Approximation of Geothermal Gradients in Northern West Virginia Using Bottom-Hole Temperatures from Electric Logs[1]

T. W. GRISAFI,[2] H. H. RIEKE, III,[2] and D. R. SKIDMORE[2]
Morgantown, West Virginia 26506

Abstract Nonequilibrium bottom-hole temperature data and well depths were obtained from electric logs run on oil and gas wells in several northern West Virginia counties. Geothermal gradients were calculated from the temperature data, the mean surface temperature, and the well depths. These gradients ranged from 0.808°F/100 ft to 1.892°F/100 ft. The mean geothermal gradient was found to be 1.108°F/100 ft. Isothermal maps were developed for the base of the Pennsylvanian and the Mississippian formations in northern West Virginia.

A linear regression analysis of the geotemperature data yields a seventh-degree equation which can be approximated by the following straight line: $T_F = 55.0 + 1.11 \times 10^{-2}(D_F)$, where T_F is temperature in °F, and D_F is well depth below the surface in feet. The gradient as expressed by this equation seems to agree fairly well with published literature for other geologically quiescent regions.

INTRODUCTION

Information on the temperature gradients and temperatures at a specific depth is scarce in northern West Virginia. There are no published data on detailed geothermal gradients for this state. Interest in such information is most pronounced for plate-tectonic theory interpretation, heat-flux categorization, and geothermal-energy utilization.

A potential source of "point" temperature data is the "bottom-hole temperature" recorded on electric logs from wells. This temperature (BHT) is obtained from a maximum-reading thermometer contained in the body of the logging tool. But the temperature recorded by the thermometer is not necessarily the temperature at the bottom of the well nor is it necessarily the temperature of the formation. In general, the thermometer, although usually of excellent quality, is not standardized or calibrated. Mud circulating in the well bore while a hole is being drilled tends to raise the temperature at shallow depths and lower temperatures near the bottom. If the time between cessation of drilling and initiation of temperature logging is short, the bottom-hole temperature may not have time to reach equilibrium. Although these sources of error may be present in the use of bottom-hole temperature data to predict geothermal gradients, several authors have shown that this technique gives reasonable approximation of the true geothermal gradient (Schlumberger, 1937; Uyeda, 1960; Schoeppel and Gilarranz, 1966; Summers, 1972).

Data for this study were obtained from the geophysical well-log files of the West Virginia Geological Survey. These files contain drillers' logs as well as mechanical logs for over 3,300 wells from almost every county in West Virginia. Because many of the data were inappropriate for this study, only 31 wells were applicable for use in establishing the data base for this paper.

ISOTHERMAL MAPS

Nichols (1947) assumed a linear relation between the geothermal temperature and the depth of the well. This relation will be shown to be present in the study area. Temperature calculations for the generation of isothermal-mapping data were based on the following linear equation:

$$T_F = (T_{BH} - T_{MS})(D_F/D) + T_{MS}, \qquad (1)$$

where T_F is the temperature at the formational surface in question in °F; T_{BH} is the temperature at the bottom of the well in °F; T_{MS} is the mean surface temperature in °F (the mean surface temperature for northern West Virginia is approximately 55°F); D is the total depth of the well in feet; and D_F is the depth of the well to the formation in question in feet.

The temperature data from the well logs were used in Equation 1 to calculate the temperature at the base of two significant sedimentary horizons in the Appalachian basin: the Third Salt sand (Pennsylvanian) and the Berea Sandstone (Mississippian; Figs. 1, 2).

Figures 1 and 2 show that the geothermal temperature at specified stratigraphic horizons increases from east to west in northern West Virginia. This is mainly the result of a westward increase in depth of the two basal formations. Local apparent highs and lows in the geothermal temperatures may be explained by (1) variations in the geothermal gradients, (2) abrupt structural changes in the rock strata, and (3) possible anomalies or uncertainties in the original data.

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[2] School of Mines, West Virginia University.

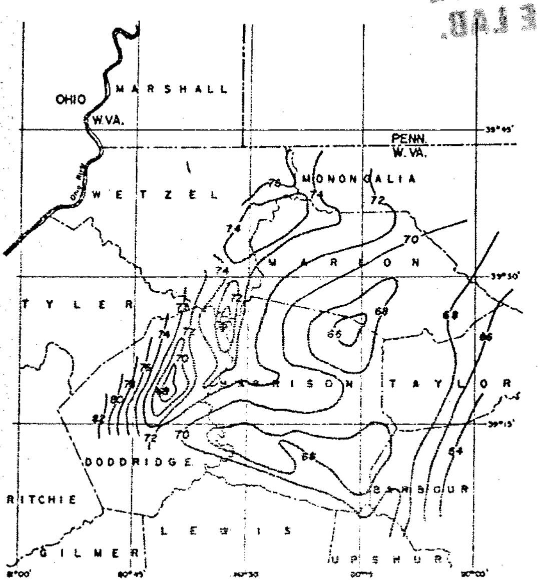

FIG. 1—Temperature (°F) at base of Pennsylvanian system for section of northern West Virginia.

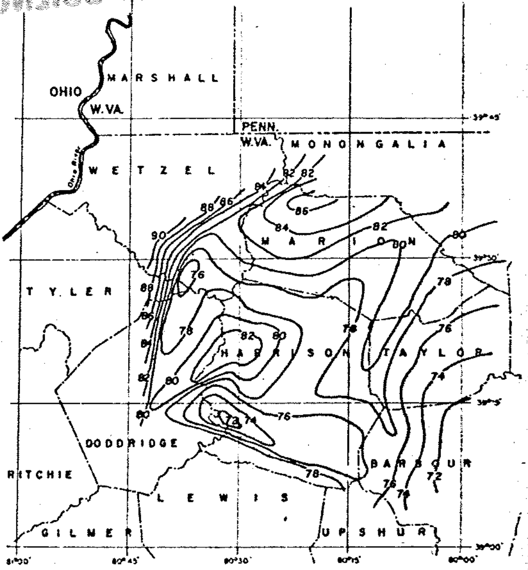

FIG. 2—Temperature (°F) at base of Mississippian system for section of northern West Virginia.

The temperature profiles determined in this study were converted to temperature gradients and compared with the gradients plotted for the same region on the Geothermal Map of North America (Am. Assoc. Petroleum Geologists, 1973). The results from this study were found to be 0.2–0.3°F/100 ft lower. The differences probably reflect the absence of the correction which was applied on the Geothermal Map of North America for nonequilibrium bottom-hole temperatures. The scale for the Geothermal Map of North America probably should be reduced so that the map would be more precise and easier to apply for practical purposes.

LINEAR REGRESSIONS

The idea that the temperature varies directly with depth seems to be confirmed by the results depicted in Figure 3, which shows a plot of depth versus bottom-hole temperature for all the wells studied. A linear-regression computer program was used to determine by best least-squares fit the coefficients of a seventh-degree polynomial.

A high-degree polynomial was deemed desirable so that results from later simplification could be compared with those from an admittedly precise though complex reference alternative. The program operated on a depth-temperature data set defined by the use of two readings for each well. The first reading was the mean-surface temperature, whereas the second reading was the bottom-hole temperature and depth. The seventh-degree polynomial is as follows.

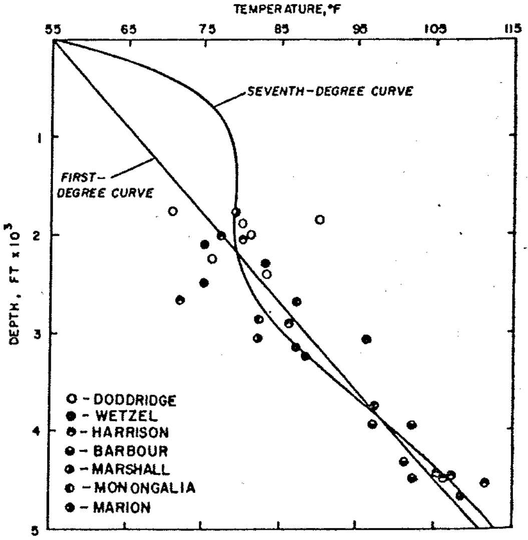

FIG. 3—Depth versus bottom-hole temperature for all wells studied; symbols indicate northern West Virginia counties.

$T_F = 55.0 + 0.5096 \times 10^{-1}(D_F) -$

$+ 0.1097 \times 10^{-7}(D_F)^3 - 0.11$

$+ 0.1325 \times 10^{-15}(D_F)^5 - 0.4$

$+ 0.5009 \times 10^{-23}(D_F)^7.$

Deviation is 1.93955612 and si
where T_F is temperature °F
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$T_F = 55.0 + 1.11 \times 10$

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adds less than 3°F to the temper
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\begin{aligned}
T_F = 55.0 &+ 0.5096 \times 10^{-1}(D_F) - 0.3749 \times 10^{-4}(D_F)^2 \\
&+ 0.1097 \times 10^{-7}(D_F)^3 - 0.1110 \times 10^{-11}(D_F)^4 \\
&+ 0.1325 \times 10^{-15}(D_F)^5 - 0.4755 \times 10^{-19}(D_F)^6 \\
&+ 0.5009 \times 10^{-23}(D_F)^7. \qquad (2)
\end{aligned}
$$

Deviation is 1.93955612 and sigma is 11.13415, where T_F is temperature °F and D_F is well depth from the surface in feet.

Although Equation 2 does not represent a straight line, the degree of curvature as prescribed by the data between 1,800 and 4,750 ft is so slight that for small changes in depth the curve approximates a straight line. The formula for the straight line is:

$$T_F = 55.0 + 1.11 \times 10^{-2}(D_F). \qquad (3)$$

At a depth of 5,000 ft the second through the seventh degree of the seventh-degree polynomial have little effect upon the calculated temperature. At 5,000 ft the seventh-degree equation adds less than 3°F to the temperature estimated by the straight-line equation. This amounts to about a 2.7 percent error in the estimated temperatures at that depth. With the methods commonly used today to determine the bottom-hole temperature of wells, it is quite probable that the original data used in this paper will contain an error greater than 3 percent. Therefore, the geothermal gradient can be represented adequately by Equation (3).

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