PART 5

THE mud temperature in a rotary hole after circulation has ceased varies not only with time but also with the hole size. Inasmuch as the degree of caving depends to some extent upon the nature of the formations drilled, a temperature log made under such condition exhibits variations which are directly correlatable with the nature of the beds penetrated by the drill.

Temperature

Wells Not in Thermal Equilibrium

A. Rotary Holes

THE LAWS controlling the temperature distribution in formations which are in thermal equilibrium are fairly simple to investigate because only the conductivity and the dimensions of the media need be considered. Where a mathematical treatment is not possible, these laws can be readily established by conducting experiments on electrolytic scale models. On the other hand, the problem is much more complex when the media under investigation are not in thermal equilibrium. In such cases, more media have to be considered (the drilling mud, for example) as well as other physical quantities (specific heat, time). Evidently, an analytical solution of the problem is out of the question, and the only method of approach is to use electric analogues.

Unfortunately, the equipment which is necessary for this work is far more complicated, and the time involved for the measurements is far greater, than for steady state investigations. Because of these obstacles no laboratory experiments were made by the writer on unsteady state temperatures, and the data here offered are based mainly on actual measurements made in wells.

For the present purpose the wells are classified as follows:

1. Rotary holes shortly after mud circulation is discontinued,
2. Producing wells (oil, gas, or water),
3. Wells recently cemented.

In all these wells the temperature of the fluid in the hole is usually different from the temperature of the formations situated at the same level close to the well. The latter, in turn, is different from the temperature which would be found if the well did not exist. For the sake of convenience these three temperatures will be respectively termed:

fluid temperature,
apparent formation temperature,
true formation temperature.

Effect of Mud Circulation

Referring to Figure 5-1, H represents the cross section of a rotary hole, 7500 feet deep for example. In first approximation it will be assumed that the apparent formation temperature equals the true temperature at all points. This temperature, T_F, is represented by graph F showing an increase from 60° at the top to 180° at the bottom. The nature of the formations penetrated need not be considered now. It will only be assumed that a few sections (marked C on the figure) caved appreciably, while the others (marked B) did not.

The temperature T_M of the mud immediately after circulation is discontinued is represented by graph M whose slope is much greater than the slope of graph F. Near the bottom, the mud temperature is appreciably less than the formation temperature at the same level, while near the top it is much higher. Therefore, graphs F and M intersect at a point P situated at some intermediate depth, 3000 feet for example.

If the well is left idle for several days, the mud will evidently cool in the upper part of the hole and warm up in the lower section until it reaches the formation temperature T_F. At any time during this intermediate stage the graph representing the mud temperature T is a curve which rotates from M to F. The rate of temperature change at any given depth D is controlled primarily by the two following factors:

1. The temperature difference $T - T_F$ at point D,
2. The volume of mud situated at that particular depth.

The difference $T - T_F$ is particularly great in the top section and in the bottom section of the hole. These sections will therefore exhibit the greatest and fastest temperature changes, while in the central section these will be much small-

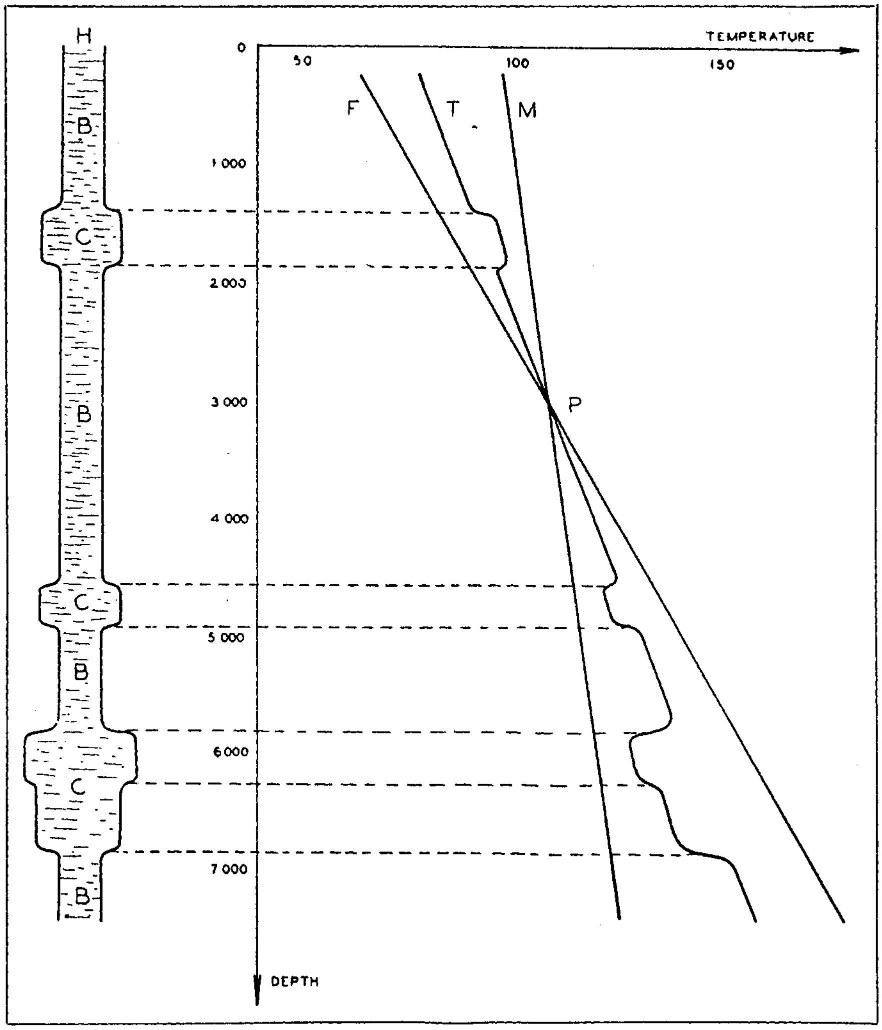

Figure 5-1. Principle of transitional method.

REFERENCES

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WELL LOGGING

By HUBERT GUYOD

er and slower, especially in the vicinity of point P.

If the hole had a uniform diameter, the transitional temperature graph T would, at any time, be approximately a straight line rotating about point P. However, because the hole is not uniform, the volume of mud opposite sections C is greater than the volume of mud opposite sections B and it will therefore warm up (or cool) slower than the latter. The result is that at any time during the transitional stage the mud temperature is greater at C than at B in the top part of the hole, while the converse is found in the bottom section. Of course, the greater the degree of caving, the greater will be the difference.

Temperature Graph Picks Shale Beds

To summarize, a temperature graph taken in a rotary well a few hours after circulation is discontinued exhibits temperature changes which are correlatable to the degree of formation caving. Usually, shales cave appreciably, while sands and sandstones do not. A transitional temperature graph will therefore exhibit significant breaks at formation boundaries.

Figure 5-2 illustrates the foregoing discussion. This figure represents two sections of a temperature graph, caliper log and electric log recorded in a Mid-Continent well. The graphs to the left are from a shallow section while those to the right were taken at much larger depths. The dash line shown on the temperature graphs is an imaginary baseline representing approximately the transitional temperature opposite sands sections or, more exactly, in sections where the diameter of the hole is approximately equal to the size of the bit. Where the actual temperature differs from that shown by the base line, the hole has an abnormal diameter, usually indicating the presence of a shale bed.

It is possible to calculate approximately the mud temperature T at a given point of the hole during the transient condition described above.

Consider a thin horizontal section of the mud column (Figure 5-3). Its volume is ΔV and its curved surface is ΔA. Let D designate the diameter of the hole, T_F the formation temperature, T_M the initial mud temperature, and T the transitional mud temperature. At any time after mud circulation ceased, the quantity of heat dQ transferred in the short time dt is proportional to the area ΔA, to the temperature difference $T_F - T$, and to the time interval dt.

$$dQ \propto \Delta A \, (T_F - T) \, dt$$

The heat transferred dQ is proportional also to the resulting temperature increase dT and to the volume of mud considered,

$$dQ \propto \Delta V \times dT$$

ΔA and ΔV are proportional to D and D^2, respectively. Combining the foregoing relations gives:

$$\frac{dT}{T - T_F} = -\frac{C\,dt}{D}$$

where C can be considered as being a constant in first approximation.

Integration between temperatures T_M and T_F gives the transitional temperature at any time t after circulation stopped.

$$T = T_F - (T_F - T_M)\, e^{-\frac{Ct}{D}} \qquad (1)$$

This relation is only approximate because it was established with

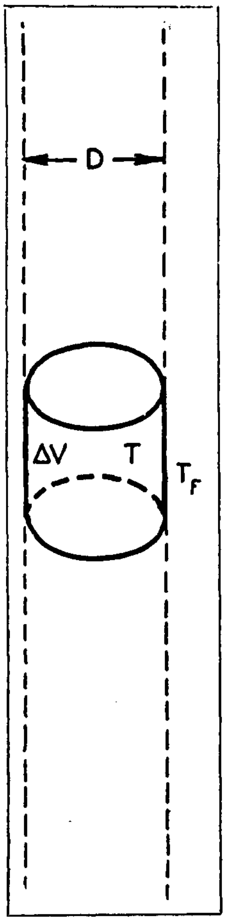

Figure 5-3

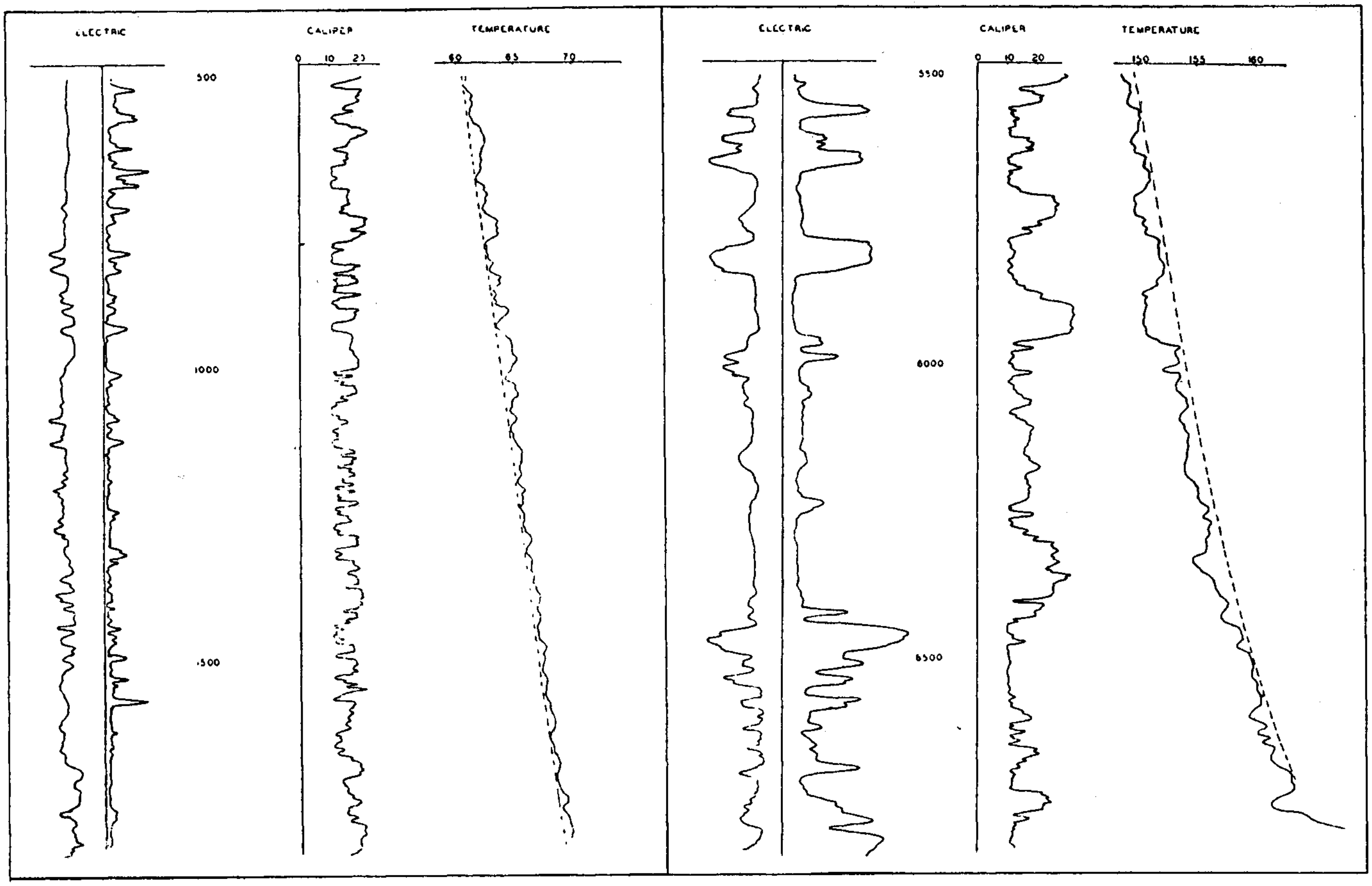

Figure 5-2. Electric log, caliper log and temperature log from an Oklahoma Well.

the assumptions that the apparent formation temperature T_F is constant and that the mud temperature is the same in the center of the hole as on the sides. Relation (1) gives therefore for the mud column an average temperature T which is different from the actual average temperature, especially for muds in which there is little convection (gel type muds). Nevertheless, this relation gives an excellent qualitative idea of how the mud temperature varies with time, especially if the influence of the foregoing factors is embodied in the factor C.

Although the quantity C varies slightly with the type of mud and the size of the hole, in this work it will be assumed that it is a constant. From a few temperature logs it is estimated that C is of the order of 2 when the temperature is in degrees Fahrenheit, the hole diameter in inches and the time in hours. Using this value of 2 in equation (1) shows that in a seven-inch hole, the temperature increase has reached half its total value after about 2½ hours. Evidently, the rate of increase diminishes appreciably thereafter. Also, in holes of large diameter the temperature rise is less than indicated above for a seven-inch hole.

The foregoing remarks are summarized on Figure 5-4 which represents the time-temperature graphs X and Y for hole diameters of 10 inches and 15 inches respectively. The temperature values are relative and the ordinates can be calibrated to fit any desired condition, for example, for a formation temperature of 170° and an initial mud temperature of 100°.

Maximum Anomaly

The temperature difference (i.e., temperature anomaly given by the log) observed in the mud column between a section which cave (diameter D′) and one which does not cave (diameter D) is measured by the difference in ordinate ΔT between graphs X and Y.

$$\Delta T = (T_F - T_M)\left(e^{-\frac{Ct}{D}} - e^{-\frac{Ct}{D'}}\right) \qquad (2)$$

It is found from this equation that the maximum anomaly occurs at a time t_M given by the following expression:

$$t_M = 1.15\,\frac{DD'}{D - D'}\,\log_{10}\frac{D}{D'}$$

which is graphically represented on Figure 5-5 in terms of D′/D (relative caving) and for several values of D (bit size). It can be seen from this chart that with the usual bit sizes (7 to 10 inches) and caving (D′/D less than 2) the maximum temperature anomalies are observed from about four to seven hours after circulation is discontinued. After that time the anomalies become less, but they do not diminish appreciably until ten to fifteen hours after circulation is stopped.

Referring to Figure 5-5, it is seen that the maximum anomalies found in a hole whose diameter varies from ten to fifteen inches (Figure 5-4) are observed six

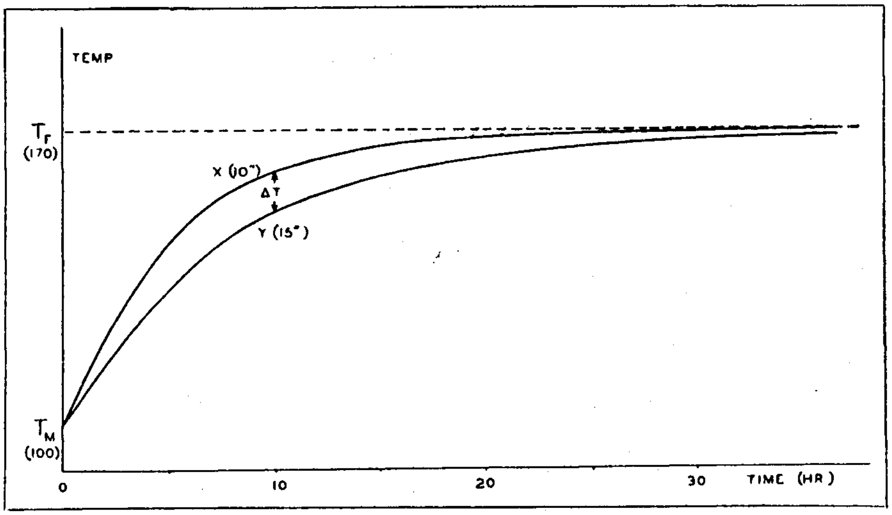

Figure 5-4 (top). Approximate mud temperature in terms of time after mud circulation is discontinued.

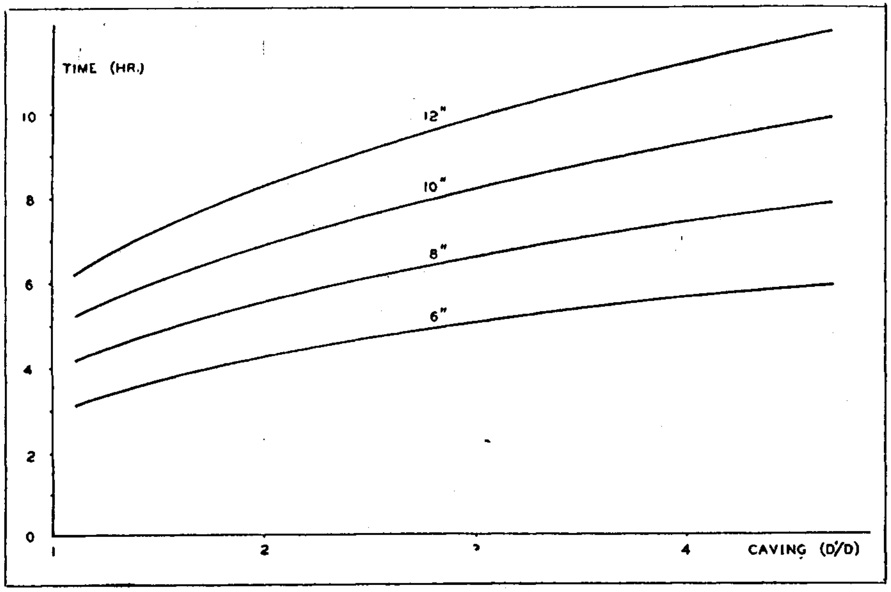

Figure 5-5 (middle). Chart for estimating time at which maximum transitional temperature anomaly occurs.

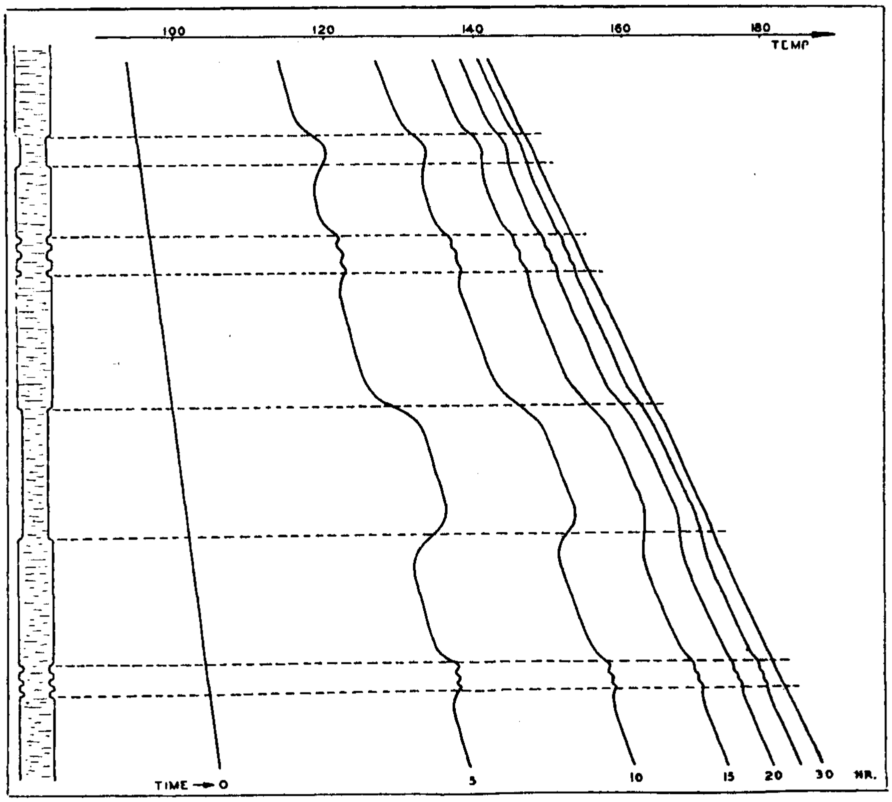

Figure 5-6 (bottom). Transitional temperature logs taken at regular time intervals (computed from preceding charts).

hours after circulation is stopped. The numerical value of these anomalies equals about 15 percent of $T_F - T_M$. Ten hours later $(t = 16)$ the anomalies are reduced to about 4 percent of $T_F - T_M$. In deep holes where $T_F - T_M$ may reach 70°, this represents 3°, which is easily measurable with good accuracy.

In the top section of deep holes the temperature decreases, instead of increasing, after mud circulation is stopped. Nevertheless, the foregoing discussion and charts still apply provided the correct numerical values are used.

Influence of Convection

The graphs of Figure 5-4 were obtained with the assumption that heat transfer takes place between mud and formation only. Actually, because of the temperature differences existing between two adjacent hole sections having a different diameter, there is also some heat transfer by convection and conduction between these points, and the temperatures observed are slightly different from the values given by the graphs X and Y. They are comprised between these graphs, but the divergence is extremely small during the first hours. It becomes important only after 24 to 36 hours. After about 48 hours, depending upon conditions, the depth-temperature graph becomes generally so smooth that it does not permit locating formation boundaries unless the shales exhibit a considerable degree of caving, or unless the various beds in contact are very thick.

From the graphs of Figure 5-4 it is possible to construct approximately the depth-temperature logs which would be obtained at regular time intervals after circulation ceased. An example of such hypothetical logs is shown on Figure 5-6. Actual measurements verify this result, at least qualitatively.

Influence of Other Factors

It has been assumed in the preceding discussion that the apparent formation temperature equals the true temperature. In reality, the formation close to the bore hole is subjected for many days or weeks to the thermal influence of the mud stream. Its temperature is therefore different from the true formation temperature. For example, in horizontal sediments the isogeotherms in the vicinity of the bore hole are not horizontal but they are considerably warped as shown schematically by Figure 5-7. The result is that graph F of Figure 5-1 no longer represents the limiting mud temperature. The latter should be represented by a graph having a smaller slope and a slightly different shape. The mud temperature reaches asymptotically the apparent formation temperature which, in turn, reaches asymptotically the true formation temperature. Nevertheless, the time-temperature distribution discussed above would still be qualitatively the same.

A few other factors play also a certain part in the temperature changes observed in rotary holes, for example:

1. The specific heat of the drilling fluid, which is greater for water base mud than for oil base mud,
2. The specific heat of the formation, which is usually greater for sands than for shales,
3. The heat conductivity of the formation, which is also greater for sands than for shales,

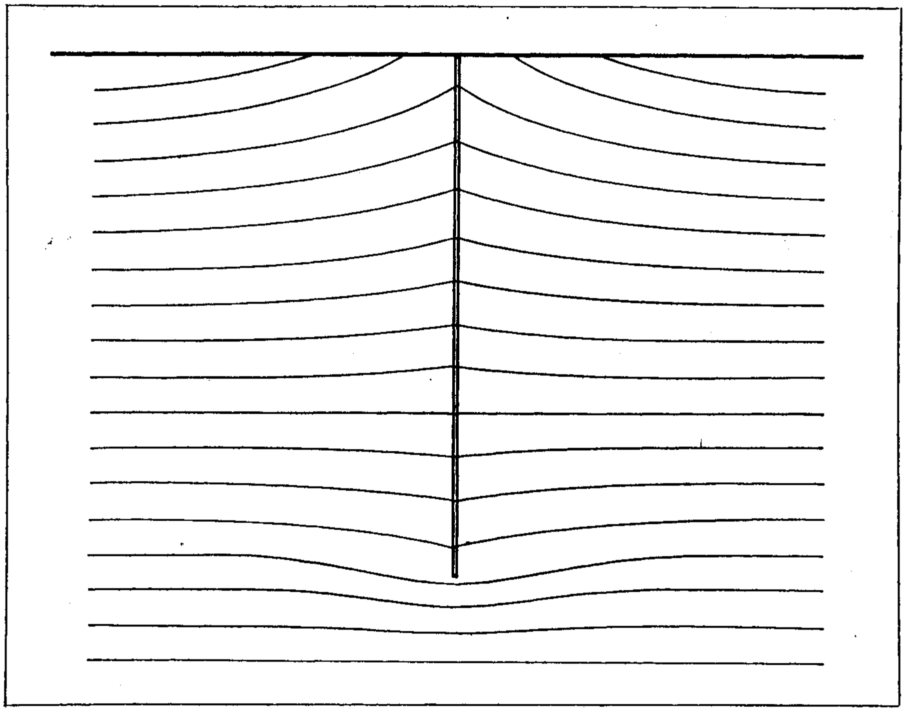

Figure 5-7. Vertical cross-section of isogeothermal pattern in the vicinity of a rotary well (estimated).

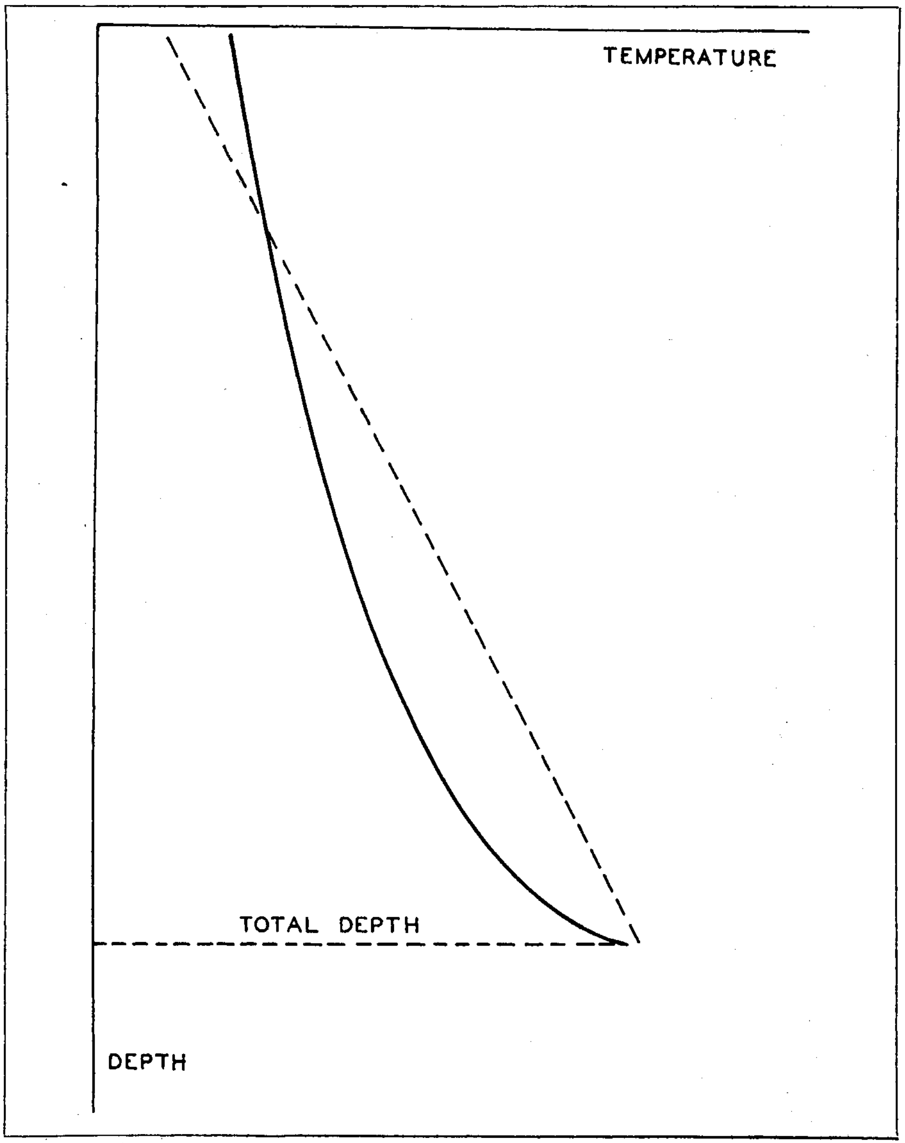

Figure 5-8. Approximate mud temperature graph in a rotary hole drilled at a relatively fast rate.

4. The heat evolved by friction of the bit and drill pipes,
5. Chemical reactions between mud and formation.

The effect of (2) and (3) is usually to increase the temperature anomalies caused by hole diameter changes but it is probable that these effects are very small as evidenced by the extremely small anomalies observed in wells where shales do not cave appreciably.

The effect of factors (4) and (5) is generally small also. It may account for part of the abnormally high mud temperatures found in the bottom section of rotary holes (see Figure 5-8). It is probable, however, that a large part of this high temperature is due to the fact that the bottom formations have not been subjected for a long time to the cooling effect of the mud stream. Their temperature is much greater than higher up, and the transitional temperature of the mud must therefore be much greater than at some short distance above.

It should be finally noted that the change in the slope of a depth-temperature graph observed at formation boundaries in wells which are in thermal equilibrium (see part 4 of this series) does not exist on a transitional temperature curve. This effect is entirely dominated by the influences discussed above.

Shallow Holes

The relative position of graphs F and M is not necessarily as shown on Figure 5-1. For instance, if a relatively shallow hole is drilled in very cold weather, the mud temperature may remain less than the formation temperature in the whole section penetrated. In this case, the mud temperature opposite sands is greater than opposite caving shales, although the well is very shallow (Figure 5-9). Of course, this result will be found only if shales cave more than sands. If the opposite condition exists, the temperature opposite sands is evidently less than opposite shales.

Cased Holes

The temperature anomalies which exist in an open hole are found also when the measurements are made after the well is cased, and even when the casing is cemented.

In the sections which are cased but not cemented, the condition is very similar to that existing in open hole. The only difference is that part of the mud or water is inside the pipe while the other part is outside. But, because of the relatively great heat conductivity of steel, the casing does not impede the heat transfer from the inside mud to the outside mud, and from there to the formation. The resulting temperature graph cannot be much different from that which would have been obtained in open hole under the same conditions.

In holes which are cased and cemented, the situation is different, although the result remains about the same. In the sections which had cavities when the well was still open, there is considerably more cement than where the hole was to gauge. Now, Portland Cement has a somewhat smaller heat conductivity than ordinary sediments (1 to 2×10^{-3}C.G.S.). It will therefore impede to some extent the exchange of heat between the fluid in the hole and the formation outside. The greater the amount of cement, the slower will be this exchange of heat. In

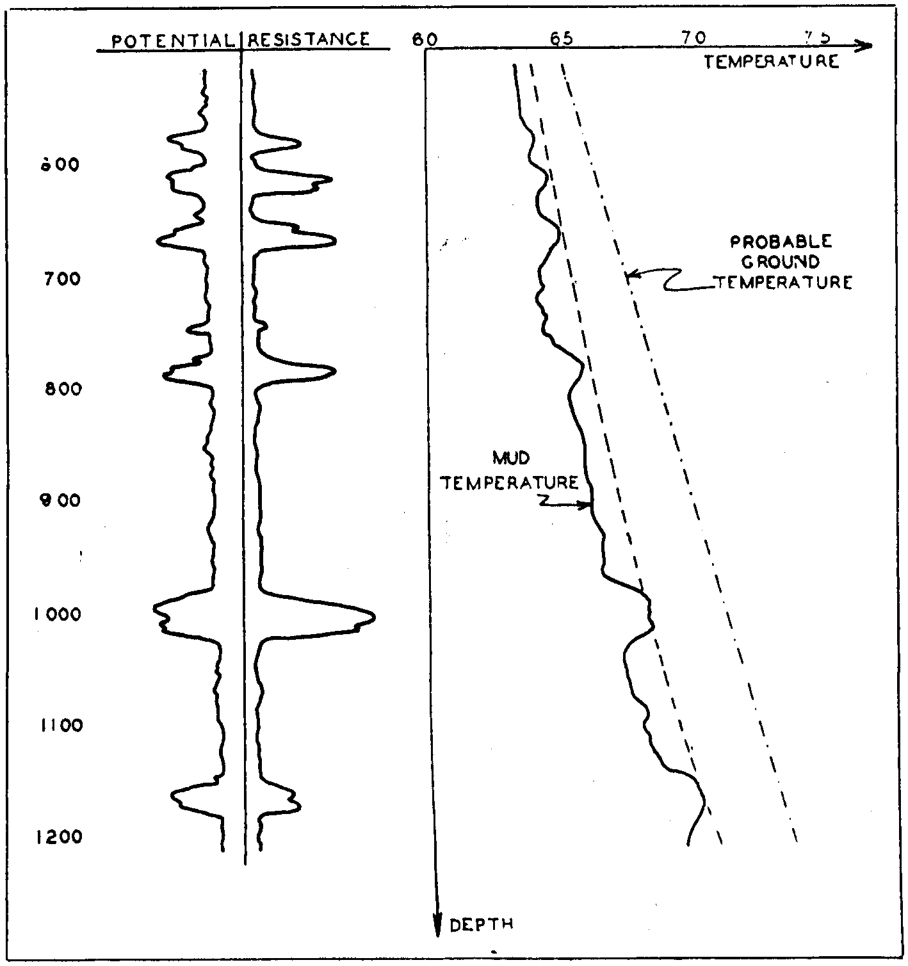

Figure 5-9. Electric log and temperature log of a shallow hole (South Texas).

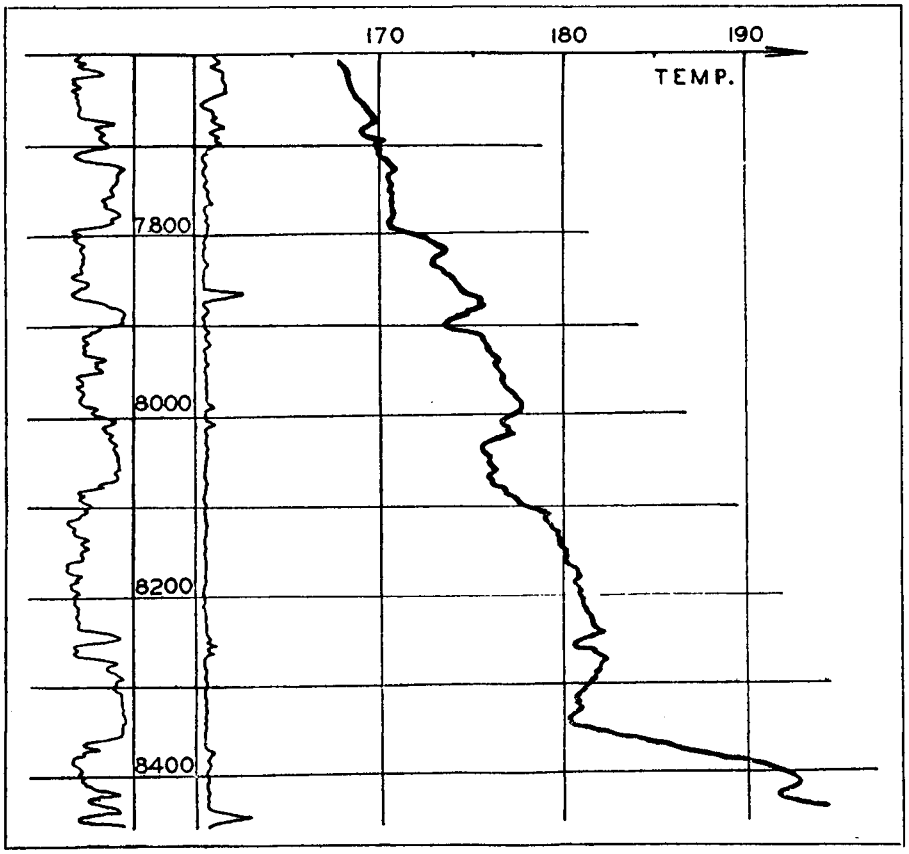

Figure 5-10. Electric log and temperature log from a Lake Peigneur well (Louisiana Gulf Coast).

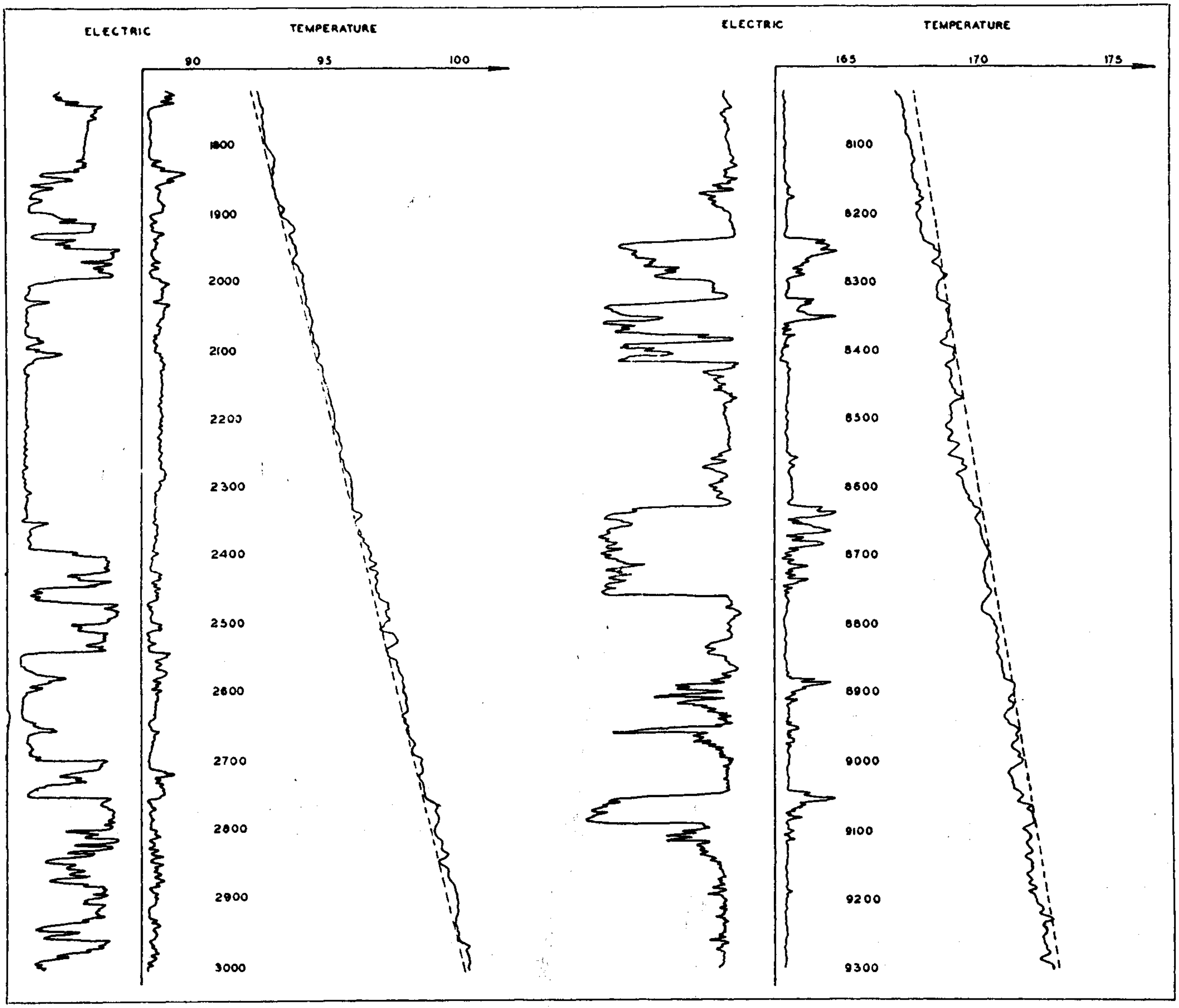

Figure 5-11. Electric log and temperature log from a well of Quarantine Bay field (South Louisiana).

Courtesy Gulf Oil Corporation

the bottom part of the hole, for example, the transitional temperature will be less than normal opposite the sections containing large amounts of cement. When it is remembered that the latter correspond to those sections which exhibited some caving when the hole was still open, it will be appreciated that, qualitatively, the transitional temperatures in open holes and in cemented holes are analogous.

From the logs available it is felt that the transitional temperature anomalies are somewhat greater in wells containing a cemented string of pipe than in open holes, all other factors remaining the same.

Figure 5-10 represents the temperature log of a section of a cased hole in South Louisiana. By comparing this graph to the electric log given also, it can be seen that relatively large temperature differences exist between sands and shales.

Limitations of the Method

The foregoing presentation may leave the impression that transitional temperature measurements are well adapted to the logging of wells, either open or cased. Although this is correct to a certain extent, the method has a few limitations which sometimes prohibit its use.

1. It has been explained that transitional temperature anomalies are primarily caused by changes in the size of the hole. If the physical characteristics of the formations drilled, or the drilling method, are such that the diameter of the hole does not change much from bed to bed, the temperature anomalies are small and the interpretation of the log is very difficult. For example, referring to Figure 5-11 it can be seen that the temperature changes from sand to shale are not always significant. If no electric log were available, the temperature data alone would not be very reliable for the location of sands or shales. On the other hand, if the shales traversed cave consistently, a temperature log may be as reliable as a caliper log or a potential graph in many sections of the hole (Figure 5-10). In general, shales of Eocene age or older cave appreciably and can be located by transitional temperature measurements. Younger shales cave irregularly, and the resulting temperature data are frequently unreliable.

2. If formation changes are accompanied by appreciable hole diameter changes, the method can be applied successfully except in the center section where graphs M and F of Figure 5-1 are close together. This inactive section is usually 1500 to 2500 feet thick. Of course, a second temperature run can be made under different thermal conditions in order to bring the new pivotal point P several thousand feet higher or lower than it was during the first run. From the two runs it is then possible to obtain a complete log of the hole. This procedure is evidently time consuming and may be objectionable in certain instances. A similar remark can be made regarding the bottom section of rotary holes being drilled at a rather high speed (see Figure 5-8) in which the mud temperature is not very different from the formation temperature.

3. From Figure 5-4 it can be seen that transitional temperatures favorable for

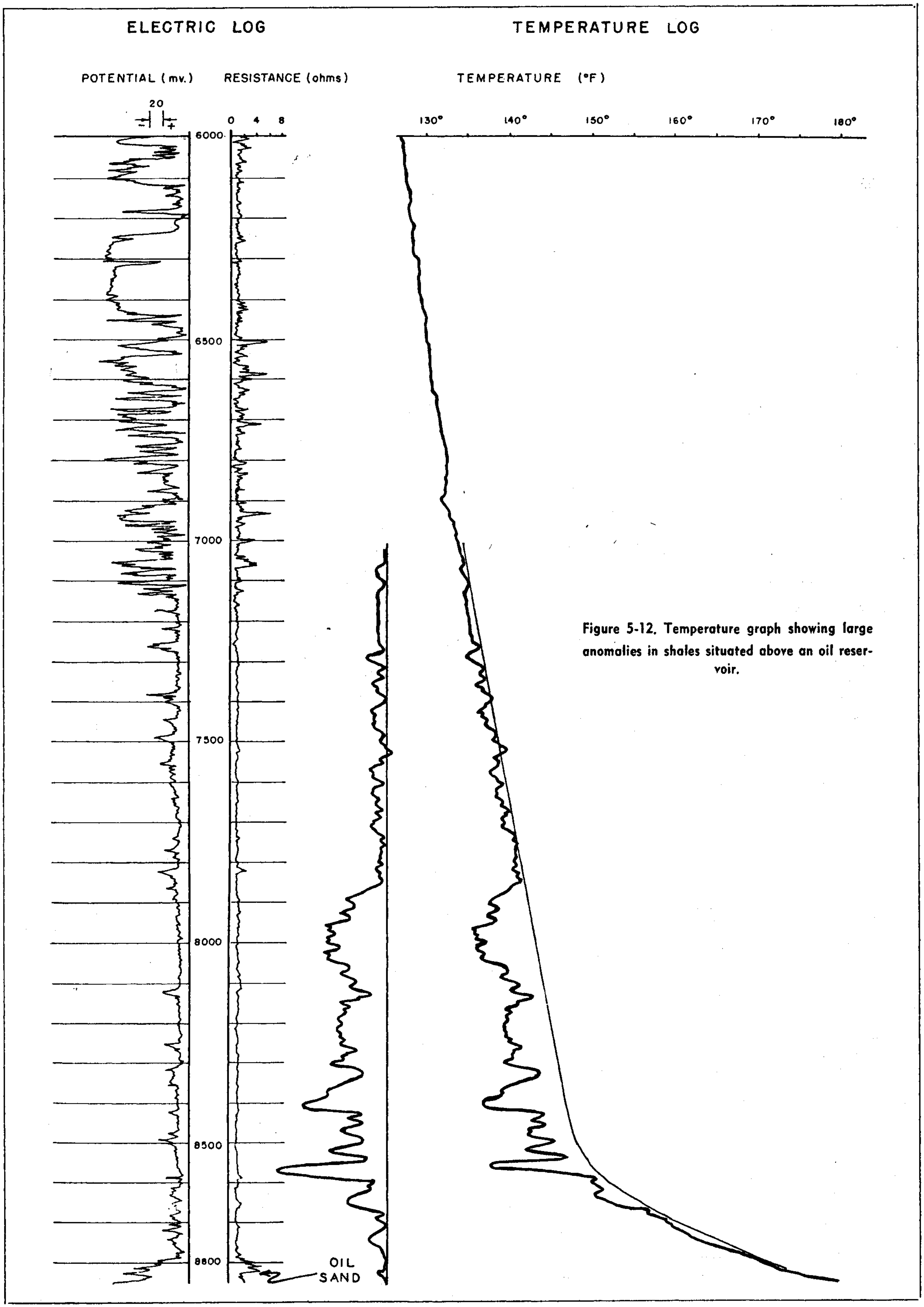

Figure 5-12. Temperature graph showing large anomalies in shales situated above an oil reservoir.

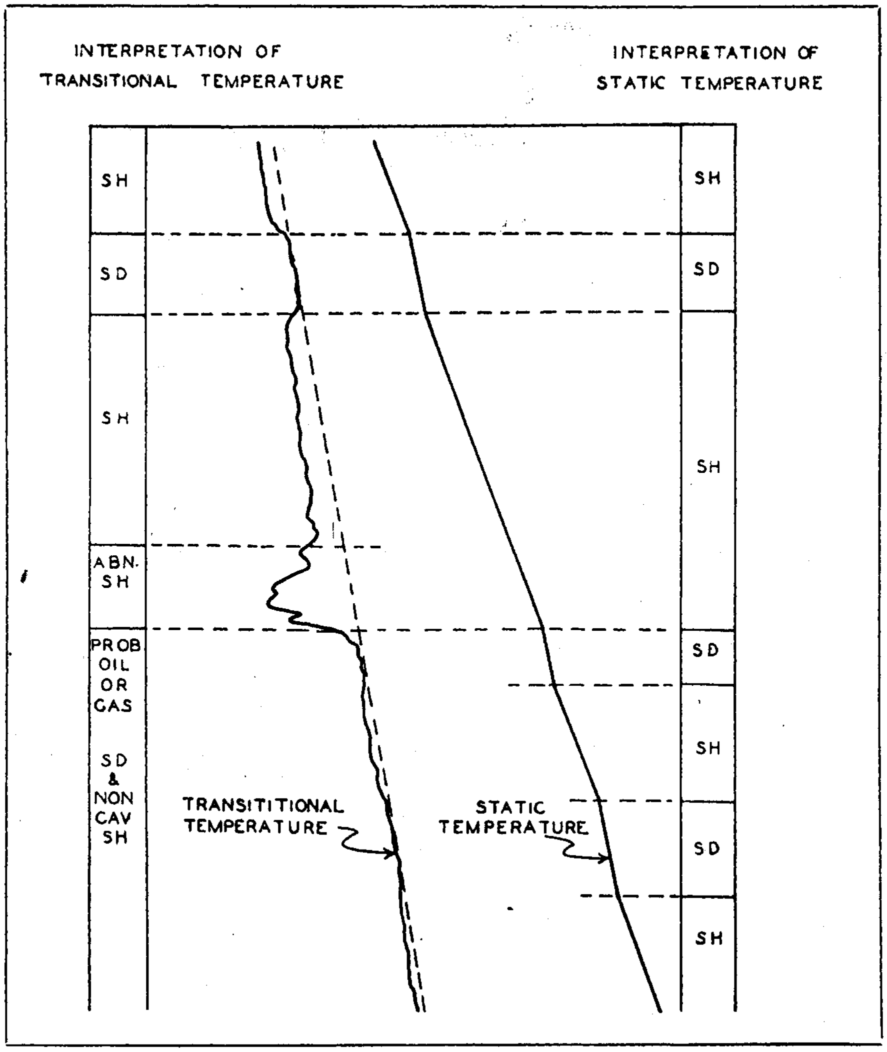

Figure 5-13. Interpretation of temperature data.

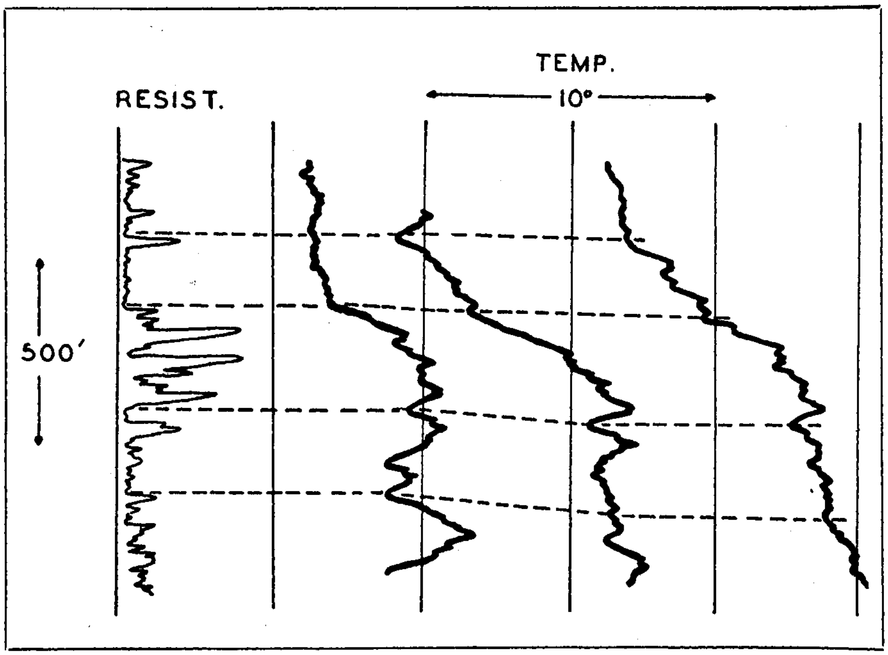

Figure 5-14. Transitional temperature graphs of three wells of the Rodessa field (Louisiana), showing good correlation in the anhydrite section.

After Deussen & Guyod, courtesy AAPG

logging are found from a few hours up to about 24 hours after circulation is discontinued. Measurements made later give a log which is sometimes so flat that formation boundaries cannot be picked unless there is considerable caving in shales.

To summarize, a transitional temperature log is, at best, a non-calibrated caliper log. In open holes, it cannot compete technically with an electric log or a caliper log. In cased holes, it usually cannot compete with a radioactivity log except in certain areas where radioactivity interferences exist. On the other hand, when electric logs, or radioactivity logs cannot be used, transitional temperature logs have a real value.

Abnormal Shales

Shales associated with petroleum reservoirs frequently cave to a much greater degree than those interbedded with water bearing formations[2]. These abnormal shales vary in thickness from a few feet to several hundred feet. A transitional temperature graph having penetrated this type of shale, for example, at a depth greater than 3 or 4000 feet, will exhibit an abnormally low temperature in the corresponding section. An example is represented on Figure 5-12 where the electric log shows an oil sand at 8800 feet and oil bearing shaley sands above. It can be seen from the temperature log that extremely large cavities exist in the shale section situated above the petroleum reservoirs. To illustrate this more clearly, the resulting temperature anomaly has been replotted with reference to a straight base line in the center column of the plat.

Temperature measurements can be made for the particular purpose of locating abnormal shales as an indirect method of finding petroleum reservoirs. However, it should be remarked again that, if the hole is still open, better results will probably be obtained from a caliper log. On the other hand, if the well is cased, a transitional temperature log can be of very great value. This graph, accompanied if possible, with a temperature graph made when the well is in thermal equilibrium (or with a radioactivity log) should frequently find petroleum reservoirs where no other known method would succeed. The hypothetical graphs of Figure 5-13 show how the data are interpreted.

Correlations

Since, under certain conditions, transitional temperature measurements can be used for logging, many formations can be correlated from well to well by means of temperature graphs made under proper conditions. Figure 5-14 is a plot showing the temperature logs made in the anhydrite section of three wells of the Rodessa field, North Louisiana.

Conclusion

At present, it seems that transitional temperature logs in uncased rotary holes have almost no practical value if other types of logs are available. In cased holes, they are very useful in several instances, in particular if abnormal caving exists above petroleum reservoirs.

The data presented in this artice, although not always quantitatively correct, are nevertheless representative of the usual thermal conditions existing in rotary holes.

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[1] Hubert Guyod, "Caliper Well Logging, Part 2," The Oil Weekly, September 3, 1945.

[2] Hubert Guyod, "Caliper Well Logging, Part 3," The Oil Weekly, September 10, 1945.