Part 4

Temperature

Wells in Thermal Equilibrium

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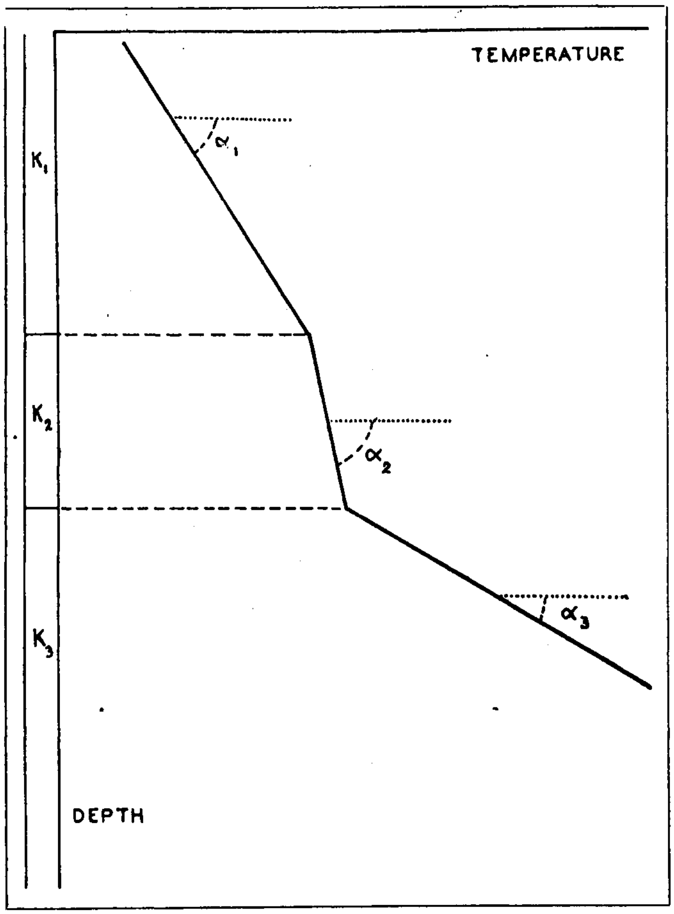

Figure 4-1. Logging of horizontal beds having different heat conductivity.

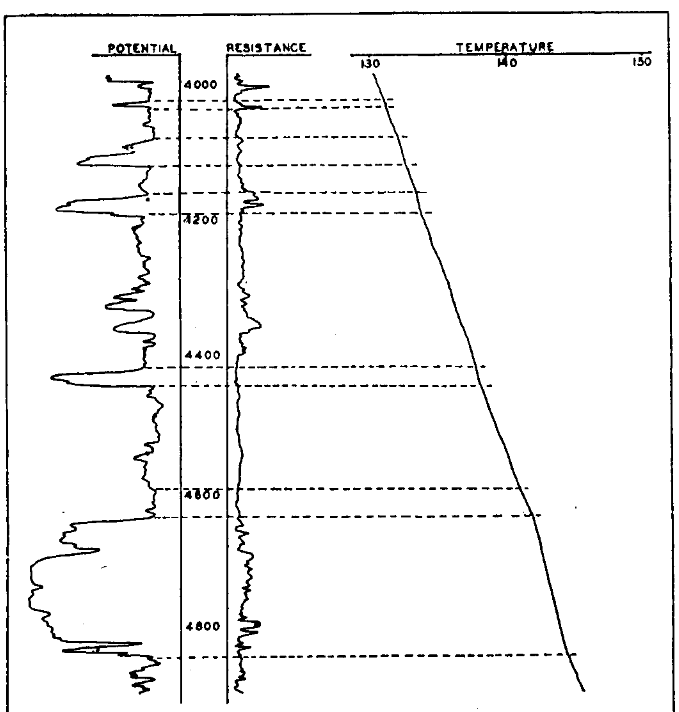

Figure 4-2. Electric log and temperature log in a well in thermal equilibrium (Dickinson field, Texas.)
Courtesy Humble Oil & Refining Company.

AS FAR as temperature logging is concerned wells can be classified into the two following groups:

1. Wells which are in thermal equilibrium. The temperature in such wells will be termed "static."
2. Wells which are not in thermal equilibrium. The temperature in these wells will be termed "transitional."

Only wells of the first group will be considered in the present article. These comprise primarily:

a. Cable tool wells at almost any stage of the drilling period,
b. Rotary holes which have been idle for a few months,
c. Producing wells which have been shut down for an appreciable time (several months).

The type of well considered is immaterial because, when the fluids situated in the hole are in thermal equilibrium with the adjacent formation, the temperature in the hole is dependent almost exclusively upon the temperature of the ground.

Effect of Casing Negligible

Since many of the wells in which temperature measurements are taken are cased, it is advisable to investigate to what extent the casing modifies the temperature of the ground.

The heat conductivity of steel is much greater than that of sediments and other rocks. A conventional steel casing will therefore modify locally the temperature distribution of the ground. A simple calculation shows that the effect of a casing of average size containing water or mud is the same as that of a uniform cylinder whose diameter is equal to the casing diameter and whose heat conductivity is of the order of 30×10^{-3} C.G.S., namely about ten times as high as the average conductivity of sediments.

Measurements conducted on a scale model have shown that the presence of such a cylinder does not modify the ground temperature, except perhaps very close to the pipe (at a distance less than 20 feet) where no definite data could be secured because of the smallness of the model (1" = 400'). Data are also lacking on the temperature of the fluid inside the casing. However, it is probable that the temperature of this fluid is modified qualitatively as follows:

In the bottom half of the casing the temperature is somewhat less than normal. Near the top of the casing, the temperature is slightly greater than normal.

The foregoing statements are based on the fact that, basically, a casing is similar to a very conductive salt dome turned upside down. Therefore, the isogeothermal pattern inside a casing must be, in some respects, similar to the pattern obtained in a salt plug (see Part 2 of this series). How much the presence of the casing modifies the temperature of the fluid situated inside is not known

WELL LOGGING

BECAUSE the heat conductivity of sediments varies from bed to bed, there is a geothermal gradient change at each formation boundary. Temperature measurements made in wells which are reasonably in thermal equilibrium can be used for logging formations, even if the well is cased.

but it is presumed that the resulting temperature anomaly must be very small.

Regardless of the magnitude of this anomaly, it is certain that the general trend of a depth-temperature graph taken in a casing is qualitatively identical to that of a graph obtained far from it. In particular, the two graphs exhibit breaks, or other gradient changes, at exactly the same geologic levels.

Similar remarks can be made regarding the effect of cement, mud invasion, etc., behind the pipe. The influence of these factors is very small and most likely negligible.

Typical Temperature Logs

From the foregoing discussion it is evident that the influence of the casing may be disregarded unless, perhaps, extremely accurate absolute temperature measurements are required. Such accuracy is not necessary for logging purposes.

It has been explained (Part 1 of the series) that, in horizontal sediments and far from intrusions, the depth-temperature graph consists of straight sections whose slopes vary from bed to bed. If α designates the angle of slope (Figure 4-1) then

$$\tan \alpha = CK$$

where K is the heat conductivity of the bed, and C a constant whose value depends upon the scales of the graph.

The slope of a temperature graph is greater for good heat conductors than for poor conductors. Since the heat conductivity of the ground varies from bed to bed, a temperature log made in a well which is in thermal equilibrium exhibits breaks at the level of each boundary. This is illustrated on Figure 4-2 which represents the temperature log of a well near the Dickinson oil field (Galveston County, Texas). By comparing this record to the potential graph of the electrical log plotted to the left, it can be seen that the slope of the graph is significantly greater in sands than in shales. However, where the beds are thin (less than about five feet) the change in slope usually cannot be seen because the logging speed was too great (about two feet per second). If this graph had been recorded for the particular purpose of logging the formations traversed by the well, there is no doubt it would have shown a change of slope for each bed more than about two feet thick. When it is remembered that the temperature distribution in the ground obeys Fourier's law, it cannot be doubted that the temperature gradient breaks sharply at each formation boundary, even when the thickness of the beds involved is only a fraction of an inch.

This sudden change in temperature gradient from bed to bed is different from the smooth changes obtained in

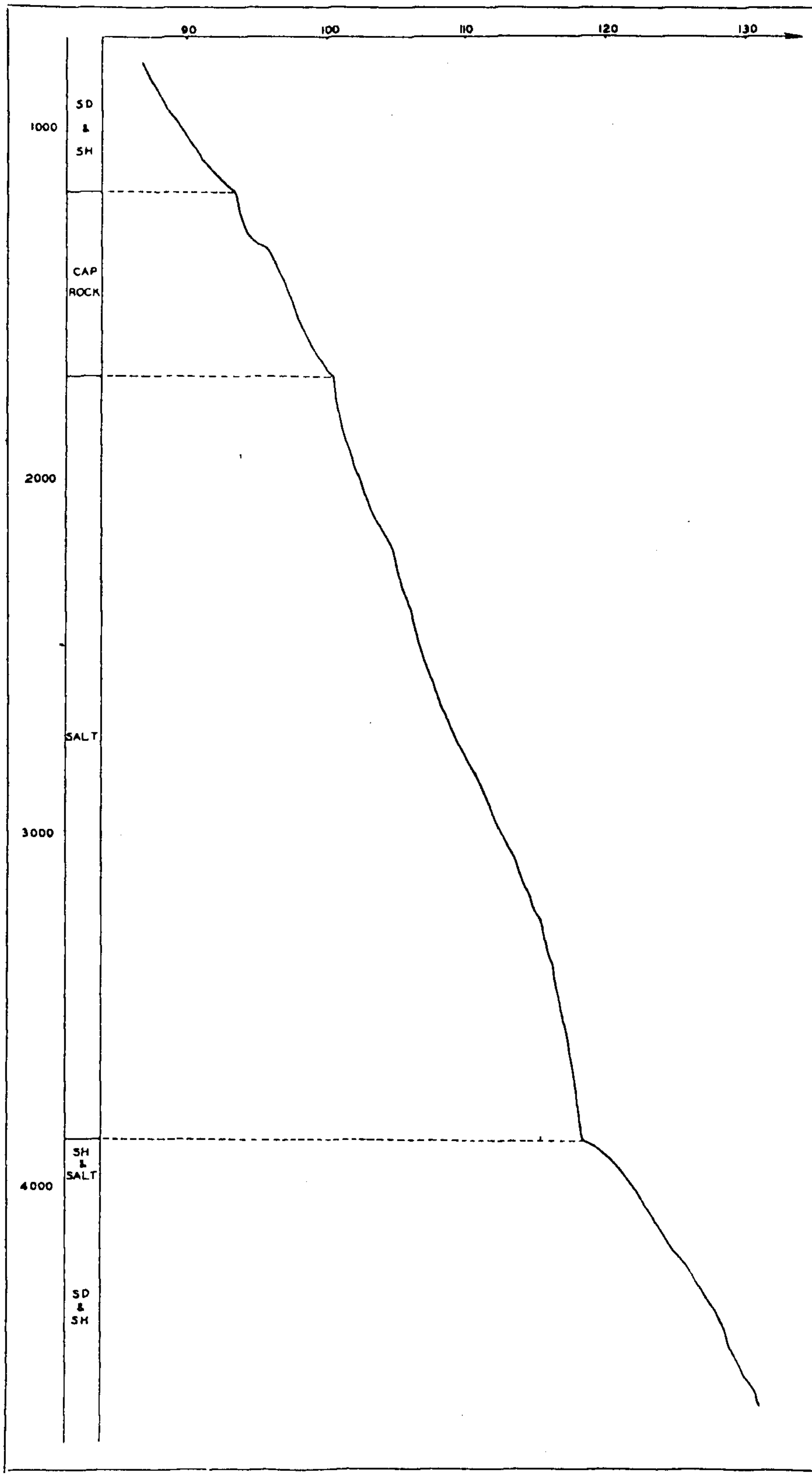

Figure 4-3. Temperature graph obtained in a Gulf Coast well having penetrated a salt overhang.

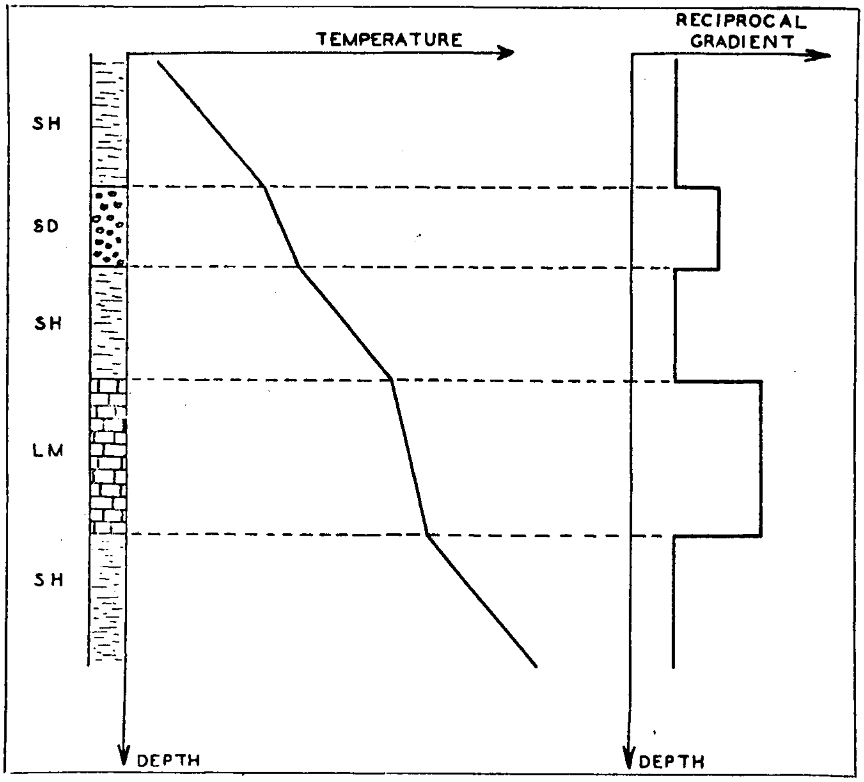

Figure 4-4. Temperature graph and corresponding reciprocal-gradient graph.

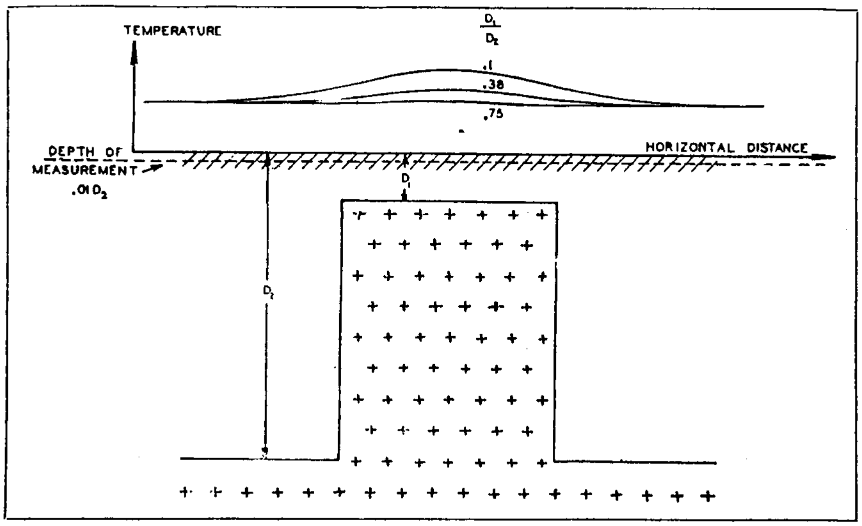

Figure 4-5. Horizontal temperature changes above salt domes of various depths (scale model data).

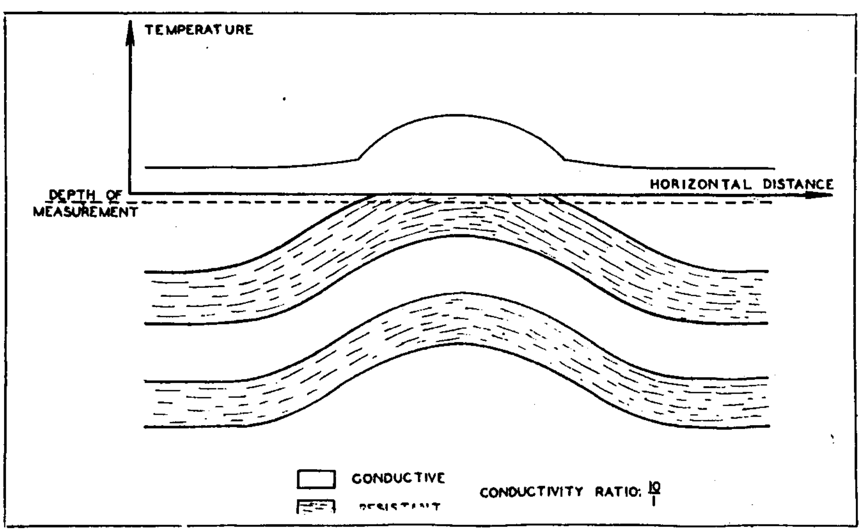

Figure 4-6. Horizontal temperature changes near an anticline comprising heat-resistant beds (scale model data).

electrical logging. The difference is due to the two following facts:

1. The heat flow pattern in the ground is entirely different from the electric flow pattern artificially produced for resistivity logging.
2. Resistivity measurements are averaged on several feet (the distance between pickup electrodes) while temperature measurements are taken at one point (more exactly, they are averaged over the length of the thermometer which is always small: usually a few inches).

Figure 4-3 is a temperature log obtained in a Gulf Coast well having penetrated a salt overhang. The top of the cap rock and the bottom of the salt are sharply indicated by changes in slope. The anomaly at 1300-1350 corresponds to cavities reported by the driller (causing perhaps some circulation of water although the well was cased at the time the measurements were taken). The numerous slope changes found in the salt section are due to a lack of uniformity within the salt. This is possibly caused by impurities and/or by the anisotropy created by folding.

Gradient Graph

A shortcoming of depth-temperature graphs is that the breaks, i.e. the formation boundaries, are difficult to pick from the log. A graph showing a discontinuity at each boundary would be more readily interpretable. This can be obtained by plotting the temperature gradient, or its reciprocal, in terms of depth instead of the temperature itself. For example, if the section being logged comprises sands, shales and a dense lime, the reciprocal gradient log would be as shown to the right of Figure 4-4. It is obvious that this graph is more readily interpretable than the equivalent temperature graph.

It has been explained that, in horizontal formations, the heat conductivity and the reciprocal gradient are proportional. Therefore, the graph to the right of Figure 4-4, if properly calibrated, is a conductivity log. Since the heat conductivity varies from one type of sediment to another, it is obvious that this graph not only can log formation changes, but it can even help identify many formations when enough local data are available.

If the sediments are not horizontal, or if the measurements are taken near intrusions or ridges, the reciprocal gradient graph does not give correct conductivity values. The "apparent conductivity" data thus obtained are nevertheless readily interpretable in almost every instance because the relative conductivity values are not appreciably modified.

Application

To summarize, continuous temperature measurements when properly made can be used to log wells, even cased ones. A temperature log, however, is not as versatile as an electric log and it is probable that it will not generally supplant the latter in open holes. Its main shortcomings are as follows:

1. It is probably of no value for detecting petroleum directly.
2. It does not permit formation identification as well as a multiple-curve electric log.

On the other hand, a temperature graph is extremely useful to log cased holes especially when the formation consists of relatively thick beds, or for correlation purposes. However, it will probably never give a record as detailed as that given by radioactivity measurements.

In short, temperature measurements can be used successfully for the logging of many cased holes, in particular when extreme detail is not imperative, or when radioactivity measurements are not available or when their price is prohibitive.

Shape of Temperature Graphs

It is difficult to predict the shape which a depth-temperature graph will have unless the nature of the formation considered is reasonably well known. When this information is available, it is not too difficult to estimate the general trend of the graph and conversely, from the trend of a temperature graph it is sometimes possible to draw a few conclusions regarding the nature of the formations either actually traversed, or situated nearby. For example, if the general direction of the graph is a straight line it can be assumed that the well is far from any dome or anticlinal ridge. If the graph is convex toward the temperature axis it is probable that the well is bottomed above a salt or igneous intrusion. Finally, if the graph is concave toward the temperature axis it is likely that the well was drilled near a conductive intrusion, or that the actual heat conductivity increases with depth. Such an increase is usually caused by the gradual compaction increase with depth observed in most sediments. (The heat conductivity increases slowly with temperature, i.e. with depth. This effect is very small and is generally dominated by the influence of the other factors.)

To summarize, a depth-temperature graph may have almost any shape and it is therefore dangerous to extrapolate it in order to estimate the temperature existing at relatively great depths, unless the nature of the formations in the area involved is reasonably well known.

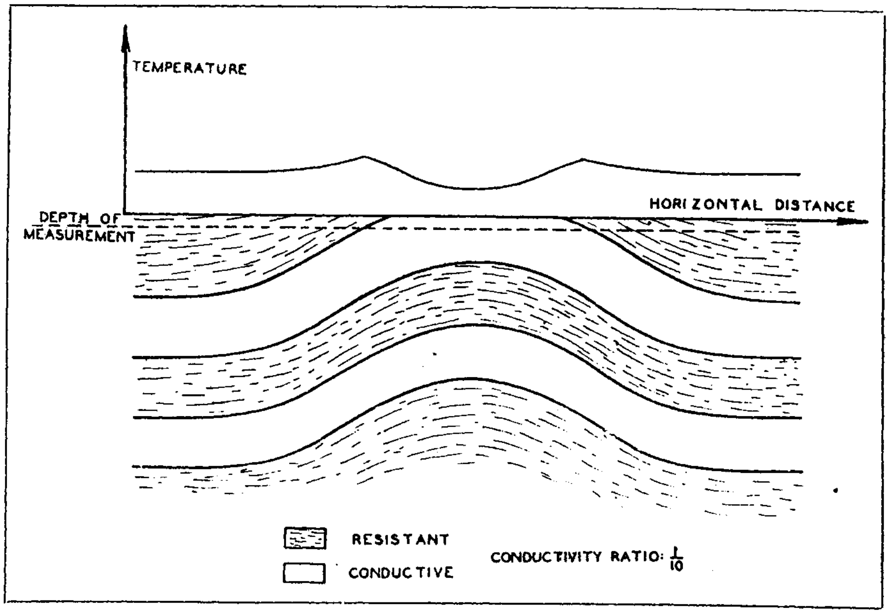

Figure 4-7. Horizontal temperature changes near an anticline comprising heat-conductive beds (scale model data).

Exploration

In the two preceding articles it has been seen that salt domes, anticlines, etc., modify the temperature distribution of sediments in every direction over large distances, and in particular near the surface of the ground. Therefore at any depth, even small, the temperature varies in a significant manner over structures, and the data can be used for exploration purposes. Because of its simplicity the method has been applied for years, in particular in petroliferous provinces.

The general method of interpretation used at present seems to be that anticlinal structures produce temperature highs, and conversely. It has been seen (part 3 of the series) that this is not generally correct and that certain types of anticlines produce a temperature low near the surface, while certain synclines result in a temperature high. In other words, a correct interpretation of the data is more elaborate than is usually realized.

Figures 4-5, 4-6 and 4-7 are typical horizontal temperature profiles obtained above various types of structures. These data are given only to illustrate the foregoing comments and should not be used quantitatively. Figure 4-5 gives data for salt domes whose relative depths are 1, .75 and .38, respectively. Figures 4-6 and 4-7 refer to anticlines.

A more elaborate discussion of the problem will be given at a later date when all the necessary information is assembled.

Location of Ore Deposits

Because of their high heat conductivity, many ore deposits modify appreciably the temperature distribution in the ground (see Part 3 of this series). If an exploratory well fails to penetrate the deposit but passes close by, there is a good possibility that a temperature graph will exhibit a significant anomaly permitting to determine the depth of the mineral. The more uniform the surrounding formation, the greater the resolving power of the method.

If the ore oxydizes in the ground, the heat evolved by chemical reaction further modifies the temperature distribution and the location of the mineral is appreciably facilitated. Graph A of Figure 4-8 is an hypothetical depth-temperature graph obtained in a well drilled near an ore deposit of high conductivity (10 times greater than that of the surrounding formation). Graph B is the graph which would be obtained if the same ore generates enough heat to raise its temperature about ten degrees.

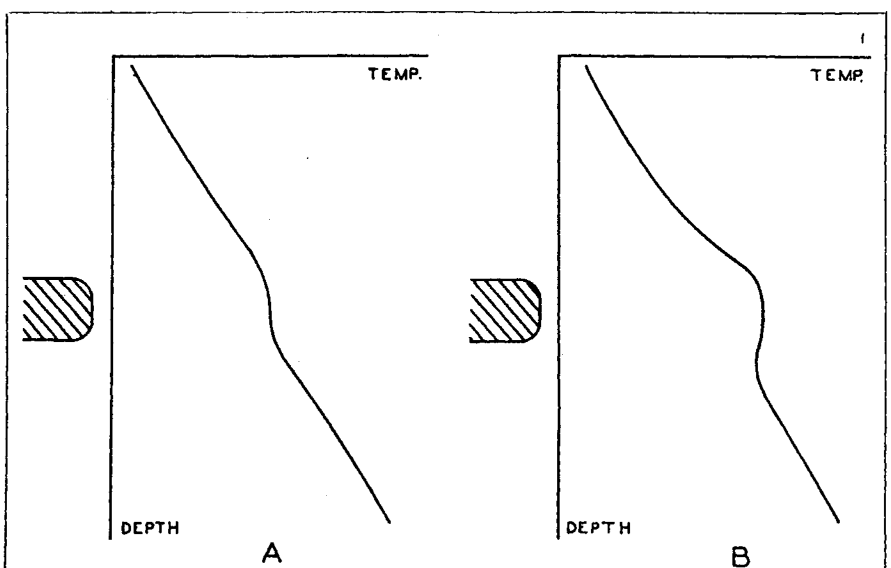

Figure 4-8. Depth-temperature graphs in the vicinity of an ore deposit. A. Ore does not generate heat. B. Ore generates heat.

Fourth of a series of seven articles based on research work sponsored by Halliburton Oil Well Cementing Company. Previous parts have appeared in THE OIL WEEKLY of October 21 and 28 and November 4.