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# Temperature

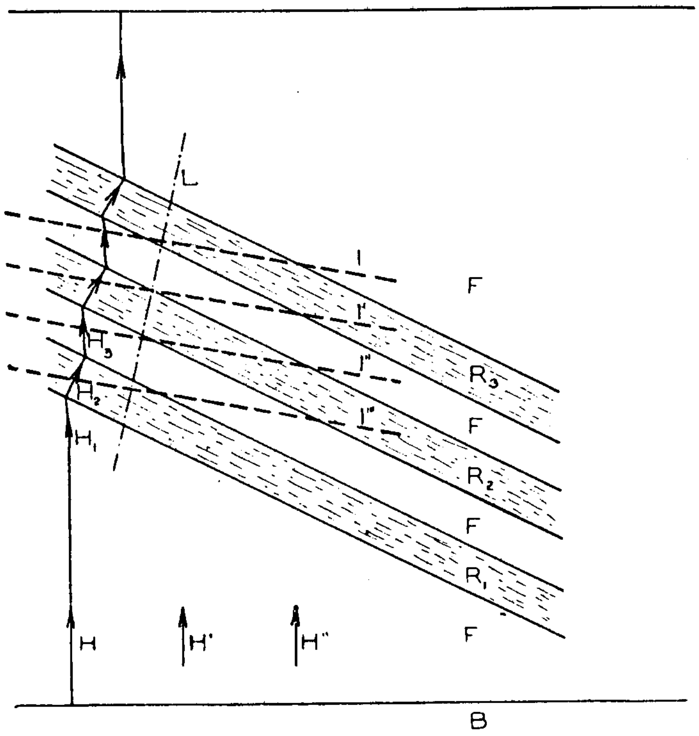

**Figure 3-1.** Illustration of heat flow in a heat-resistant monocline (estimated).

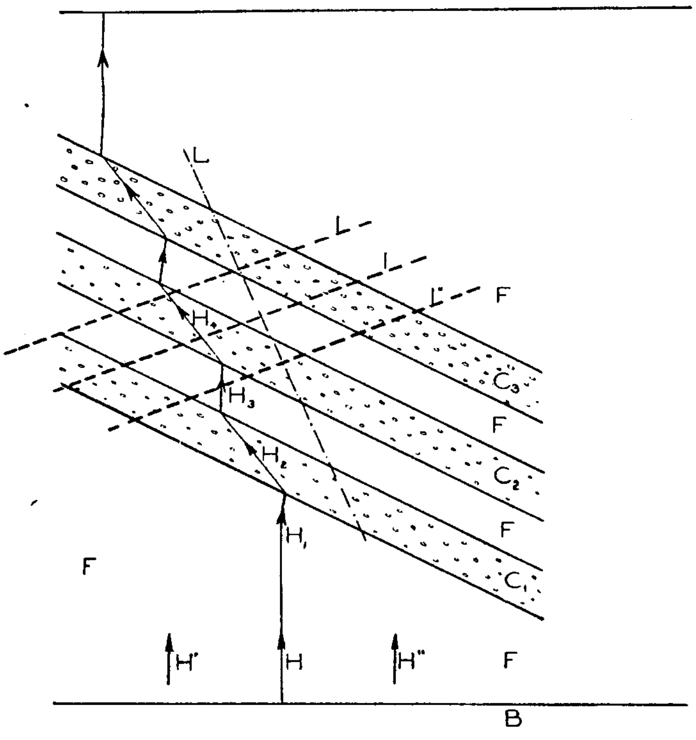

**Figure 3-2.** Illustration of heat flow in a heat-conductive monocline (estimated).

A GOOD procedure for visualizing the effect of dip on the temperature distribution in the ground is to use a simplified graphical method. This is based on the fact that isothermal surfaces are at right angles to the direction of heat flow.

While isotherms are usually difficult to determine directly by a graphical method, the flow lines are much easier to trace approximately by thinking in terms of fluid flow or electric flow. From the flow pattern thus obtained, the main isotherm direction can be readily obtained. This procedure will be used to investigate the two following types of monoclinal structures:

1. A formation F (see Figure 3-1) containing a few resistant parallel and tilted beds $R_1$, $R_2$ and $R_3$. These beds are assumed to have the same thickness T and their interval equals T also, for simplicity. F is, for instance, ten times more conductive than beds R. This conductivity ratio is abnormally high and probably never found in practice, but it has been selected in order to more clearly understand how the heat flows in this type of monocline.
2. A geometrically identical monocline in which the tilted beds, $C_1$, $C_2$ and $C_3$ are ten times as conductive as formation F (Figure 3-2).

### Resistant Monocline

Referring to Figure 3-1, the flow lines coming from the horizontal basement rock B are shown as the vertical arrows H, H', H'' etc. When one of these lines, H for example, nears resistant bed $R_1$ it is slightly distorted to the left (arrow $H_1$). This is analogous to the electrical current distortion (dodging effect) observed in electrical logging near the boundary of two formations having different resistivities.[1]

Inside resistant bed $R_1$, the flow seeks the path of least resistance, which evidently is the shortest distance between the two faces of the resistant bed; the flow line is therefore appreciably shifted to the right (arrow $H_2$). After bed $R_1$ is crossed, the heat resumes approximately its normal direction of travel, i.e., it flows vertically (arrow $H_3$). Then when the flow line crosses beds $R_2$ and $R_3$ its direction is exactly as it was in bed $R_1$.

It is evident from an examination of the figure that the presence of the resistant beds results in a shifting to the right of the mean line L of heat flow. The general direction of the isogeotherms, which is perpendicular to the general direction of flow, is therefore tilted also, as shown by lines I, I', I'' etc. The direction of the isogeotherms is therefore the same as that of the formation, but the slope angle of the iso-

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This is the third of a series of seven articles, based upon research work sponsored by Halliburton Oil Well Cementing Company. Parts 1 and 2 appeared in THE OIL WEEKLY of October 21 and 28, respectively.

# WELL LOGGING

## *Part 3*

### Temperature Distribution in the Ground

TEMPERATURE distribution in the ground is controlled primarily by the heat conductivity and by the geometry of the formations. The influence of these two factors on a few typical cases is explained in this article.

geotherms is less than the angle of formation dip.

Very far from beds R, the flow lines have almost their normal direction of travel and, in these areas, the isogeotherms are approximately horizontal.

The foregoing result has been verified by experimenting on electrolytic scale models. Figure 3-3, for example, represents a formation similar to that of Figure 3-1. The dash-lines are the equipotential lines actually determined on the model. As pointed out in a preceding article (Part 1), these lines simulate the isogeotherms of Figure 3-1. Their general direction is found to be as described above. The temperature interval between the isogeotherms shown on this figure is constant.

### Conductive Monocline

If formation F contains conductive beds instead of resistant beds, the general direction of the isogeotherms is different from that found above.

Referring to Figure 3-2, $C_1$, $C_2$, and $C_3$ are beds ten times as conductive as formation F. The heat flow coming from the horizontal basement rock B follows vertical paths until it nears bed $C_1$, at which time it is slightly deflected to the right (attracting effect). When the flow line enters bed $C_1$, which is much more conductive than F, it has a tendency to remain in $C_1$ (path of least resistance): therefore it travels as shown by arrow $H_2$, i.e., it is considerably deflected to the left. The end of the heat travel is self-explanatory and it is represented by arrows $H_3$, $H_4$, etc.

In the region containing beds C, the general direction L of the heat flow is tilted to the left. The mean direction of the isogeotherms—which is perpendicular to L—is therefore as shown by lines I, I', I'', etc. It dips in a direction opposite to that of the monocline.

This behavior has been verified on the electrolytic model shown on Figure 3-4 where the dash lines simulate the isogeotherms. The temperature interval between them is constant, except for the line marked (1).

From the foregoing it is easy to understand that the tilting of isogeotherms is great when the conductivity ratio of the sediments involved is great, and small when this ratio is small. This tilting depends also upon the thickness of formation F above and below the layers R or C, as well as upon the thickness and distance of these layers which, in practice, vary from bed to bed. Finally, the angle of formation dip has to be considered also.

### Influence of Dip Angle

In horizontal or nearly horizontal formations the isogeotherms are not appreciably warped, i. e. they are nearly horizontal. The same result obtains when the sediments are vertical or nearly so. The maximum isotherm dip is

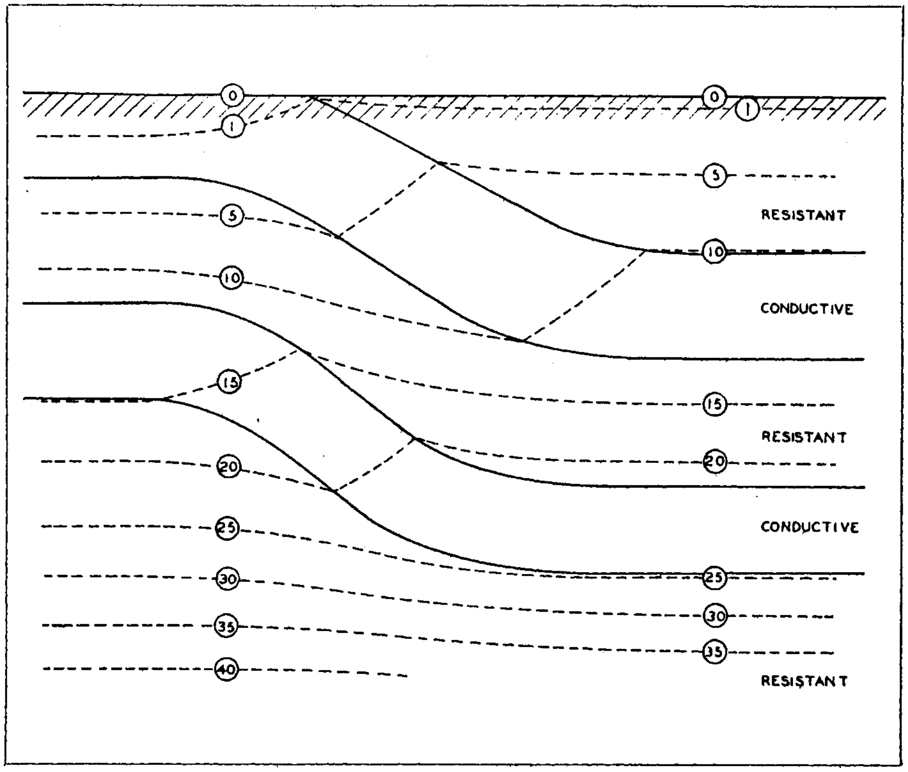

Figure 3-3. Isogeotherms in the vicinity of a heat-conductive monocline (scale model data).

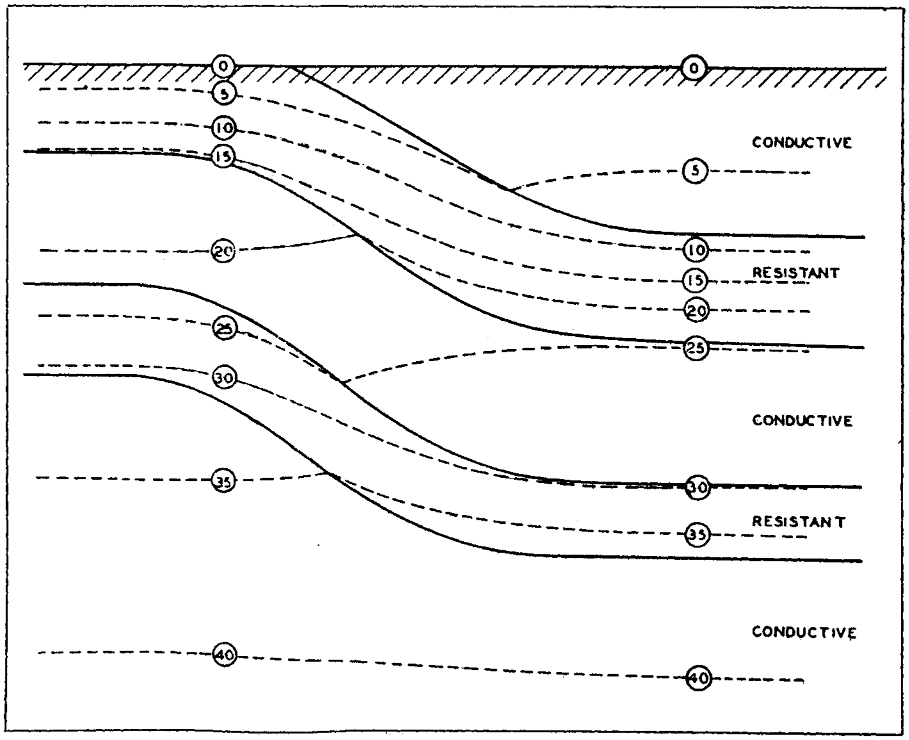

Figure 3-4. Isogeotherms in the vicinity of a heat-resistant monocline.

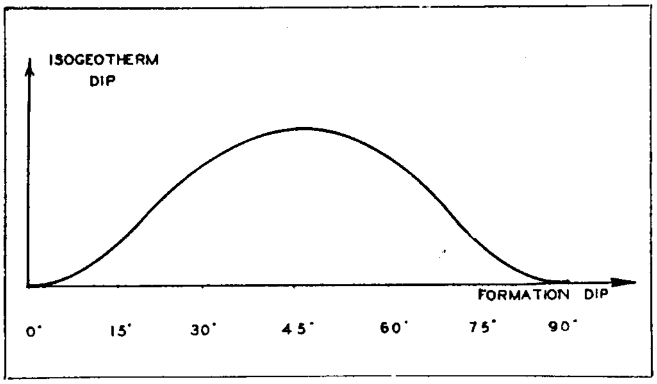

Figure 3-5. Relation between isogeotherm dip and formation dip (estimated).

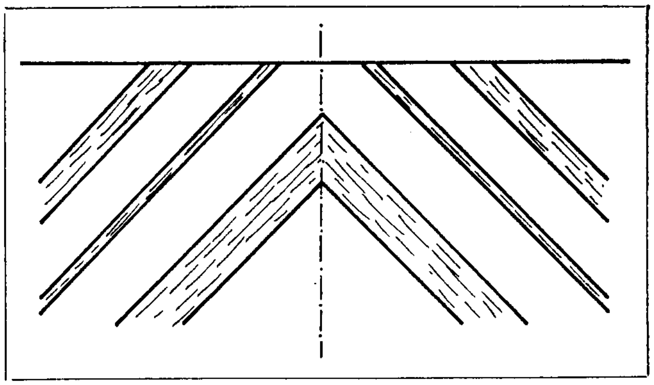

Figure 3-6. Anticline as a combination of two monoclines.

observed when the formation dip is in the neighborhood of 45° (see Figure 3-5), all other factors remaining the same.

The preceding figures refer to extremely large conductivity ratios (ten to one), for which a considerable distortion of the isogeotherms would exist. The actual ratios are much smaller. For example, for an alternation of shales and sands the ratio would be in the neighborhood of two, for which the mean isogeotherm distortion would be smaller than shown on the preceding figures, especially in sections where these two formations are roughly in equal amounts. On the other hand, if the section being investigated comprises shales and limes, the distortion will be greater (conductivity ratio: about three) especially if the angle of formation dip is comprised between 30 and 60°.

To summarize, the exact isogeothermal pattern in monoclinal structures is usually difficult to analyze because of the many factors involved, and a complete discussion of the problem cannot be offered here. For our purpose it will be sufficient to remember the two following results:

1. The isogeotherms can be either raised or lowered in the direction of formation dip, according to conditions.
2. The angle of isogeotherm dip is relatively small and is usually less than that caused by shallow salt domes, salt anticlines or other shallow intrusions. It is generally dominated by the effect of the latter factors. However, in the case of deep-seated intrusions, the influence of formation dip is frequently preponderant.

## Effect of Anisotropy

Many sediments are anisotropic: their heat conductivity—as well as their permeability and their electrical conductivity—is generally greater parallel to the strata than perpendicular thereto.

An anisotropic formation is actually an alternation of extremely thin beds having different heat conductivities. The effect of an anisotropic bed upon the temperature distribution in the ground is therefore identical, except for the scale, to the effect of an alternation of thick beds, such as those illustrated on Figures 3-1 and 3-2.

Shales are much more anisotropic than almost any other sediment and, as a first approximation, it can usually be assumed that all sediments, except shales, are not anisotropic.

It has been seen that shales are less conductive to heat than the other formations. Therefore, a tilted section comprising an anisotropic shale situated within a substantially isotropic formation is basically similar to the media shown on Figure 3-1.

## Anticlines

An anticline can be considered, in first approximation, as being an association of two monoclines which are symmetrical about a vertical plane (Figure 3-6). The temperature distribution in such a formation is readily obtained by combining the isogeotherms of the two component structures.

Figures 3-7 and 3-8, for example, represent the temperature distribution in two typical anticlines.

All that has been said regarding monoclines applies evidently to anticlines. In particular, the isogeotherms are either raised near the axis of the

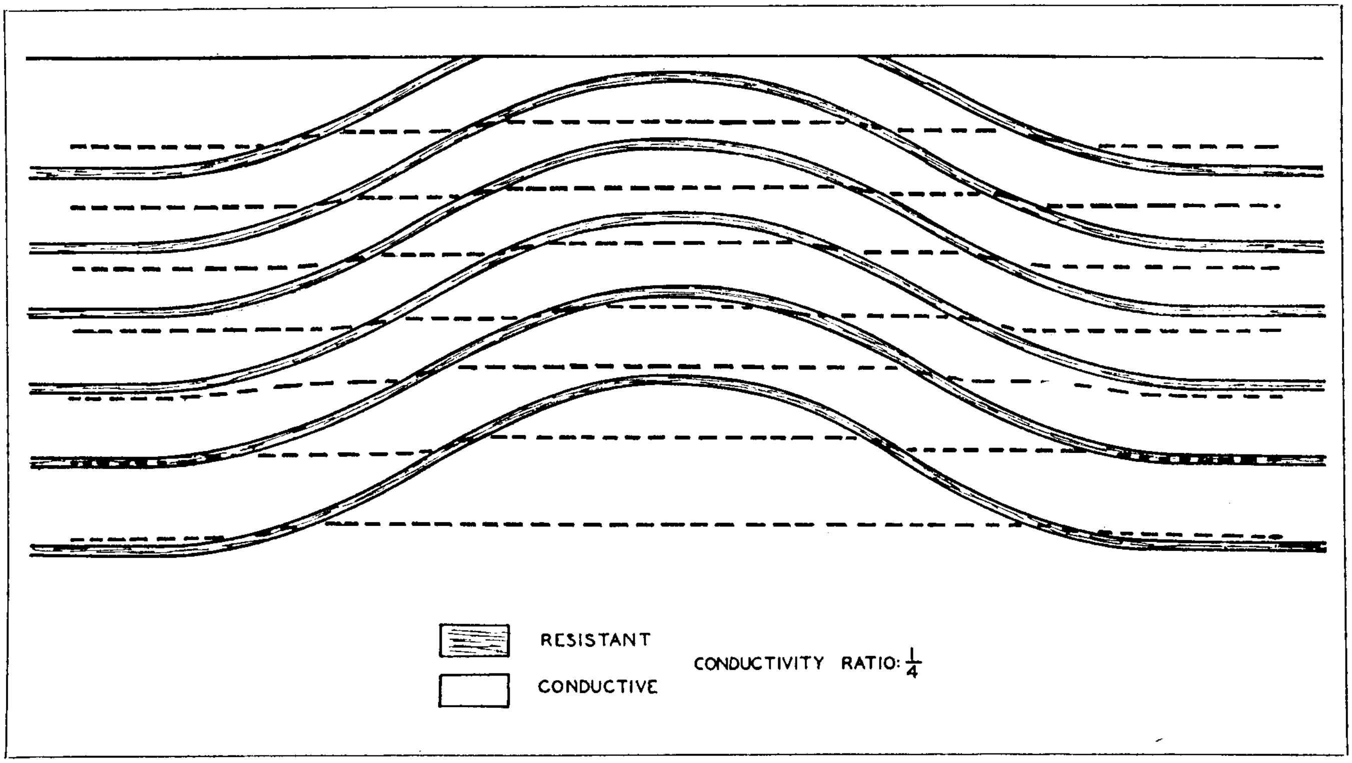

Figure 3-7. Isogeotherms in an anticline containing resistant layers (scale model data).

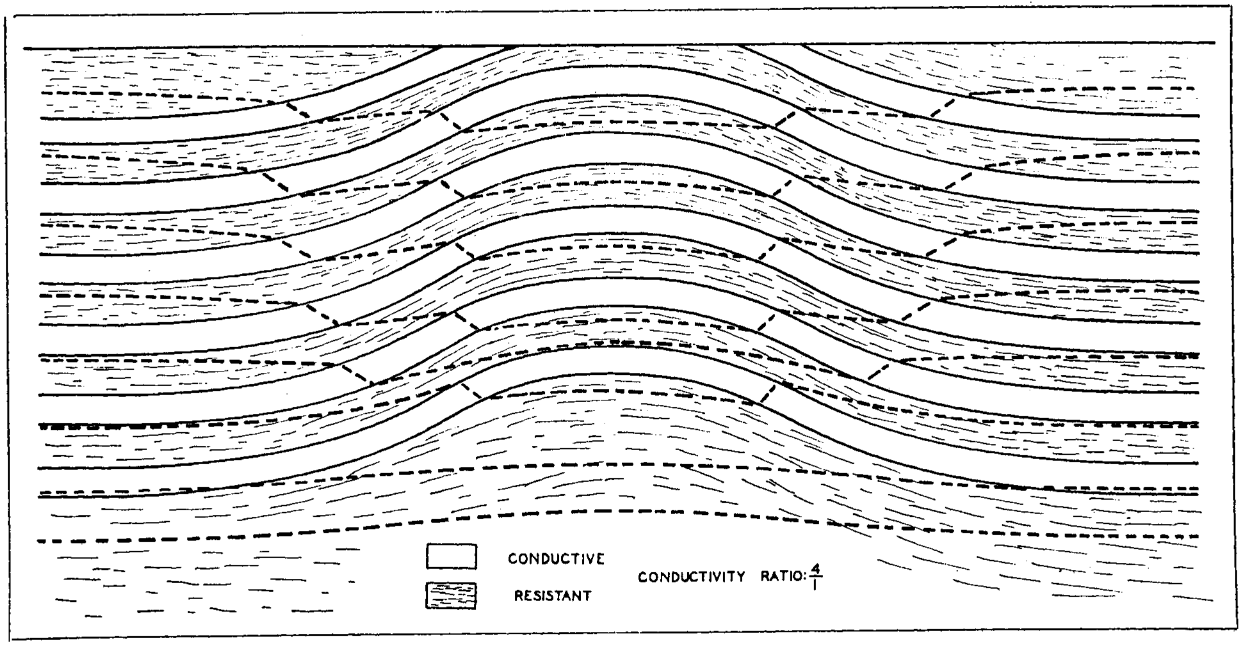

Figure 3-8. Isogeotherms in an anticline containing conductive layers (scale model data).

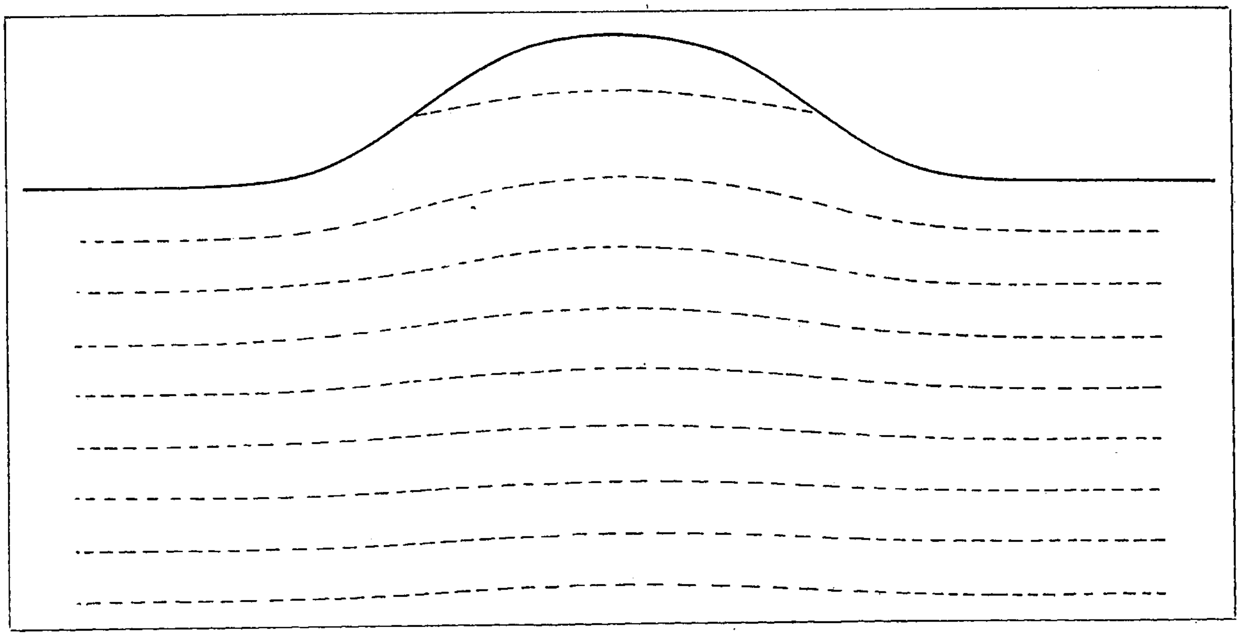

Figure 3-9. Isogeotherms in the vicinity of a topographic high (estimated).

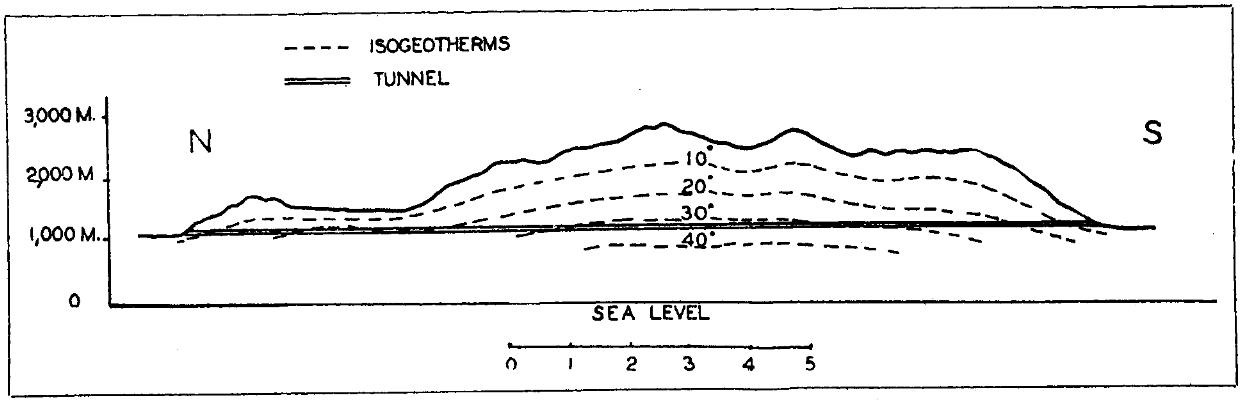

Figure 3-10. Isogeotherms in the mountain traversed in Saint-Gothard tunnel (data extrapolated).
After Albert Heim, "Der Mechanismus der Gebirgsbildung," 1878.

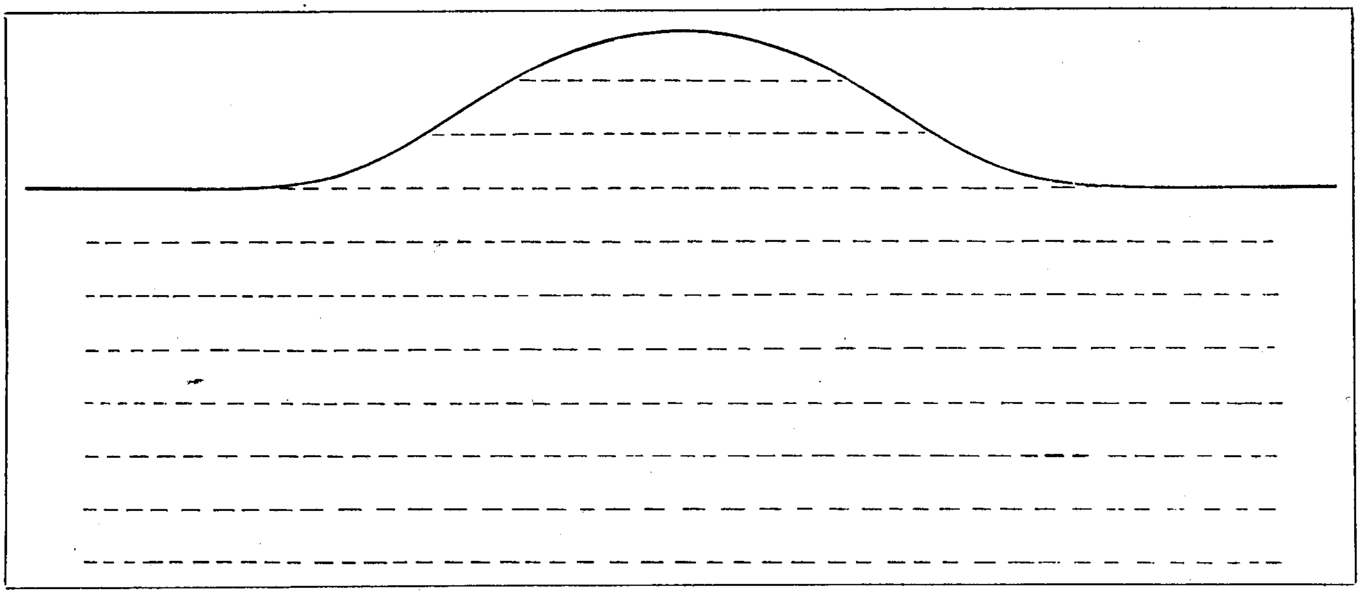

Figure 3-11. Isogeotherms in the vicinity of a very conductive topographic high (calculated).

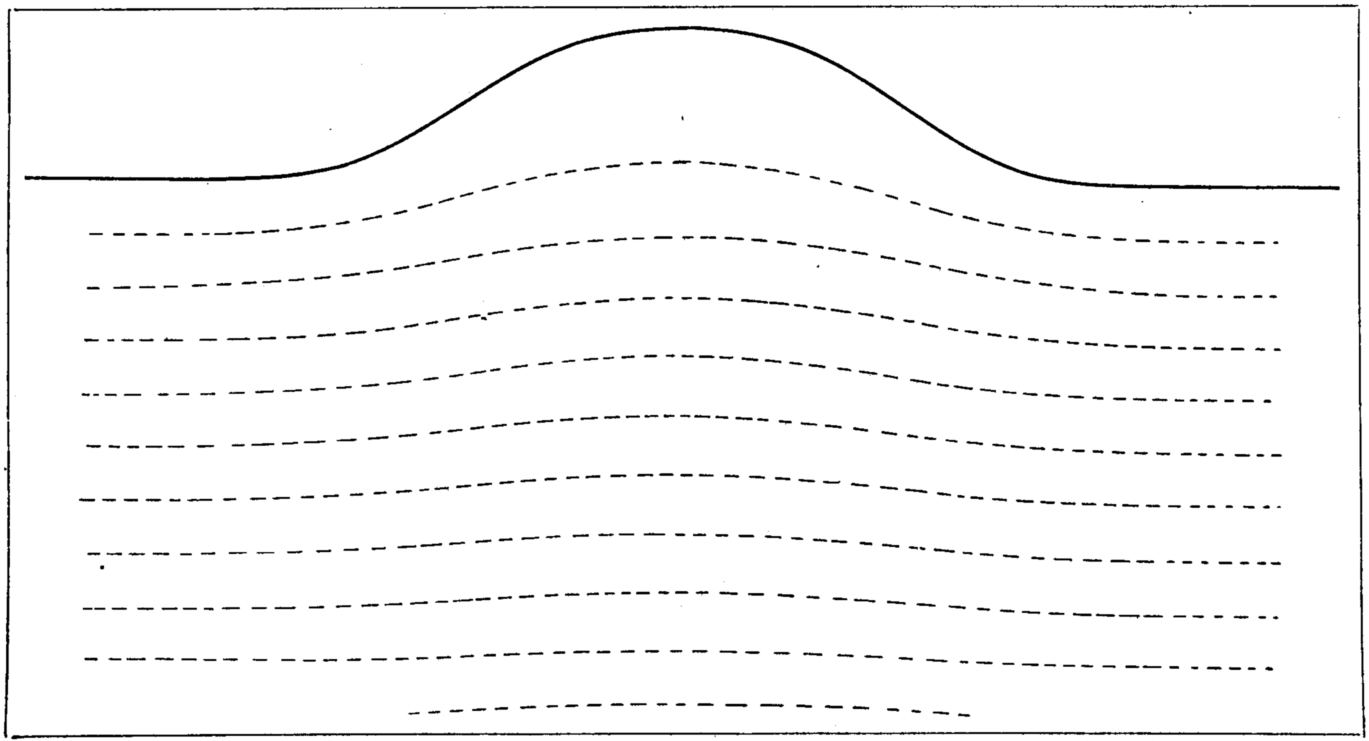

Figure 3-12. Isogeotherms in the vicinity of a topograhpic high w hen the influence of the atmosphere is neglected (scale model data).

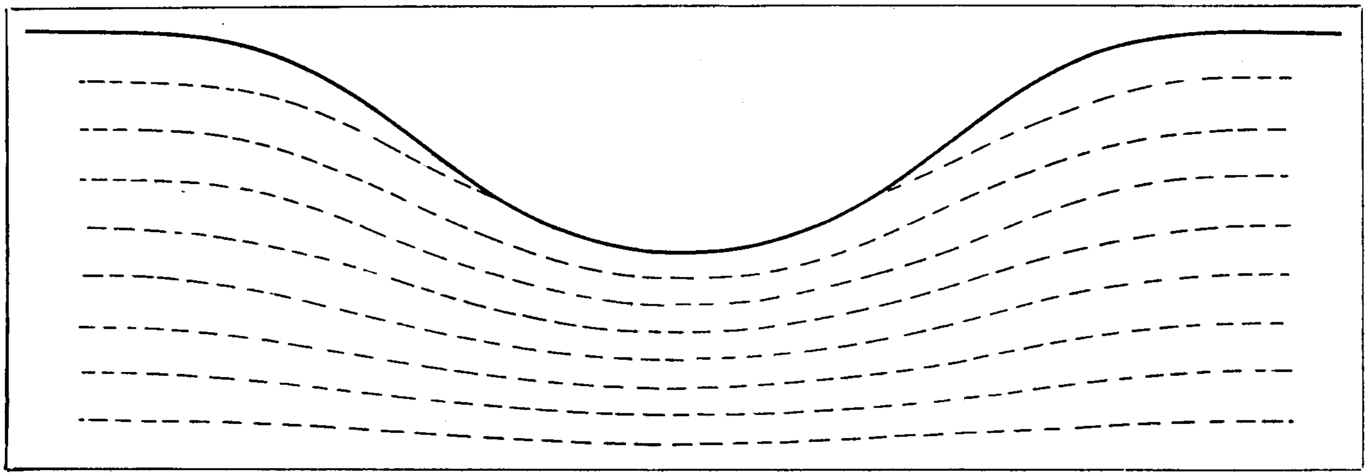

Figure 3-13. Isogeotherms below a topographic depression (estimated).

structure, or depressed, according to conditions.

### Synclines

A syncline can also be considered as an association of two symmetrical monoclines. The temperature distribution in a syncline can therefore be readily established from the foregoing data. If, in a given formation, the isogeotherms are raised in an anticline they will be depressed when the same formation has a synclinal structure, and conversely.

### Topographic High

The effect of topography can be visualized easily by remembering that the atmosphere acts like a good heat conductor. It is true that the thermal conductivity of air ($0.05 \times 10^{-3}$C.G.S.) is only a small fraction of that of sediments. However, heat transfer in air by convection and by the action of the wind is extremely important in the atmosphere. In the present work we can therefore consider that the effect of these two factors increases considerably the heat conductivity of air. In other words, we may disregard the effect of these factors provided we substitute for the actual air conductivity a much higher conductivity which here will be called "apparent conductivity." Its value is perhaps of the order of $16 \times 10^{-3}$C.G.S., or roughly four times as great as the conductivity of non-consolidated sediments. This value is based on reciprocal gradient determinations in air which, according to the literature available, average 325 feet.

With the foregoing concept, the investigation of the effect of topography is considerably simplified. For example, a topographic high can be considered as being a resistant intrusion in a more conductive material. This case is represented on Figure 3-9, which shows that the isogeotherms are raised in a mountain or hill. An actual example is shown on Figure 3-10. The measurements were taken in a tunnel and the results extrapolated. The actual isogeotherms are probably slightly different from those indicated.

If the topographic high is a good heat conductor (an igneous rock, for example) its heat conductivity and the apparent conductivity of air may have approximately the same value. In this case the isogeotherms are approximately flat (Figure 3-11).

A few investigators neglect the influence of air and assume that the surface of the ground is an isotherm. This condition was investigated on a scale model and the result is shown on Figure 3-12. This simplification results in temperatures which are in excess of the actual temperatures found in the ground.

If the mountain is ridge shaped, rather than dome shaped, the isogeotherms are slighly higher than shown on Figure 3-12.

The warping of the isogeotherms below mountains or hills diminishes gradually with depth and is probably negligible at a depth equal to about three times the height of the superficial relief.

All the data contained in this section and in the following one should be used in a qualitative manner only, since the figure used for the apparent conductivity of air is somewhat uncertain.

### Topographic Depression

The effect of a topographic depression can be investigated in a manner similar to that which was used for a mountain. Basically, such a feature is as illustrated on Figure 3-13 where the lower medium (the ground) has a lower conductivity than the upper one (the air). This figure shows that the ground temperature below and around a depression is generally lower than in flat territory. However, if the ground has a very high conductivity (igneous rocks), the isogeotherms are nearly horizontal and no appreciable temperature anomalies are observed.

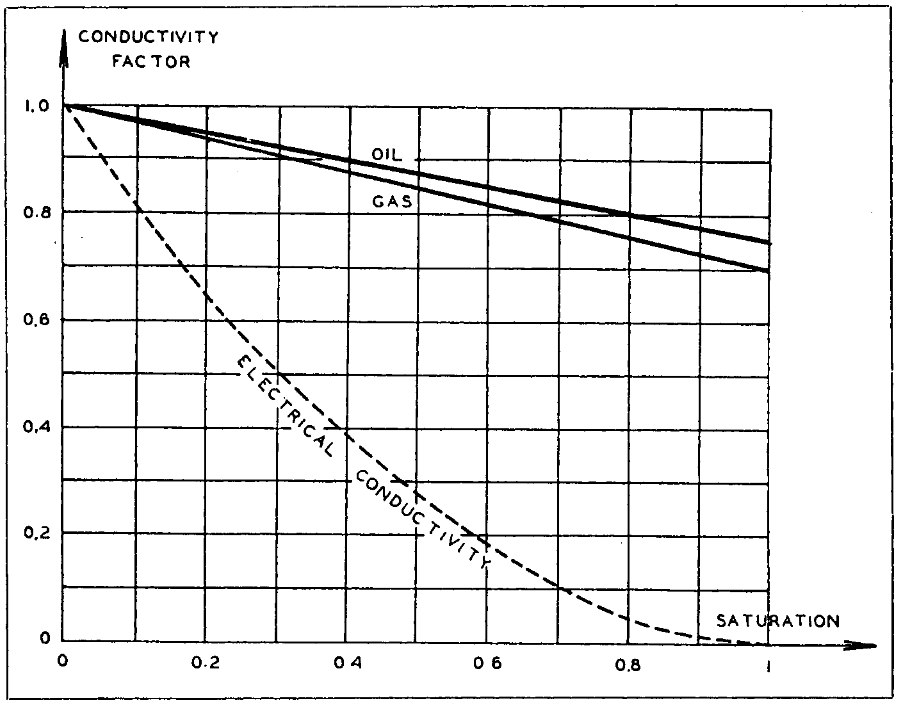

Figure 3-14. Approximate conductivity factor of oil and gas reservoirs (estimated).

### Petroleum Reservoirs

Crude oil and natural gas are poorer heat conductors than water. The conductivity of oil is probably only a fourth to a fifth that of water, while the conductivity of gas is still smaller: perhaps a fifteenth that of water. A petroleum reservoir is therefore a poorer heat conductor than a similar reservoir containing only water. Unfortunately, the volume occupied by oil or gas in a reservoir is only a small fraction of the total volume (usually less than 25 percent) and the resulting effect on the reservoir conductivity is small. Figure 3-14 illustrates tentatively the relation between conductivity factor and saturation (fraction of pore space). The conductivity factor is defined as the ratio $K_p/K_w$, where $K_p$ is the conductivity of the petroleum reservoir and $K_w$ the conductivity of the same reservoir when it contains only water. Figure 3-14 shows also the exact electrical conductivity factor in terms of saturation.

Although the heat conductivity data given by this chart have been estimated, it is likely that they represent roughly the desired relation. It can be seen from the figure that the heat conductivity is a much poorer index of saturation than the electrical conductivity (or its reciprocal, the resistivity). When it is remembered how difficult it is to locate petroleum reservoirs in exploratory wells from resistivity data, even when a potential graph is available, it will be appreciated that temperature measurements (made in formation which are in thermal equilibruim) probably cannot be used to solve this problem.

Gamma ray measurements made in bore holes have shown that petroleum is not radioactive. Therefore, no abnormally high temperatures due to radioactive disintegration can be expected near petroleum reservoirs. The high temperatures mentioned in the old literature are probably caused by the presence of conductive intrusions with which many oil or gas pools are associated.

### Ore Deposits

Many ores have a much greater heat conductivity than sedimentary or igneous rocks. Pyrite, for instance, is at least ten times as conductive as the common sediments. If the volume of the ore deposit is large enough, appreciable temperature anomalies can be observed in its vicinity. This is illustrated in the upper part of Figure 3-15, which gives the isogeothermal pattern and a few temperature graphs near an ore deposit ten times as conductive as the surrounding formation which is assumed to be uniform. The scales are relative and can be calibrated as explained in the preceding article.

Certain ores oxydize in the ground. This chemical reaction generates heat, the result of which is to further modify the ground temperature. Temperature increases of more than 10° F. have been reported near pyrite deposits. The central section of Figure 3-15 illustrates tentatively the combined effect of heat generation and high conductivity of an ore deposit. A few depth-temperature graphs are also given.

It is interesting to note on some of these graphs that the temperature at point M is less than in the area situated higher. This is due to the fact that, in addition to the heat source constituted by the core of the earth, there is another source in the vicinity of the area under investigation. Under normal conditions, in particular if the ground is

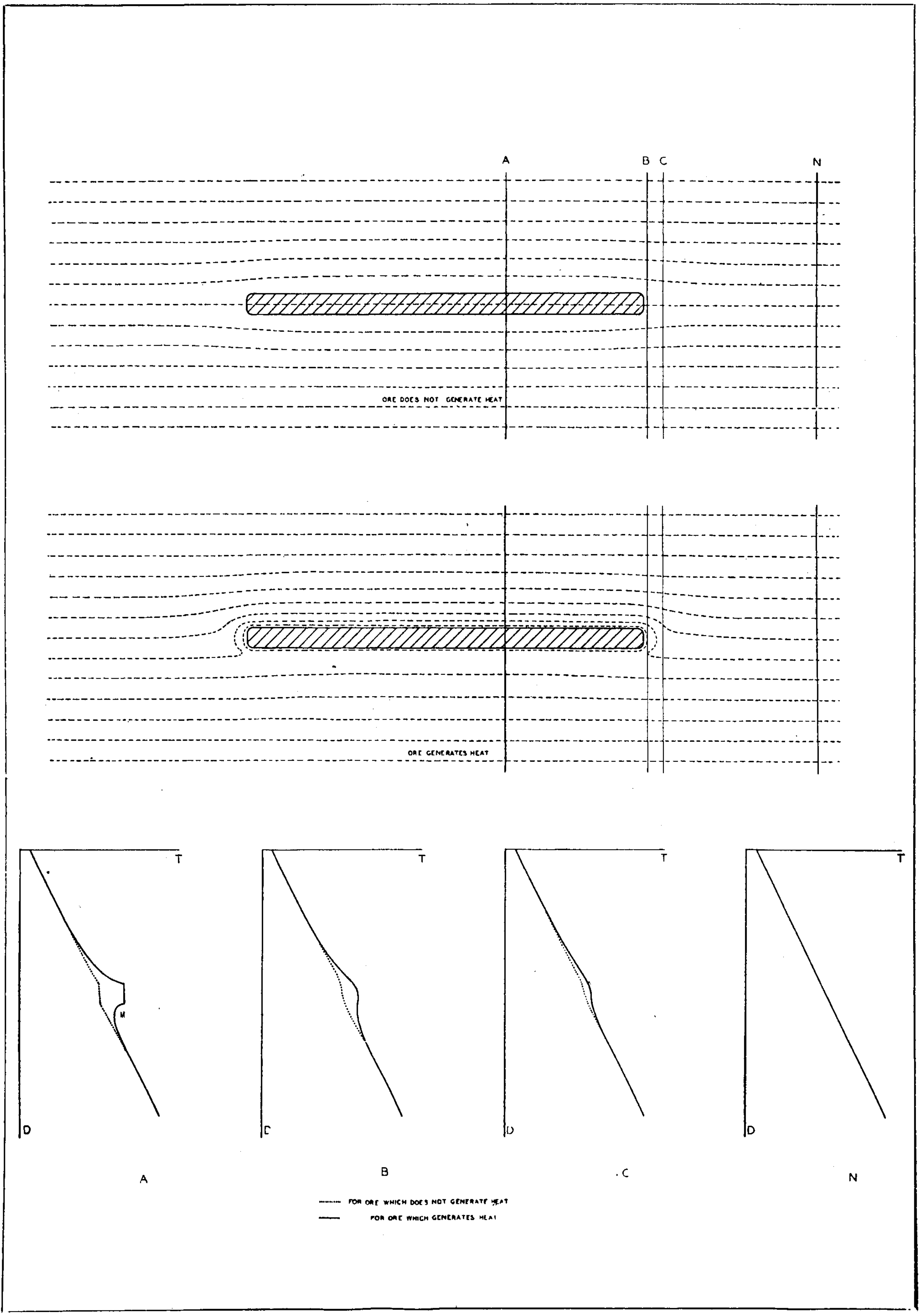

Figure 3-15. Isogeotherms and depth-temperature graphs in the vicinity of ore deposits.

in thermal equilibrium, the temperature steadily increases with depth.

### Faulting

A fault having an appreciable thickness can modify by itself the temperature of the ground if the conductivity of the materials it contains differs from that of the sediments. When the fault plane is tilted, the resulting condition is basically similar to a monocline.

If the fault has a small thickness it does not modify by itself the temperature of the ground. However, where it brings in contact beds of different nature, a few minor and local temperature changes take place. This is illustrated on Figure 3-16, which represents a bed B cut by a fault F. B is assumed to be only a fourth as conductive as the surrounding formation S.

If water migrates along the fault, an unsteady state is created, which further modifies the temperature distribution. This condition will not be discussed here.

### Shallow Formations

Because the amount of heat received from the sun changes continually, the temperature of the ground down to a depth of 80 to 100 feet varies also—although slowly—with time. However, the mean temperature at any point remains approximately constant.

From a number of observations[2] it has been found that the mean temperature $T_A$ of the air at the surface of the ground (point A of Figure 3-17) is frequently several degrees less than the temperature $T_G$ which would be obtained by extrapolating the depth-temperature graph B C obtained below 100 feet. Since it is unlikely that a discontinuity of several degrees can exist at the surface of the ground, the upper part of graph B C must pass through point A, or close to this point. This means that, at shallow depths, the reciprocal gradient in many areas is appreciably smaller than at greater depths and, consequently, that the heat conductivity of very shallow formations is less than normal.

Such low conductivities are likely due, at least partly, to the fact that shallow formations are probably not entirely saturated with water. In fact, it has been reported[2] that in Southern California—where the ground surface is comparatively dry—the temperature difference $T_G$-$T_A$ is, on the average, greater than in the other petroliferous provinces.

### Conclusion

The temperature data presented in the foregoing discussions refer to relatively simple conditions. Actual formations are usually more complex and present a combination of many of the individual factors investigated here. The temperature distribution for these more complex cases can generally be estimated reasonably well by superposition.

It is appreciated that many other phases of the problem have also been oversimplified, especially quantitatively. This was unavoidable in an elementary treatment of the problem of the ground temperature.

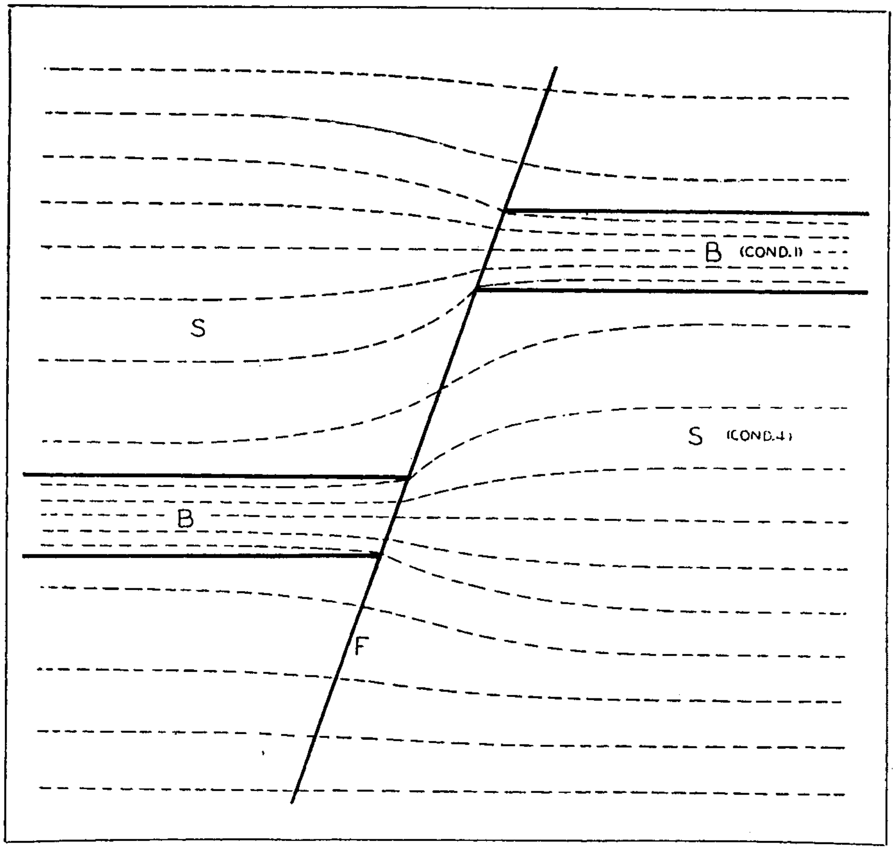

Figure 3-16. Temperature distribution in the vicinity of a fault cutting a resistant bed (scale model data).

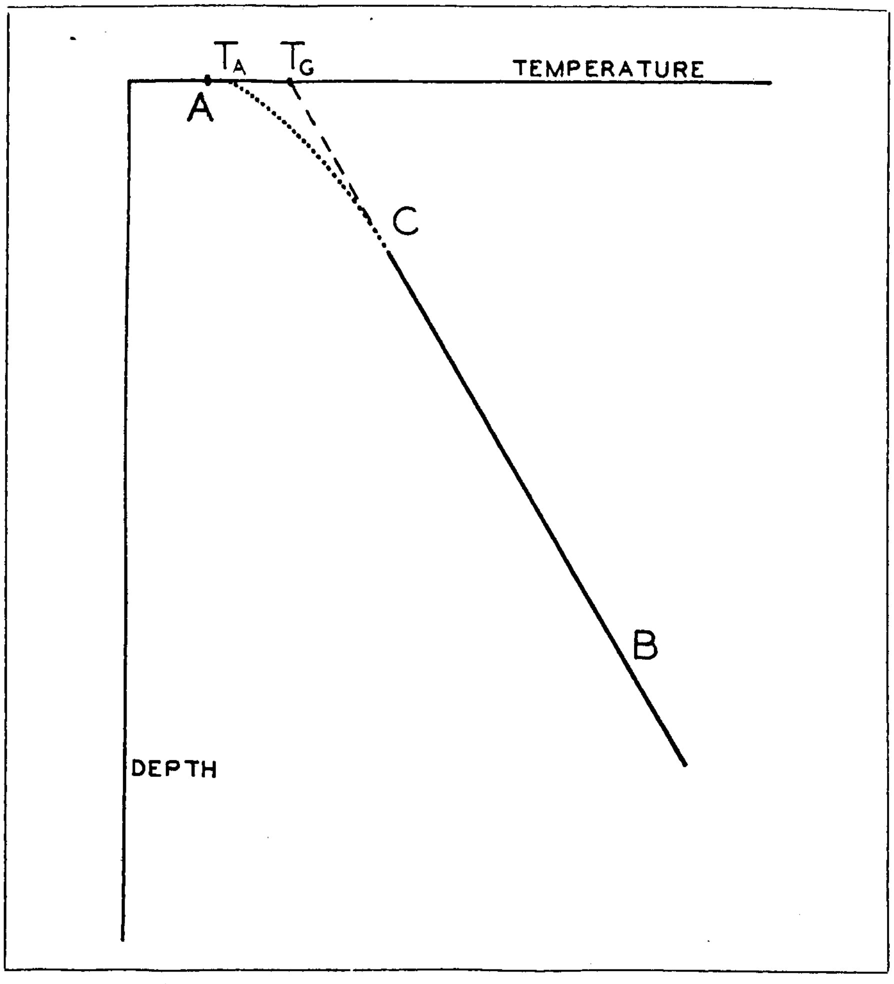

Figure 3-17. Temperature near the surface of the ground.

**REFERENCES**

[1] Hubert Guyod, "Electrical Well Logging, Part 5," The Oil Weekly, September 4, 1944.
[2] A.P.I., Production Bulletin No. 205.