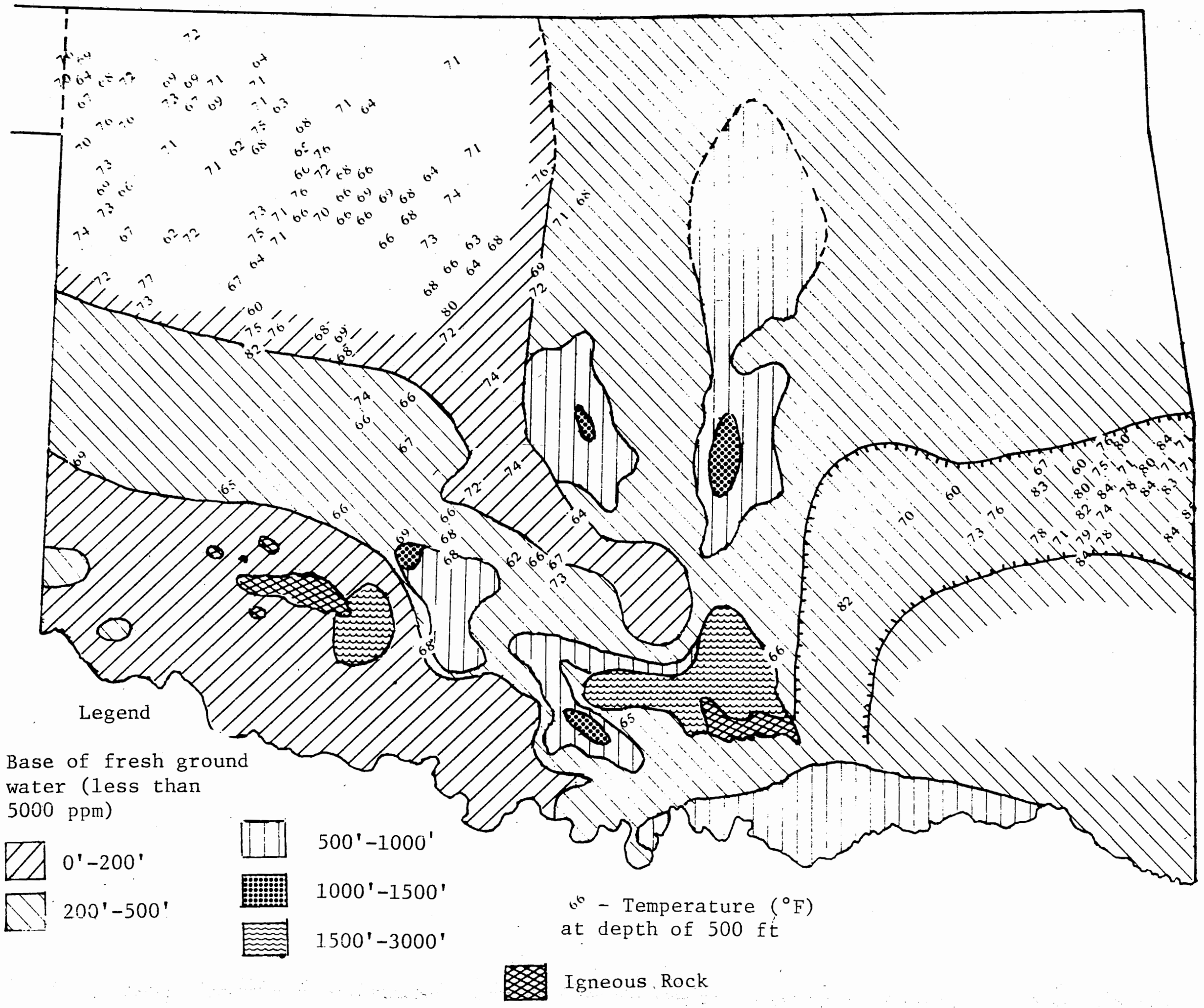

Fig. 8.-Depth to base of fresh ground water (after Hart, 1966); temperature values at depth of 500 feet are based on geothermal gradients from reliable temperatures at greater depths

A correction factor is applied to the calculated average bottom-hole temperature at a specific depth to compensate for the cooling effect of 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 determination of a reliable average temperature. The temperature gradient of a township is obtained by drawing a straight line through the assumed nearsurface temperature and the best fit for corrected temperature at depth (Fig. 9).

Determination of correction factor. The correction factor was determined by comparing the average of the log bottom-hole temperatures to the reliable temperatures at the corresponding depths. The reliable temperatures used here refer to temperature readings from pressure tests, temperature logs, or interpolative temperatures from reliable gradients. For this comparison, western and northwestern Oklahoma were divided into shelf and basin areas and each was subdivided into four smaller areas (Fig. 10). Differences between reliable temperatures and average bottom-hole temperatures plotted according to depths for each small area (Figs. 11, 12) suggest that there is a single population. A correction curve for all the data is given in Fig. 13. This curve represents the deviation of bottom-hole temperatures from true formation temperatures, and it was used in this study to correct the mud-drilled well temperatures. The correction curve compares quite well with the curve used by the Geothermal Survey of North America (1972) in mapping Oklahoma (Fig. 13).

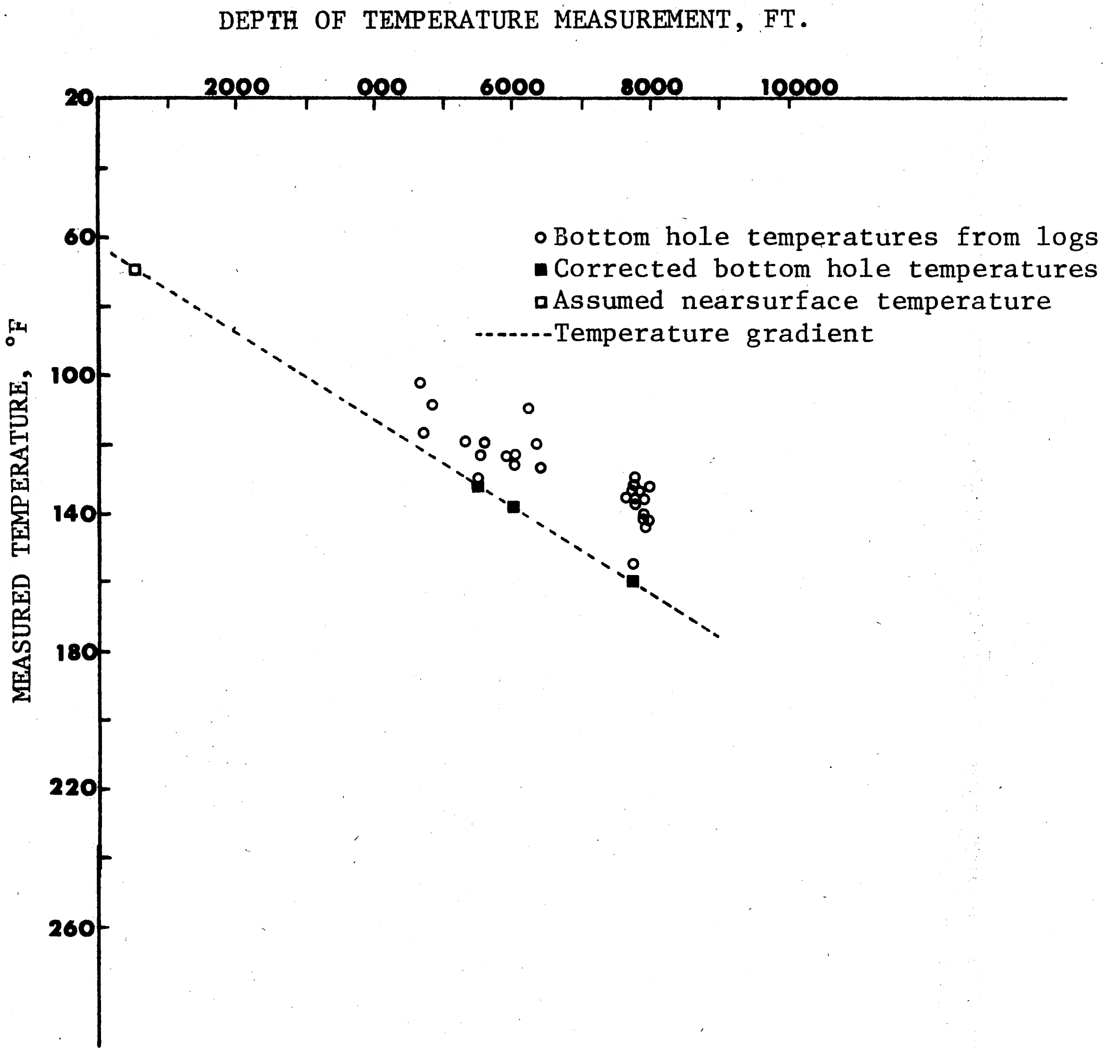

Fig. 9.-Geothermal gradient from corrected bottom-hole temperatures and an assumed nearsurface temperature, T28N, R22W

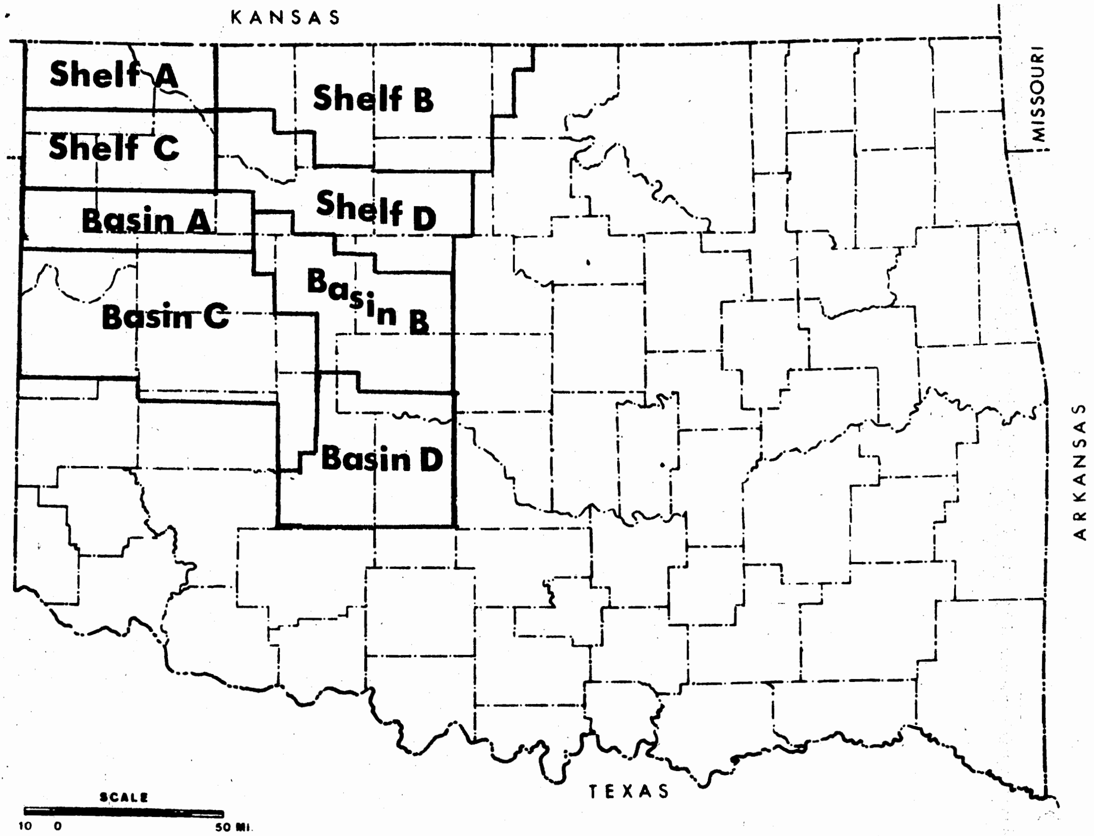

Fig. 10.-Areas where data are available and used for development of the correction scheme for bottom-hole temperatures

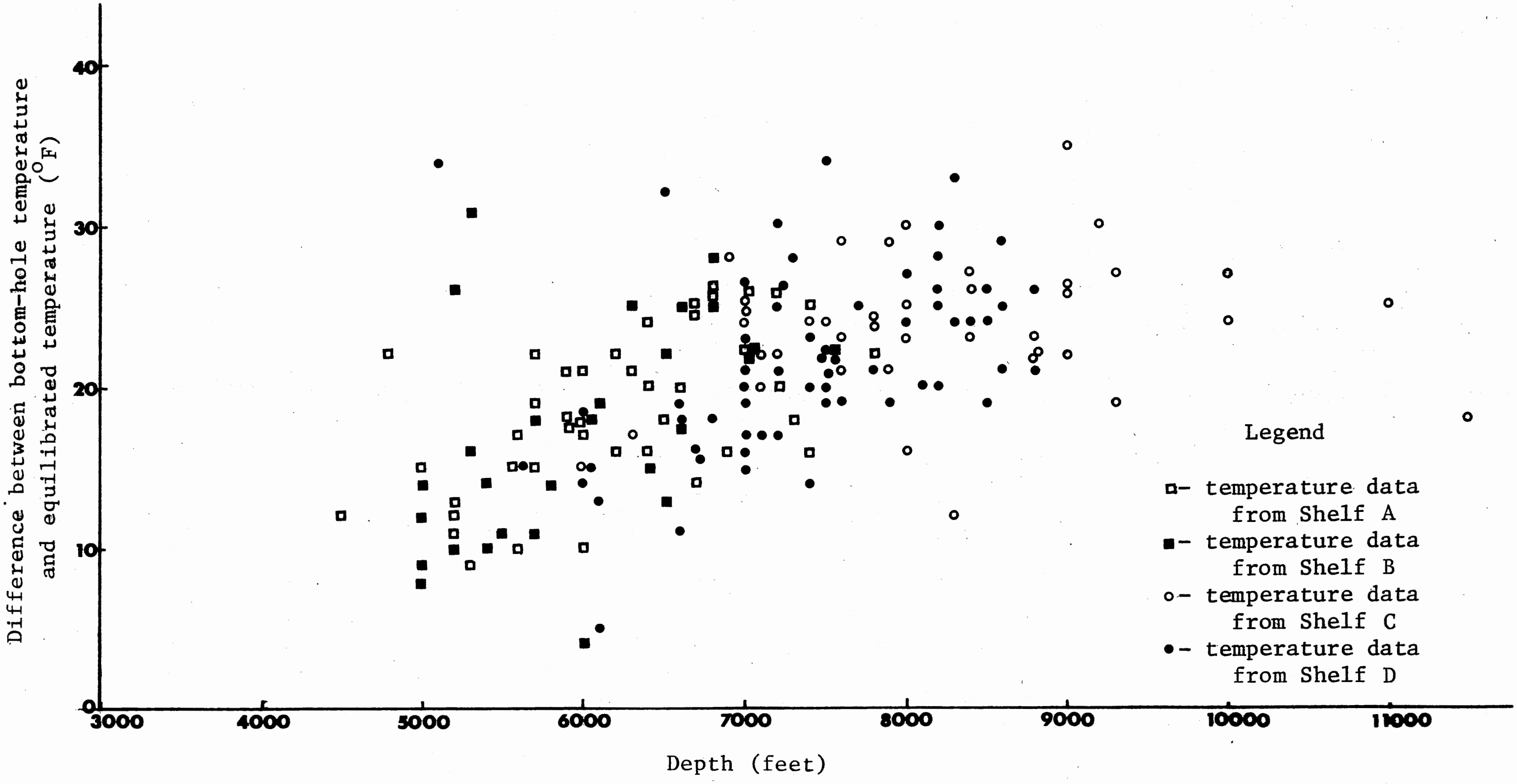

Fig. 11.-Differences between bottom-hole temperatures and equilibrated temperatures as a function of depth for shelf area of Anadarko basin (Northern Oklahoma platform)

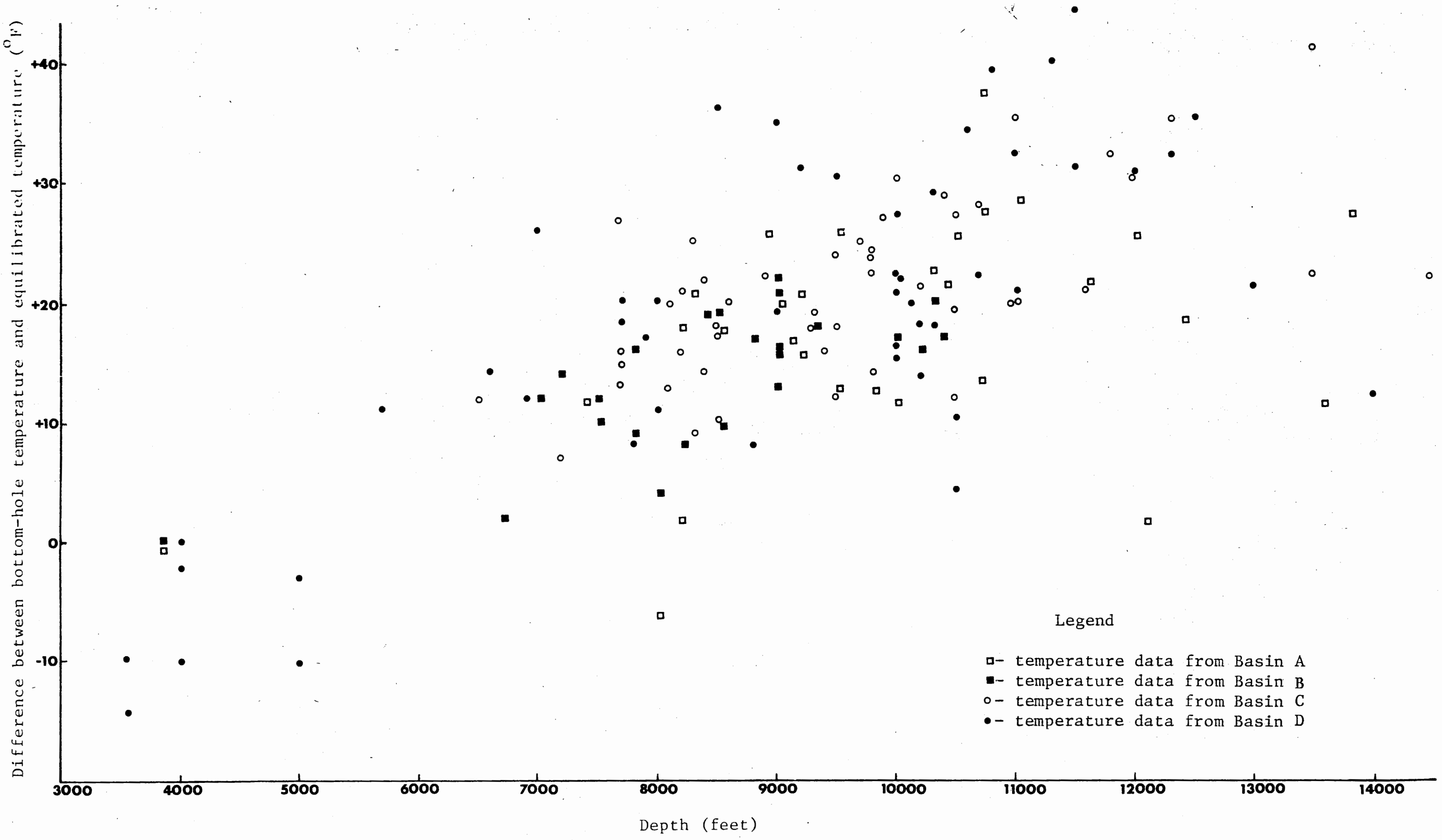

Fig. 12.-Differences between bottom-hole temperatures and equilibrated temperatures as a function of depth for basinal area of Anadarko basin

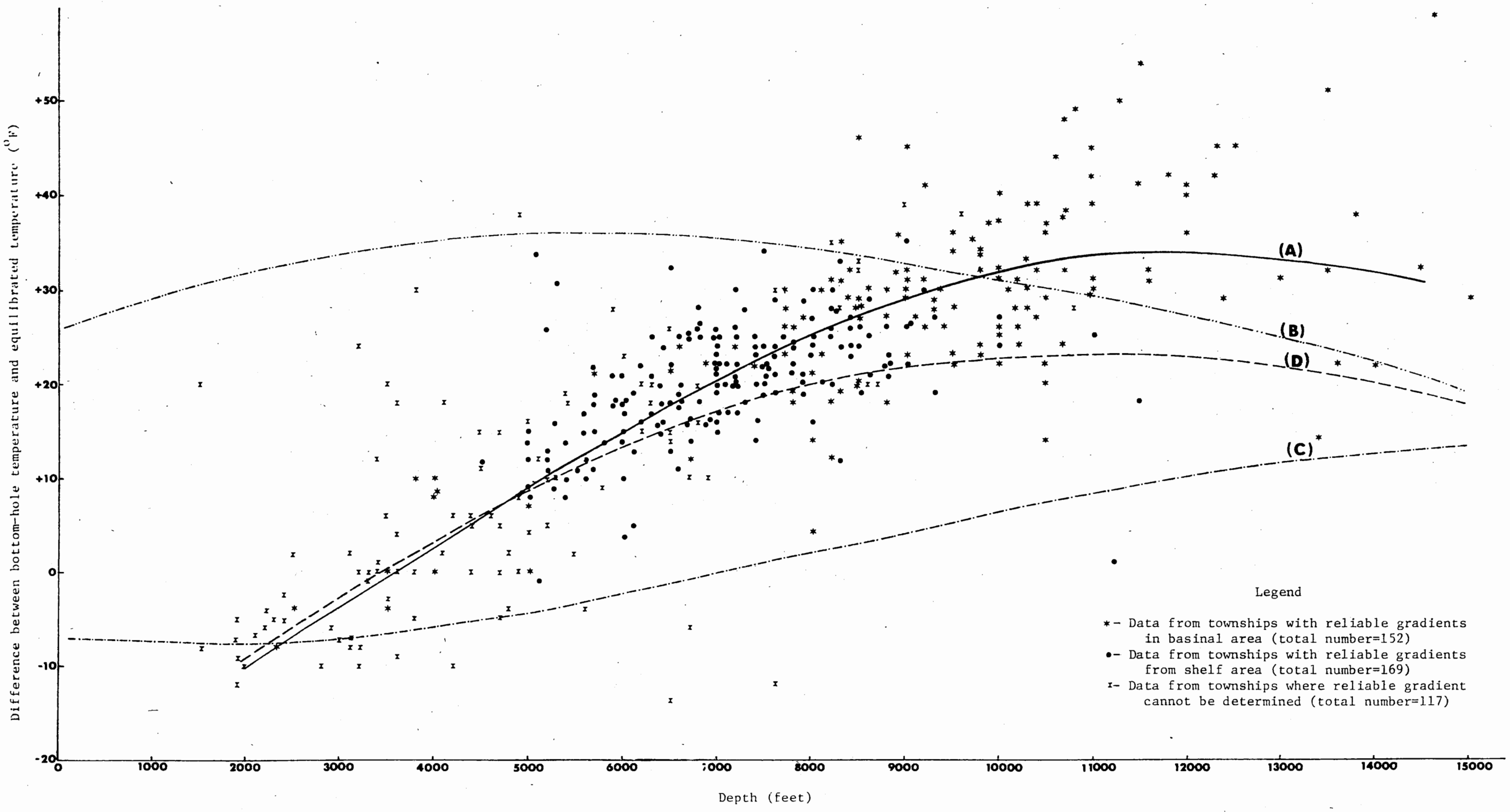

Fig. 13.-Correction curve for bottom-hole temperatures of wells in Oklahoma

The correction curve suggests that at the 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 with confidence for depths greater than 10,000 feet. Correspondingly, the curve was used to correct bottom-hole temperatures between 3,000 and 10,000 feet in the State.

Abnormal Temperature Gradient Map

In the deep part of the Anadarko and in the Ardmore basins, the Morrow-Springer section is abnormally pressured. This abnormally pressured zone is readily identified on logs generally by abrupt increases in mud weight. Because reliable temperatures of the abnormally pressured zone are available for very few wells, no correction scheme can be derived to correct the bottom-hole temperatures of this zone. The uncorrected bottom-hole temperatures are the only data available for determination of the abnormal temperature gradients. Data required are a sufficient number of bottom-hole temperatures from depths immediately above and within the high-pressured zone. The abnormal temperature gradient is obtained by constructing best-fit straight line segments for the two sets of temperature values representing, respectively, normally and abnormally pressured zones. The abnormal gradient determined in this manner is considered to be valid because the two sets of temperature data are generally only a few hundred feet apart. In other words, penetration of the abnormally pressured zone commonly is no more than 1,000 feet. Time lapses between drilling and measurements of temperatures of wells bottomed immediately above the zone and those bottomed within the zone should be approximately equal. Correspondingly, errors within the data should be essentially constant, and the gradient derived from them should not be affected appreciably. This hypothesis is supported by the close agreement of the gradients from the bottom-hole temperatures and those from temperatures of pressure tests in the few townships where the latter type of data is available (Fig. 14).

The change of the temperature gradient from normal to abnormal may be sharp or gradational. The abnormal gradient determined in this study is assumed to be linear, and it may be less than the maximum gradient of the pressured formation.

Data Presentation

Geothermal Gradient Map of Oklahoma

The geothermal gradient, obtained by averaging all the temperature data within a township, is plotted on the map as a control point at the center of that township. If temperature data from only one section are used in determination of the gradient, the gradient is plotted in that section within the township. The hand-contoured map has a contour interval of 0.10°F per 100 feet of depth. Outcrops of the basement rock and the pre-Pennsylvanian rocks are shown on the map for purposes of reference.

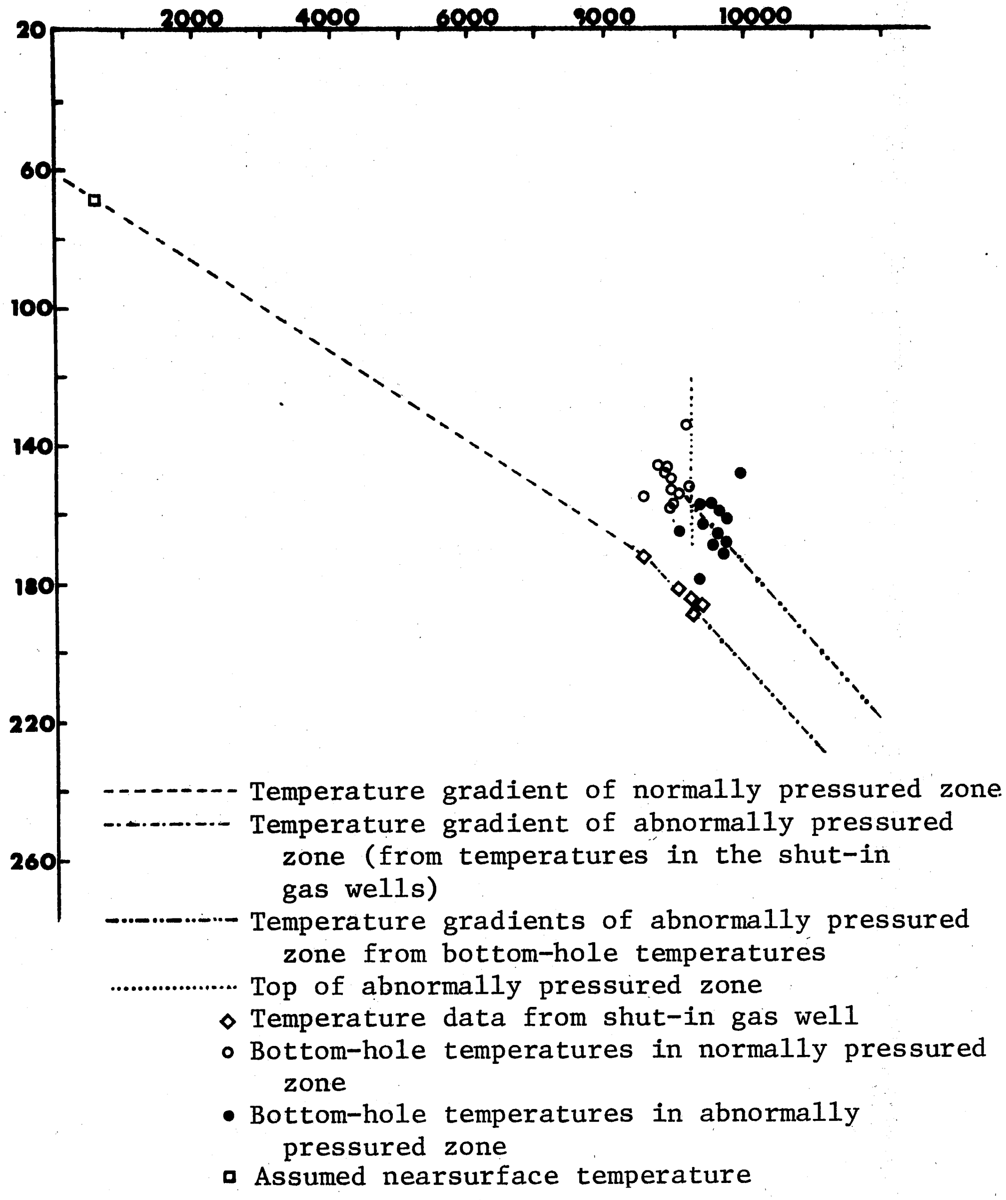

Fig. 14.-Determination of abnormal temperature gradient from bottom-hole temperatures and temperatures in shut-in gas wells in T17N, R13W.

Abnormal Temperature Gradient Map

The "abnormal" gradient values are plotted in the same manner as the "normal" values. The normal temperature gradients of the townships adjacent to the area with abnormal gradients are also plotted on the map and are used to reflect the thermal conditions immediately away from the abnormal gradients. The hand-contoured map has a contour interval of 0.25°F/100 feet for gradients less than 2.00°F/100 feet, 0.50°F/100 feet for gradients between 2.00°F/100 feet and 4.00°F/100 feet, and 1.00°F/100 feet for gradients greater than 4.00°F/100 feet. Outlined are areal extends of the abnormally pressured Morrow-Springer section and the area with abnormal temperature gradients. The structural configuration of the abnormally pressured zone, based on the changes in mud weight, is superimposed on the gradient map.

CHAPTER V

FEATURES OF THE MAPS

Geothermal Gradient Map of Oklahoma

The geothermal gradient map shows that the temperature gradient of Oklahoma ranges between a minimum of 1.04°F/100 feet, in the Anadarko basin, to a maximum of 2.34°F/100 feet, in the Arkoma basin. Most major geologic features in Oklahoma are delineated by the geothermal gradient map.

The Arkoma basin area, with gradient contours ranging from 1.30°F/100 feet to 2.30°F/100 feet, is the largest and most prominent anomaly. The Wichita province, with a range in contours of 1.40 to 1.70°F/100 feet, is the longest anomaly. Its prominence is accentuated by a belt of low gradient anomalies to the north, in the deeper ("foredeep") part of the Anadarko basin. There gradient contours range from 1.10 to 1.30°F/100 feet, the lowest values in the State. Also, gradients are low to intermediate (1.30 to 1.50°F/100 feet) in the Palo Duro (Hollis) basin south of the Wichita province. The major parts of the Arbuckle uplift and the Ardmore basin are not characterized by coincident anomalies or corresponding trends. Rather, several north-northeast to northeast-trending anomalies characterize an area which includes contiguous parts of the Anadarko basin-Ardmore basin-Arbuckle uplift. With the township grid, the Criner uplift is not portrayed, and one of the north-northeast trends apparently reflects the combination of the Criner Hills-Overbrook anticline area and the Caddo anticline, which are inseparable by the spacing of control points. A small but quite distinct anomaly, with gradients as high as 1.60°F/100 feet and trend parallel to the structural grain, is located on the south-southwest flank of the Marietta basin. An east-west anomaly, with a maximum gradient of 1.64°F/100 feet, corresponds to part of the Hunton-Pauls Valley uplift where pre-Pennsylvanian units crop out.

The temperature gradients of the Central Oklahoma platform, on the average, are approximately 0.10°F/100 feet higher than those of the Northern Oklahoma platform. However, there are two groups of prominent "high" anomalies in the latter area. The one located in Alfalfa and Grant counties has a maximum gradient of 1.72°F/100 feet. It is part of a series of local anomalies, with high gradients, which extend east-west from R18W to R5E. The other "high" extends north-south from Grant County into Kingfisher County. It parallels a prominent trend which extends from T2N, R1-2W, to T23N, R2W. Two large anomalies, with gradient contours ranging from 1.40 to 1.60°F/100 feet, occupy much of the Central Oklahoma platform. The larger one, in Pottawatomie County and Seminole County and part of Hughes and Lincoln counties, consists of several small anomalies. The high anomaly in Osage County is flanked by "low" anomalies on the east and southeast. Two low anomalies are present in eastern Oklahoma north of the Arkoma basin. There are a number of small anomalies rather randomly distributed on Northern and Central Oklahoma platforms.

The Ozark and Ouachita areas do not have sufficient data for mapping purposes. The western part of the Ozark province, which is mapped, shows eastward-increasing gradients, whereas southward-decreasing gradients apparently characterize the northernmost part of the Ouachita province.

Abnormal Temperature Gradient Map

The area mapped coincides with the deeper part of the Anadarko basin, the Ardmore basin, and part of the Marietta basin. In the Anadarko basin the top of the abnormally pressured zone commonly is about 500 feet below the top of the Morrow Formation, and both have similar structural configurations (Breeze, 1971). The area outlined by the geothermal gradient contour of 1.50°F/100 feet corresponds, in a general way, to the areal extent of the abnormally pressured zone.

The range of the abnormal geothermal-gradient contours is from 1.50 to 4.00°F/100 feet. Most abnormal anomalies trend northwest. Some are north-northwest trending, and two are west-trending. The most prominent trend of anomalies extends in a sinuous fashion from Blaine County, through the western part of Canadian County, into Grady County. It lies near the eastern edge of the abnormal pressures and temperature gradients. An anomaly, with a maximum gradient of 3.63°F/100 feet, is present in northern part of Washita County and northeastern Beckham County. The other anomalies, which are distributed somewhat randomly, generally are smaller in areal extent.

CHAPTER VI

CORRELATIONS

Correlation With Geologic Features

Tectonic-Structural Features

Maps used in comparison of geothermal-gradient features and tectonic-structural features are those by Jordan (1962), Tarr, Jordan, and Rowland (1965), Arbenz (1956), Fritz (1977), and Flawn (as chmn., 1967).

The general tectonic framework of Oklahoma (Fig. 1) is reflected quite well by the regional geothermal gradient map. As noted heretofore, the deeper part of the Anadarko basin is represented by lower-than-average values. The Ardmore basin contains higher values than 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.

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. The distribution of the abnormal gradients corresponds generally to the areas of low gradients on the regional geothermal gradient map (Plates 1 and 2).

With the exception of the Arkoma basin, the temperature gradient increases as depth of basement rock decreases. For example, the

Northern Oklahoma platform has gradients approximately 0.20°F/100 feet higher than the gradients of the deeper part of the Anadarko basin.

The Arkoma basin may have been more closely associated with oceanic crust along a continental margin or part of a major rift system during basinal development as well as having been associated with the Ouachita orogeny. Either or both may be responsible in large part for the high gradients.

Two trends of anomalies parallel the Blanchard graben south of the Oklahoma City uplift. The causes for low anomalies on both sides of the Muenster-Waurika arch are not known. The low anomaly east of the Hollis basin parallels the structural grain and includes the oil-bearing Altus structure (Mayes, Westheimer, Tomlinson, and Putnam, et al., 1959).

The Wichita uplift is reflected by a prominent geothermal-high 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 defining the southern edge of the Arkoma basin. The Arbuckle uplift is not defined by the gradients. The Hunton-Pauls Valley uplift, Muenster-Waurika arch, Oklahoma City uplift, Seminole uplift, Cushing uplift, and Red River uplift are reflected, to varying extents, by high anomalies. The Nemaha uplift in the area north of the Oklahoma City uplift is parallel to, but not coincident with, the long northerly trend of anomalies in the central part of the State. The high anomaly in Osage County apparently reflects the irregular shallow basement. Anomalies in the Garfield-Noble County area correspond, to varying extents, to pre-Pennsylvanian structural features.

Some of the trends on the abnormal geothermal gradient map reflect structures. For example, the northwest-trending feature in southwestern Roger Mills County and western Beckham County probably reflects the Sayre anticline. Other northwest trends near the Wichita uplift may represent en echelon anticlines associated with strike-slip faulting along the northern edge of the Wichita province.

Occurrences of Hydrocarbons

Data used in correlating the geothermal gradient maps to the known distribution of oil and gas include *Oil and Gas Fields of Oklahoma* (Petroleum Information Corp., 1977 edition), and *Petroleum Geology of Southern Oklahoma* (Mayes, Westheimer, Tomlinson, and Putnam, et al., 1959).

The high gradients in Arkoma basin probably explain the gas, rather than oil, production of the area. Gas production in the Anadarko basin is not reflected by the low values on the regional gradient map, but it is anticipated from the great depth of burial and the high values on the abnormal gradient map.

Many individual fields correlate well with gradient anomalies, especially those on the abnormal gradient map. For example, anomalies correlate with Southwest Hamburg and Northwest Reyden fields in western Roger Mills County, the Anthon field in north-central Custer County, and producing areas in southern, eastern, and southwestern Blaine County, western Canadian County, and northwestern Grady County. There are a number of anomalies which do not correspond with production. Some of these anomalies undoubtedly will be productive eventually.

A number of gradient anomalies on the regional geothermal map which correlate with tectonic-structural features also correlate with occurrences of hydrocarbons. Outstanding examples include the gas production areas in the Arkoma basin, the oil fields of the Seminole uplift, the Oklahoma City uplift, Cushing uplift and some fields along the Nemaha uplift. The production in Grant and Alfalfa counties in east-trending belts parallels trends of anomalies. Those fields produce from Pennsylvanian Cherokee sandstones in stratigraphic traps. Production in Washington County and in the Tulsa area is expressed by anomalous areas which together may be part of one trend. The prominent anomalies in Garfield and Grant counties correspond fairly well to fields in the Garber-Enid-Lamont area.

Salinity Gradient Anomalies

A comparison of the geothermal gradient map and salinity changes with depth is based on the salinity gradient maps by Buckner (1972). Low salinity gradients in the deep part of the Anadarko basin correspond quite well to low geothermal gradients within the normally pressured formations and the high gradients of the abnormally pressured zone. Both gradients increase northward toward the Northern Oklahoma platform. High salinity gradients in Osage County in pre-Pennsylvanian units correspond in part to the high geothermal anomaly. The salinity gradients in Pennsylvanian strata on the west and southwest flanks of the Ozark uplift parallel geothermal trends. The eastern part of the Arkoma basin in Oklahoma has low salinity gradients and high geothermal gradients. Widely spaced contours on the pre-Pennsylvanian salinity gradient map characterize the Seminole uplift, which also is reflected by a geothermal anomaly.

Correlations With Geophysical Features

Gravity Anomalies

Correlation to gravity data is based upon the Bouguer Gravity-anomaly Map of Oklahoma by Lyons (1964). Areas of distinct correlation are the Wichita uplift and Osage County, where gravity maxima exist. Other correlatable anomalies are the Hunton-Pauls Valley uplift and the Edmond maximum (Lyons, 1964) which apparently is related to the Oklahoma City uplift. More subtle gravity anomalies which correspond with geothermal features are the Rosston maximum in Harper County and the Heavener maximum in LeFlore County (Lyons, 1964). The maxima paralleling the Muenster-Waurika arch correspond to geothermal low anomalies. The gravity maximum in Grant County and a geothermal high anomaly are located in the same general area.

Gravity minima in the Ardmore basin and the deepest part of the Anadarko basin are located in the same areas as geothermal-low anomalies. Also, three geothermal low anomalies are located in the same area as two north-trending maxima in Washita and Custer counties.

The trend of the Ouachita minimum parallels the trend of geothermal high anomalies in the Arkoma basin. The gravity trends in southern Oklahoma also parallel trends of geothermal anomalies.

In general, the gravity maxima correspond to shallow basement, and the gravity minima reflect thick sequences of sedimentary rocks. The gravity maxima in Washita and Custer counties together with those in Kingfisher and Grant counties may express the southward extension of a

Precambrian rift filled with basaltic and associated mafic intrusives (Lyons, 1964). The corresponding geothermal low anomalies in Washita and Custer counties may reflect the low concentration of radioactive isotopes in those types of igneous rocks rather than differences in elevation of the basement.

Magnetic Anomalies

Comparison of the geothermal maps to the Vertical-Intensity Magnetic Map of Oklahoma (Jones and Lyons, 1964) indicates that the areas of correlation are essentially those which correlate with gravity anomalies. Two additional areas of correlation are the Stigler maximum in eastern Haskell County and the Lamont Ring maximum in southeastern Grant County and northeastern Garfield County (Jones and Lyons, 1964). The high geothermal gradients corresponding to the Stigler maximum appear to be related to the high gradients of the Arkoma basin rather than the specific cause of the magnetic anomaly. It has been suggested that the Lamont Ring maximum possibly represents a Precambian meteoric-impact feature (Jones and Lyons, 1964). The corresponding high geothermal gradient, however, probably reflects to a large extent Phanerozoic structural features and hydrocarbon occurrences.

CHAPTER VII

CONCLUSIONS

Determination of geothermal gradients in Oklahoma from borehole data, preparation of gradient maps from those data, and interpretation of those maps resulted in the following conclusions:

(1) Bottom-hole temperatures from well logs, if corrected properly, are useful in mapping geothermal gradients.

(2) Major tectonic-structural features of Oklahoma are reflected by the gradient anomalies and trends.

(3) Oklahoma basins are delineated by geothermal gradients, which in most cases reflect thickness and types of sedimentary rocks; the Arkoma basin may reflect a higher geothermal regime which was associated with a continental margin or major rift.

(4) Abnormal geothermal gradients coincide with occurrences of abnormal pressure.

(5) Geothermal gradients of the rocks overlying an abnormally pressured zone are anomalously low, possibly due to restriction of heat flow by the abnormally pressured zone.

(6) A number of geothermal gradient anomalies correlate well with hydrocarbon accumulations; the best correlation is between gas fields and high geothermal gradient anomalies in the abnormally pressured zone.

(7) Geothermal gradients within the normally pressured formations appear to reflect primary basement configuration and migrating fluids.

(8) Geothermal gradient anomalies of Oklahoma correlate quite well with those geophysical anomalies which are related to relief of the basement.

SELECTED BIBLIOGRAPHY

Anderson, L. A., and G. R. Johnson, 1973, The application of the self-potential method in the exploration for geothermal energy (abs): Geophysics, v. 38, p. 1190.

Arbenz, J. K., 1956, Tectonic map of Oklahoma: Okla. Geol. Survey.

Barker, C., 1972, Aquathermal pressuring - Role of temperature in development of abnormal pressure zones: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 2068-2072.

Beck, A. E., and A. S. Judge, 1969, Analysis of heat flow data - I. Detailed observations in a single borehole: Geophy. Jour. Royal Astr. Soc., v. 18, p. 145-158.

Berry, F. A. F., 1959, Hydrodynamics and geochemistry of the Jurassic and Cretaceous systems in the San Juan basin, northwestern New Mexico and southwestern Colorado: Unpub. dissert., Stanford University, 192 p.

Bingham, R. H., and R. L. Moore, 1975, Reconnaissance of the water resources of the Oklahoma City quadrangle, Central Oklahoma: U.S. Geological Survey, Map HA-4.

Bodvarsson, G., Shih-Ming Lu, and R. P. Lowell, 1974, Temperature transients in flowing boreholes: Geothermics, v. 3, p. 21-24.

Boldizar, T., 1968, Geothermal data from the Vierra Basin: Jour. Geophy. Res., v. 73, p. 613-618.

Bredehoeft, J. C., and B. B. Hanshaw, 1968, On the maintenance of anomalous fluid pressures: Geol. Soc. America Bull., v. 79, p. 1097-1122.

____________ and I. S. Papadopulos, 1965, Rate of vertical ground water movement estimated from the earth's thermal profile: Water Resources Res., v. 1, p. 325-328.

Breeze, A. F., 1971, Abnormal-subnormal pressure relationships in the Morrow sands of northwestern Oklahoma: Shale Shaker, v. 21, p. 172-193.

Buckner, D. H., 1972, Salinity gradient study of Oklahoma: Unpub. M.S. thesis, Oklahoma State Univ., 71 p.

Burst, J. F., 1969, Diagenesis of Gulf Coast clayey sediments and its possible relation to petroleum migration: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 73-93.

Cartwright, K., 1968, Temperature prospecting for shallow glacial and alluvial aquifers in Illinois: Ill. State Survey Circ., 433, 41 p.

Chang, J., 1958, Ground temperature: Harvard University, Milton, Mass., 299 p.

Chapman, D. S., and H. N. Pollack, 1977, The flow of heat from the earth's interior: Scient. American, August, 1977, p. 60-76.

____________ and ____________, 1977, Regional geotherms and lithosphere thickness: Geology, v. 5, p. 265-268.

____________ and ____________, 1975, Global heat flow - a new look: Earth Planetary Sci. Letters, v. 28, p. 23-32.

Charygin, M. M., and Y. G. Bogomolov, 1969, On the geothermal regime of certain tectonic structures: Internat. Assoc. Scientific Hydrology Bull., v. 14, p. 127-130.

Cronoble, J. M., 1969, Geothermal gradients and their application to petroleum geology: Mountain Geol., v. 6, p. 27-39.

Dickey, P. A., and J. S. Bradley, 1976, Abnormal formation pressure: Am. Assoc. Petroleum Geologists Bull., v. 60, p. 1124-1128.

____________ and W. C. Cox, 1977, Oil and gas reservoirs with subnormal pressures: Am. Assoc. Petroleum Geologists Bull., v. 61, p. 2134-2141.

Dickenson, G., 1953, Geological aspects of abnormal reservoir pressure in Gulf Coast Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 410-432.

Edwardson, M. J., et al., 1962, Calculation of formation temperature disturbances caused by mud circulation: Jour. Pet. Tech., v. 14, p. 416-435.

Elder, J. W., 1965, Physical processes in geothermal areas, in Terrestrial heat flow: Amer. Geophys. Union, mon. 8, p. 211-239.

Epp, D., et al., 1970, Heat flow in the Caribbean and Gulf of Mexico: Jour. Geophy. Res., v. 75, p. 5655-5669.

Fertl, W. H., and D. J. Timko, 1970, Occurrence and significance of abnormal pressure formations: Oil Gas Jour., v. 68, Jan. 5, p. 97-108.

___________ and ___________, 1970, Association of salinity variations and geopressures in soft and hard rock: SPWLA Trans., 24 p.

___________ and ___________, 1971, Parameters for identification of overpressure formations: SPE Paper no. 3223, 5th SPE AIME Drlg. Rock Mech. Conf., p. 125-136.

Feth, J. H., et al., 1965, Preliminary map of the conterminous United States showing depth to and quality of shallowest ground water containing more than 1,000 parts per million dissolved solids: U.S. Geol. Surv. Hydrol. Invest. Atlas HA-199, 31 p.

Flawn, P. T., as chmn., 1967, Basement map of North America: Am. Assoc. Petroleum Geologists and U.S. Geological Survey.

George, E. R., 1970, The use of subsurface temperature to detect geopressure: paper presented at the Abnormal Subsurface Pressures Conference, Louisiana State Univ., Baton Rouge, Louisiana, 44 p.

Greenberg, D. D., R. S. Cresap, and T. A. Malone, 1968, Intrinsic permeability of hydrological porous mediums; variations with temperature: Water Resources, v. 4, p. 791-800.

Griffin, G. M., and D. A. Reel, 1969, Geothermal gradients in Florida and southern Georgia: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 2037.

___________, P. A. Tedrick, D. A. Reel, and J. P. Manker, 1969, Geothermal gradients in Florida and southern Georgia: Gulf Coast Assoc. Geol. Soc. Trans., v. 19, p. 189-193.

Groush, S. T., and G. A. Thompson, 1976, Thermal model of continental lithosphere: Jour. Geophy. Res., v. 81, no. 26, p. 4857-4862.

___________ and ___________, 1975, Heat flow and thickness of lithosphere (abs): EOS, v. 56, p. 1063.

Gruntfest, I. J., and H. R. Shaw, 1969, Earth tide as a significant source of heat: Paper T47, abs., Trans. Am. Geophy. Union, v. 50, p. 318.

Gutenberg, B., 1959, Physics of the Earth's Interior: Internat. Geophy. Series, v. 1, Academic Press, New York.

Haas, I. O., and C. R. Hoffman, 1929, Temperature gradient in Pechelbronn oil bearing region: Am. Assoc. Petroleum Geologists Bull., v. 13, p. 1257-1274.

Harkins, K. L., and J. W. Baugher, 1969, Geologic significance of abnormal subsurface pressure: Jour. Pet. Tech., v. 21, p. 961-966.

Hart, D. L., 1974, Reconnaissance of the water resources of the Ardmore and Sherman quadrangles, southern Oklahoma: U.S. Geol. Survey, Map HA-3.

____________, 1966, Base of fresh ground water in southern Oklahoma: U.S. Geol. Survey Hydrologic Atlas 223.

Havens, J. S., 1977, Reconnaissance of the water resources of the Lawton quadrangle, southwestern Oklahoma: Okla. Geol. Survey, Hydrogeologic Atlas 6.

Hermance, J. F., and Grillot, 1970, Correlation of magnetotelluric, seismic, and temperature data from southern Iceland: Jour. Geophy. Res., v. 75, p. 6582-6591.

Hobson, G. D., 1977, Abnormal formation pressure: Am. Assoc. Petroleum Geologists Bull., v. 61, p. 1090.

Horae, K., 1970, Relationship among terrestrial heat flow, thermal conductivity, and geothermal gradient: Jour. Geophy. Res., v. 75, p. 1985.

____________ and G. Simmons, 1968, Seismic travel time anomoly due to anomalous heat flow and density: Jour. Geophy. Res., v. 73, p. 7577-7588.

Hutt, J., and J. W. Berg, 1968, Thermal and electrical conductivities of sandstone rocks and ocean sediments: Geophysics, v. 38, p. 489-500.

Jam, L. P., P. A. Dickey, and E. Tryggvason, 1969, Subsurface temperature in south Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 2141-2149.

Jones, P. H., 1969, Hydrodynamics of geopressure in the northern Gulf of Mexico basin: Jour. Pet. Tech., v. 21, p. 803-810.

____________, 1975, Geothermal and hydrocarbon regimes, northern Gulf of Mexico basin: Proc. First Geopressured Geothermal Energy Conf., Univ. Texas, Austin, Center for Energy Studies, p. 15-89.

Jones, V. L., and P. L. Lyons, 1964, Vertical-Intensity magnetic map of Oklahoma: Oklahoma Geol. Survey, Map GM-6.

Jordan, L., 1962, Geologic map and section of pre-Pennsylvanian rocks in Oklahoma: Oklahoma Geol. Survey, Map GM-5.

Kappelmeyer, D., 1955, The use of near surface temperature for discovering anomalies due to causes at depth: Geophy. Prospect., v. 5, no. 5, p. 239-258.

____________ and R. Haenel, 1974, Geothermics; with special reference to application: Geoexpl. Monograph, no. 4, 238 p.

Klemme, H. D., 1975, Geothermal gradients, heat flow and hydrocarbon recovery, in Petroleum and global tectonics: Princeton, New Jersey, Princeton Univ. Press, p. 251-304.

Kumar, M. B., 1977, Geothermal and geopressure pattern of Bayou Carlin-Lake Sand area, South Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 61, p. 65-79.

Lang, W. B., 1937, Geologic significance of a geothermal gradient curve: Am. Assoc. Petroleum Geologists Bull., v. 21, p. 1193-1205.

Lee, H. K., and S. Uyeda, 1965, Review of heat flow data, in Terrestrial heat flow: Amer. Geophy. Union, mon. 8, p. 87-190.

Levorsen, A. I., 1967, Geology of petroleum: W. H. Freeman and Co., San Francisco, 724 p.

Lewis, C. R., and S. C. Rose, 1970, Theory relating high temperatures and overpressures: Jour. Pet. Tech., v. 22, p. 11-16.

Lyons, P. L., 1964, Bouguer gravity-anomaly map of Oklahoma: Oklahoma Geol. Survey, Map GM-7.

____________, 1962, Geophysical background of Arkoma Basin tectonics: Tulsa Geol. Soc. Mtg., May 14, 1962.

MacDonald, G., 1963, The deep structure of continents: Rev. Geophy., v. 1, p. 587-665.

Manetti, G., 1973, Attainment of temperature equilibrium in holes during drilling: Geothermics, v. 2, p. 94-100.

Mayes, J. W., J. Westheimer, C. W. Tomlinson, and D. M. Putman, et al., 1959, Petroleum geology of Southern Oklahoma: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma.

McCutchin, J. A., 1930, Determination of geothermal gradients in Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 14, p. 535-557.

McKenzie, D. P., 1967, Some remarks on heat flow and gravity anomalies: Jour. Geophy. Res., v. 72, p. 6261-6273.

Meimhold, R., 1971, Hydrodynamic control of oil and gas accumulations as indicated by geothermal, geochemical, and hydrological distribution patterns: Proc. Eighth World Petroleum Cong., v. 2, p. 55-66.

Morgan, W. J., 1975, Heat flow and vertical crust movements, in Petroleum and global tectonics: Princeton, New Jersey, Princeton Univ. Press, p. 23-43.

Moses, P. L., 1961, Geothermal gradients now known in greater detail: World Oil, May, p. 79-82.

Muehlberger, W. R., R. E. Denison, and E. G. Lidiak, 1967. Basement rocks in the continental interior of the U.S.: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2351-2380.

Naidu, P. S., 1971, Correlation between terrestrial heat flow and thermal conductivity: Pure Appl. Geophy., v. 88, p. 154-158.

____________, 1970, Heat flow in random medium; first order theory: Pure Appl. Geophy., v. 79, p. 73-84.

Nichols, E. A., 1947, Geothermal gradients in mid-continents and Gulf Coast oil fields: Trans. AIME, v. 170, p. 44-50.

Ovnatanov, S. T., and G. P. Tamrazyan, 1970, Thermal studies in subsurface structural investigations, Apsheron, Peninsula, Azerbaijin, U.S.S.R.: Am. Assoc. Petroleum Geologists Bull., v. 54, p. 1677-1685.

Pollack, H. N., and D. S. Chapman, 1977, Mantle heat flow: Earth Planetary Sci. Letters, v. 34, p. 174-184.

____________ and ____________, 1977, On the regional variation of heat flow, geotherms, and lithospheric thickness: Tectonophysics, v. 38, p. 279-296.

Powers, M. C., 1967, Fluid-release mechanisms in compacting marine mudrocks and their importance in oil exploration: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 1240-1254.

Price, L. C., 1976, Aqueous solubility of petroleum as applied to its origin and primary migration: Am. Assoc. Petroleum Geologists Bull., v. 60, p. 213-244.

Ramey, H. J., 1962, Wellbore heat transmission: Jour. Pet. Tech., v. 14, p. 427-435.

Reel, D. A., 1970, Geothermal gradients and heat flow in Florida: Unpub. M.A. thesis, University of Southern Florida, 66 p.

____________ and G. M. Griffin, 1971, Potentially petroliferous trends in Florida as defined by geothermal gradients: Gulf Coast Assoc. Geol. Soc. Trans., v. 21, p. 31-36.

Roy, R. F., E. R. Decker, D. D. Blackwell, and F. Birch, 1968, Heat flow in the United States: Jour. Geophy. Res., v. 73, p. 5207-5222.

Schlumberger, M., H. G. Doll, and A. A. Perebinossoff, 1937, Temperature measurements in oil wells: Jour. Pet. Tech., v. 23, p. 1-25.

Schneider, R., 1966, Interpretation of the geothermal field associated with the carbonate-rock aquifer system of Florida: U.S. Geol. Survey, G.S.A. Abs., Spec. Paper 101, p. 191-192.

____________, 1964, Relation of temperature distribution to groundwater movement in carbonate rocks of central Israel: Geol. Soc. Am. Bull., v. 75, no. 3, p. 209-216.

Schoeppel, R. J., and S. Gilarranz, 1966, Use of well log temperatures to evaluate regional geothermal gradients: Jour. Pet. Tech., v. 18, p. 667-673.

Selig, F., and G. C. Wallick, 1966, Temperature distribution in salt domes and surrounding sediments: Geophysics, v. 31, p. 346-361.

Simmons, G., 1967, Interpretation of heat flow anomalies; 1. Contrast in heat flow production: Rev. Geophy., v. 5, p. 42-52.

____________ and K. Horai, 1968, Heat flow data, 2: Jour. Geophy. Res., v. 73, p. 6608-6629.

Stuart, C. A., 1970, Geopressures, _in_ Second symposium on Abnormal Pore Pressure, Proc. Suppl.: Louisiana State Univ., 121 p.

Summers, W. K., 1972, Approximation of thermal gradient in southeastern New Mexico using bottom-hole temperature from electric logs: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 2072-2074.

Tarr, R. S., L. Jordan, and T. L. Rowland, 1965, Geologic map and section of pre-Woodford rocks in Oklahoma: Oklahoma Geol. Survey, Map GM-9.

Thomeer, J. H. M. A., and J. A. Bottema, 1961, Increasing occurrence of abnormally high reservoir pressures in boreholes and drilling problems resulting therefrom: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 1721-1730.

Timko, D. L., and W. H. Fertl, 1971, Relationship between hydrocarbon accumulation and geopressure and its economic significance: Jour. Pet. Tech., August, p. 923-933.

Tozer, D. C., 1968, Pattern of geothermal heat flow: Jour. Geophy. Res., v. 73, p. 2834.

Van Orstrand, C. E., 1934, Normal geothermal gradients in U.S.: Am. Assoc. Petroleum Geologists Bull., v. 19, p. 78-115.

Zierfuss, H., 1969, Heat conductivity of some carbonate rocks and clayey sandstones: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 251-260.

____________ and G. Vliet, 1956, Laboratory measurements of heat conductivity of sedimentary rocks: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 2475-2488.

VITA 2

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