The American Association of Petroleum Geologists Bulletin
V. 60, No. 7 (July 1976), P. 1073-1077, 6 Figs.

Approximate Geothermal Gradients in Niger Delta Sedimentary Basin[1]

SILAS O. NWACHUKWU[2]
Nsukka, Nigeria

Abstract More than 1,000 well logs from the Niger delta sedimentary basin were examined for temperature-data quality. Most measurements were made within 4 to 8 hours of cessation of mud circulation. Such nonequilibrium temperatures were corrected to approximately true formation values by applying a numerical solution to a modified Lachenbruch-Brewer's equation. The subsurface temperature distributions based on both the raw and corrected temperature data, when presented as geothermal gradient maps, show that values are lowest over the center of the Niger delta, approximately 0.7 to 1.0°F/100 ft, and they increase to about 3°F/100 ft in the Cretaceous rocks on the north.

The geothermal gradient map in the Niger delta could be used in the application of the hydrocarbon liquid-window concept for oil exploration. It reveals that theoretically there is a considerable thickness of potentially hydrocarbon-bearing interval in the delta region that is unexplored by current drilling programs.

Introduction

Oil exploration activity in the Niger delta petroliferous province has resulted in the accumulation of thousands of well-log records in which borehole temperatures have been recorded. A knowledge of subsurface-temperature distribution is valuable in understanding the geologic and geophysical processes in this large and important sedimentary basin.

The usefulness of well-log temperatures for geothermal studies has been discussed by various investigators (Moses, 1961; Anglin and Beck, 1965; Schoeppel and Gilarranz, 1966; Harper, 1971; Connolly, 1972; Summers, 1972). It seemed evident from these studies that temperature data from wells logged to total depth in the Niger delta could be used to derive estimates of regional temperatures and geothermal gradients in the area.

Determination of Geothermal Gradients

The temperature data used in the present study were obtained from those wells in which the elapsed time between the cessation of mud circulation and temperature measurement has been recorded. This is because the degree of attainment of equilibrium is dependent on the elapsed time. The times ranged from 2 to 30 hours with 75 percent in the range of 4 to 8 hours.

Geothermal gradients were computed on the assumption of a linear increase of temperature with depth. With this assumption, the temperature at any depth can be specified by the relation:

$$T_z = \alpha_o + \alpha_1 Z \qquad (1)$$

where T_z = wellbore temperature in °F at depth Z ft, α_o = mean surface temperature in °F, and α_1 = geothermal gradient in °F/100 ft.

The most important locations within the Niger delta have mean annual temperature values of 80°F (27°C; White, 1970) and this value is utilized as mean surface temperature.

A single value of geothermal gradient has been recorded for each oil well. Where several determinations have been derived from many wells in an oil field, an arithmetic-mean value has been used to characterize the field. Generally, data were derived from wells with depths of more than 10,000 ft (3,048 m).

The geothermal gradients are expressed in units of °F/100 ft (Fig. 1). The map shows the presence of a region of low geothermal gradient at the center of the delta with values increasing outward in all directions. The highest values are in Cretaceous rocks on the north. In this area, regional trends are not defined clearly because of relatively fewer boreholes.

As temperatures had not attained equilibrium because of the short elapsed time (Raymond, 1969), approximately true formation temperatures were computed by use of a modified Lachenbruch-Brewer equation (Connolly, 1972) which can be expressed as:

$$T_i - T_f = -A/t_i + \alpha, \qquad (2)$$

where T_i = the recorded bottom hole temperature, T_f = true formation temperature, t_i = hours since cessation of mud circulation, α = duration of mud circulation, and A = effect of sensible heat and thermal conductivity. The quantities α and A are difficult to determine or estimate.

[1]Manuscript received, March 19, 1975; revised and accepted, February 9, 1976.

[2]Department of Geology, University of Nigeria.

The author extends his gratitude to the following oil companies for making available some temperature data: Shell BP, Texaco, Gulf, Phillips, Japan Petroleum, Elf Nigeria, Mobil, Nigeria Agip. Gratitude also is due to the Department of Petroleum Resources for permission to examine temperature data in their well-log files. Suggestions and encouragement from R. J. Schoeppel of Oklahoma University and A. Jessop of Earth Physics Branch of Dominion Observatory, Canada, also are acknowledged.

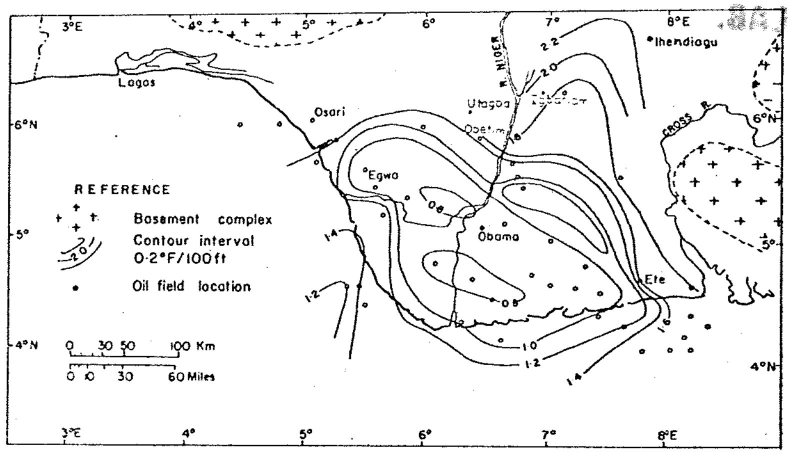

FIG. 1—Uncorrected geothermal gradient map, Niger delta.

However, where multiple logs are run to the same depth, three equations can be established which permit the elimination of the quantities α and A. The resultant equation is given by:

$$\frac{T_f(t_2-t_1)+T_1t_1-T_2t_2}{T_2-T_1}=\frac{T_f(t_3-t_1)+t_1T_1-T_3t_3}{T_3-T_1} \quad (3)$$

Equilibrium temperatures computed on the basis of equation 3 for Obetim and Utagba wells are shown in Figure 2. Correction temperature—the temperature difference between the true formation temperature and the observed temperature for given elapsed time—is plotted against the elapsed time on semilogarithmic scale. Two straight lines of differing slopes are derived for the two wells (Fig. 3). These suggest differences in the rates at which various wells attain equilibrium and may be caused by such factors as differences in borehole diameter and thermal conductivity of rocks. The correction temperature diminishes as elapsed time increases and the two curves appear to converge between 40 and 45 hours after cessation of circulation and the correction temperature approaches zero. So far, only two wells with data amenable to this type of analysis are available. Though limited, the available data suggest that in the Niger delta oil province, a good measure of temperature equilibrium for wells logged to total depth could be achieved within 48 hours after cessation of circulation.

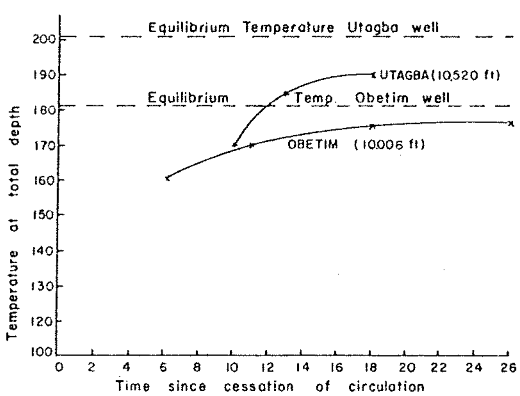

FIG. 2—Temperature-buildup curve for Obetim and Utagba wells and calculated equilibrium temperatures. Temperatures are in °F and time is in hours. Well locations are shown on Figure 1.

A mean correction line AB is used in estimating the correction to be applied to the wells where only a single temperature measurement and corresponding elapsed time have been recorded.

Geothermal gradients determined after correcting to approximate equilibrium temperatures are shown in Figure 4. These show generally steeper gradients but the pattern of geothermal-gradient variation remained essentially the same.

SIGNIFICANCE OF GEOTHERMAL-GRADIENT MAPS

Geothermal gradients range in value from 0.7 to 2.7°F/100 ft for uncorrected data (Fig. 1) and 1.0 to 3.0°F/100 ft for the corrected data (Fig. 4). The gradients are lowest at the center of the delta and increase both seaward and northward. These differences may reflect changes in thermal conductivity of rocks, ground-water movement, and endothermic reactions during diagenesis. Application in interpretation of delta tectonics is limited by the absence of thermal conductivity and lack of mineralogic data on clay sediments. However, the geothermal-gradient minimum coincides approximately with the location of the Niger delta gravity minimum of Figure 5 (Hospers, 1965), which corresponds to the area of the delta where

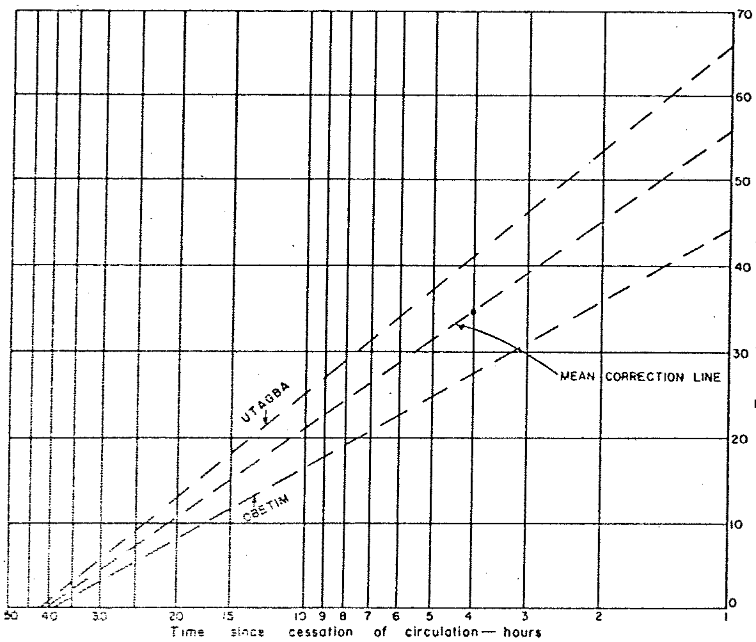

FIG. 3—Temperature-correction graph.

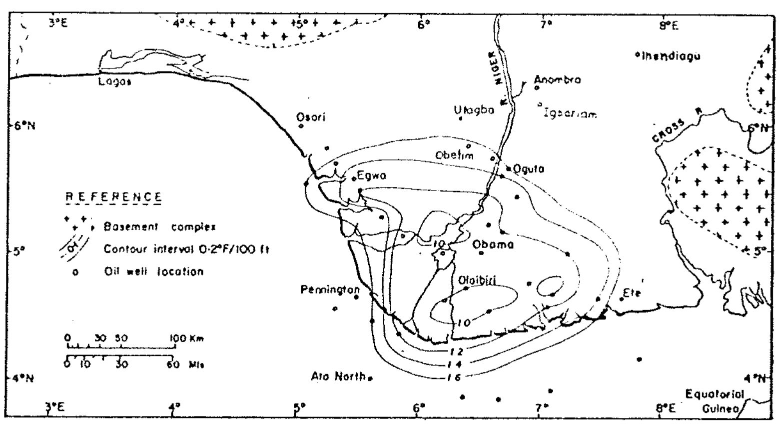

FIG. 4—Corrected geothermal-gradient map.

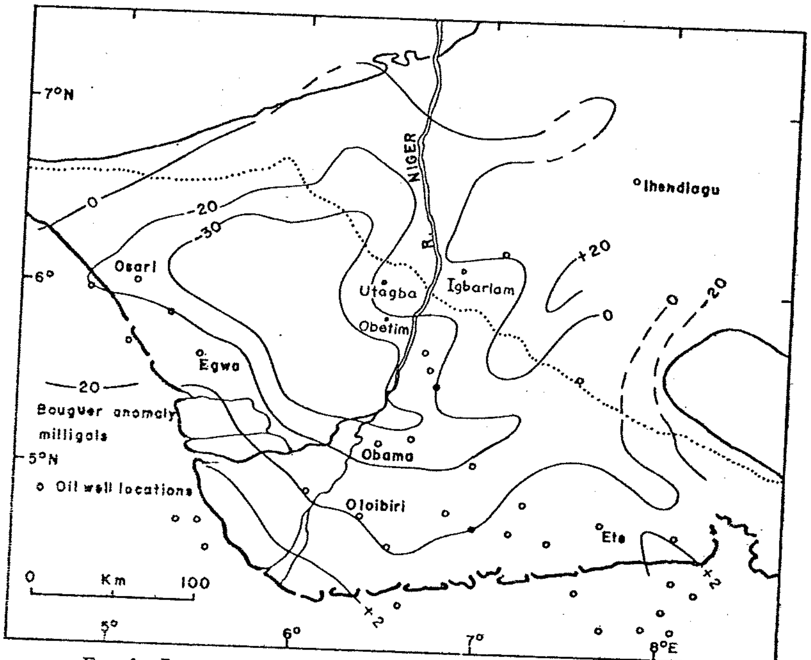

FIG. 5—Bouguer gravity map of Niger delta (after Hospers, 1965).

thickness of sediments is maximum. Geothermal gradients are steeper on the north and south where thicknesses of sediments, as inferred from pattern of variation of Bouguer anomalies, are less. Therefore, the geothermal gradient empirically seems to show an inverse relation with depth to the basement.

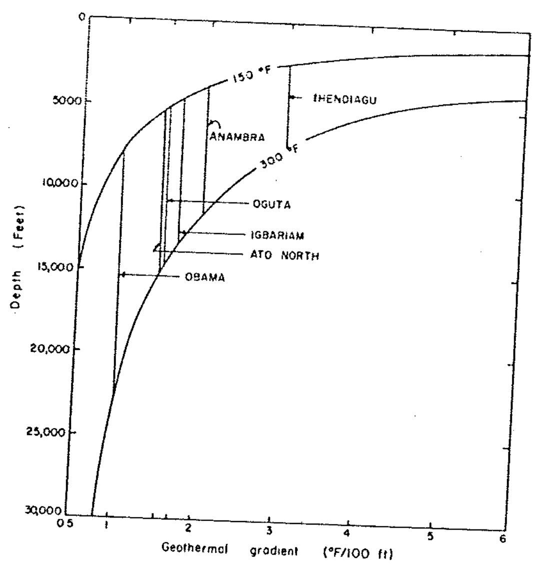

FIG. 6—Hydrocarbon-liquid window and theoretical oil prospects in various parts of sedimentary basin.

The geothermal gradient map also may be utilized as an exploration tool. Studies by Pusey (1973) indicated that hydrocarbon generation takes place within the temperature interval of 150 to 300°F (65 to 150°C). In the concept of the hydrocarbon-liquid window, ranges in depth within which liquid hydrocarbons are likely may be determined for any geothermal gradient (Fig. 6).

If it is assumed that the present temperatures represent the maximum values to which the sediments have been subjected, the depths of critical temperatures of generation and destruction of hydrocarbons in the delta region can be calculated on the basis of linear geothermal gradient. Thus, for example, oil may be generated in Obama field from a depth of 7,000 to 23,000 ft (2,134 to 7,010 m) whereas in the Ihendiagu area on the north, the depths may range from 2,300 to 7,300 ft (701 to 2,225 m; Fig. 6).

Present exploration activity does not extend much beyond a depth of 14,000 ft (4,267 m). Because the liquid-hydrocarbon window at the center of the delta extends to about 23,000 ft (7,010 m) it is evident that significant thicknesses of potentially oil-bearing sedimentary rocks have not been tested.

CONCLUSION

The following conclusions can be drawn from present investigations.

1. Regional ge
0.7 to 1.0°F/100
and then increase
maximum value o
an inverse relatio
dient and depth to
2. A considerab
prospective undril
ent. There is nee
programs below th
activity because of
mentary rocks whic
bon-liquid window.

REFERENCES CITED

Anglin, F. M., and A.
pattern in western
Sci., v. 2, p. 176-182
Connolly, E. T., 197
America—progress
ering problems: Im
rept.

1. Regional geothermal gradients range from 0.7 to 1.0°F/100 ft over the center of the delta and then increase northward and seaward to a maximum value of 2.7 to 3.0°F/100 ft. There is an inverse relation between the geothermal gradient and depth to basement.

2. A considerable thickness of theoretically oil-prospective undrilled sedimentary rocks is present. There is need therefore, to extend drilling programs below the present depths of exploration activity because of the thickness of undrilled sedimentary rocks which may be within the hydrocarbon-liquid window.

References Cited

Anglin, F. M., and A. E. Beck, 1965, Regional heat flow pattern in western Canada: Canadian Jour. Earth Sci., v. 2, p. 176-182.

Connolly, E. T., 1972, Geothermal survey of North America—progress report and associated data gathering problems: Imperial Oil Ltd., Canada, unpub. rept.

Harper, M. L., 1971, Approximate geothermal gradients in the North Sea basin: Nature, v. 230, p. 235-236.

Hospers, J., 1965, Gravity field and structure of the Niger delta, west Africa: Geol. Soc. America Bull., v. 76, p. 407-422.

Lachenbruch, A. H., and M. C. Brewer, 1959, Dissipation of the temperature effect in drilling a well in Arctic Alaska: U.S. Geol. Survey Bull. 1083-C, p. 73-109.

Moses, P. L., 1961, Geothermal gradients now known in greater detail: World Oil, v. 152, no. 6, p. 79-82.

Pusey, W. C., III, 1973, How to evaluate potential gas and oil source rocks: World Oil, v. 176, no. 5, p. 71-75.

Raymond, L. R., 1969, Temperature distribution in a circulating drilling fluid: AIME Petroleum Engineers Trans., v. 246, p. 333-341.

Schoeppel, R. J., and S. Gilarranz, 1966, Use of well log temperature to evaluate regional geothermal gradients: Jour. Petroleum Technology, v. 18, p. 669-673.

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

White, R., 1970, World weather records, 1954-1960, v. 5: U.S. Dept. Commerce, p. 315-330.