TEMPERATURE

Well Logging

Part 2

Salt Intrusions

ALTHOUGH it has been known for years that the temperature of the ground in the vicinity of salt masses is higher than normal, no accurate data could be secured on this phenomenon because of the impossibility of taking a sufficient number of temperature readings. By using electrolytic scale models, the isogeothermal pattern in and about a salt intrusion can be obtained with accuracy.

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IT HAS been pointed out in the preceding article that an analytical study of the ground temperature is usually impossible and that the only general method of approach is to conduct experiments on electrolytic models. With this procedure it is a simple matter to determine accurately the shape of isogeotherms and to establish temperature profiles under any predetermined condition, even very complex. The majority of the figures which illustrate this and the following article are typical examples of the results obtained by this method.

Only formations which are in perfect thermal equilibrium will be considered. In other words it will be assumed that there is only one source of heat in the ground: the hot core which constitutes the interior of the earth. The influence of circulating ground waters, of rocks which are not in thermal equilibrium, of radioactive disintegration, etc., will be disregarded. This simplification is permissible because it is felt that in most petroleum provinces the effect of these disturbing factors is usually extremely small and therefore negligible. For example, the effect of circulating waters cannot be large in virgin formations because the permeability of sediments is relatively small. Only sources or geysers can really modify appreciably the temperature of the ground. However, these occurrences are rare in petroleum areas and their influence will not be discussed here. Regarding the heat evolved by radioactivity disintegration, it is the consensus that the resulting temperature increase in sediments is probably so small that it is not measurable, even in sediments, associated with rocks, such as granite, which contain a relatively large amount of radioactive substances.

The Problem of the Ground Temperature

Physically, the problem of the ground temperature consists in investigating the temperature distribution in heat-conductive media whose upper and lower boundaries have a given shape and a constant temperature. Therefore, the factors to consider are:

- the heat conductivity of the materials involved,
- the geometry of these materials,
- the geometry and temperature of the outermost boundaries of the system.

As far as the last factor is concerned it will be assumed that the formation is unlimited horizontally and that the horizontal boundaries are defined as follows:

1. At a depth about twice that of the desired investigation, or shallower, there is a horizontal isogeothermal surface. Geologically, this means there is a relatively thick basement rock whose lower surface is roughly horizontal.
2. The surface of the ground in the vicinity of the area under survey is an isogeothermal surface. Actually, because of diurnal and annual variations, it would be more accurate to consider the surface situated 100 feet deeper; this, however, is not necessary as long as it is remembered that the data obtained do not apply to the top 100 feet of formation.

The two foregoing assumptions are legitimate under most conditions. In case it is found that they are not, more appropriate boundary conditions will have to be considered in order to minimize the resulting errors, as will be explained later.

The Homology Principle

The homology principle, which was mentioned previously in this magazine while discussing electrical logging[1] applies also to heat problems. According to this principle, data obtained for a given set of conditions are applicable to any other set of conditions when there exist a geometrical homology and a thermal homology. For example, referring to Figure 2-1, the graph shown to the right represents the temperature changes found in a hypothetical well penetrating sediments and a salt dome whose top is at a depth D_1, while the undisturbed salt is at depth D_2. The diameter

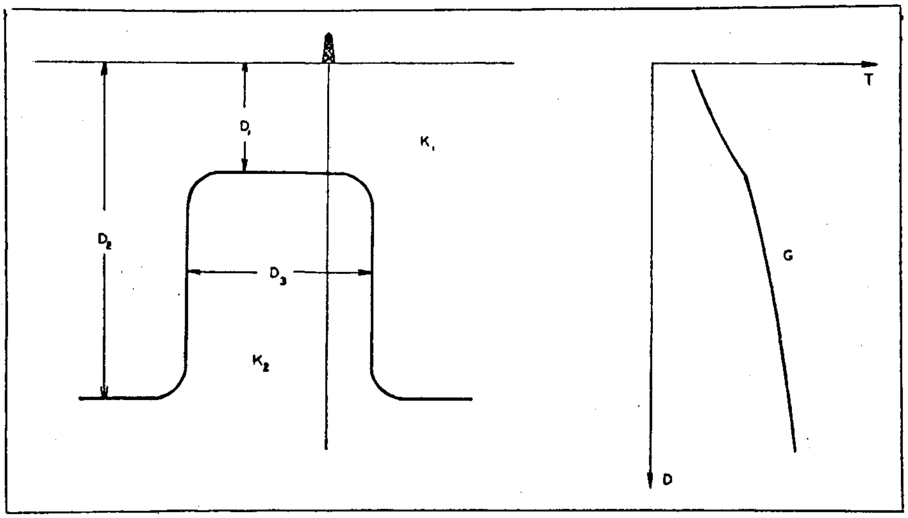

Figure 2-1. Illustration of homology principle.

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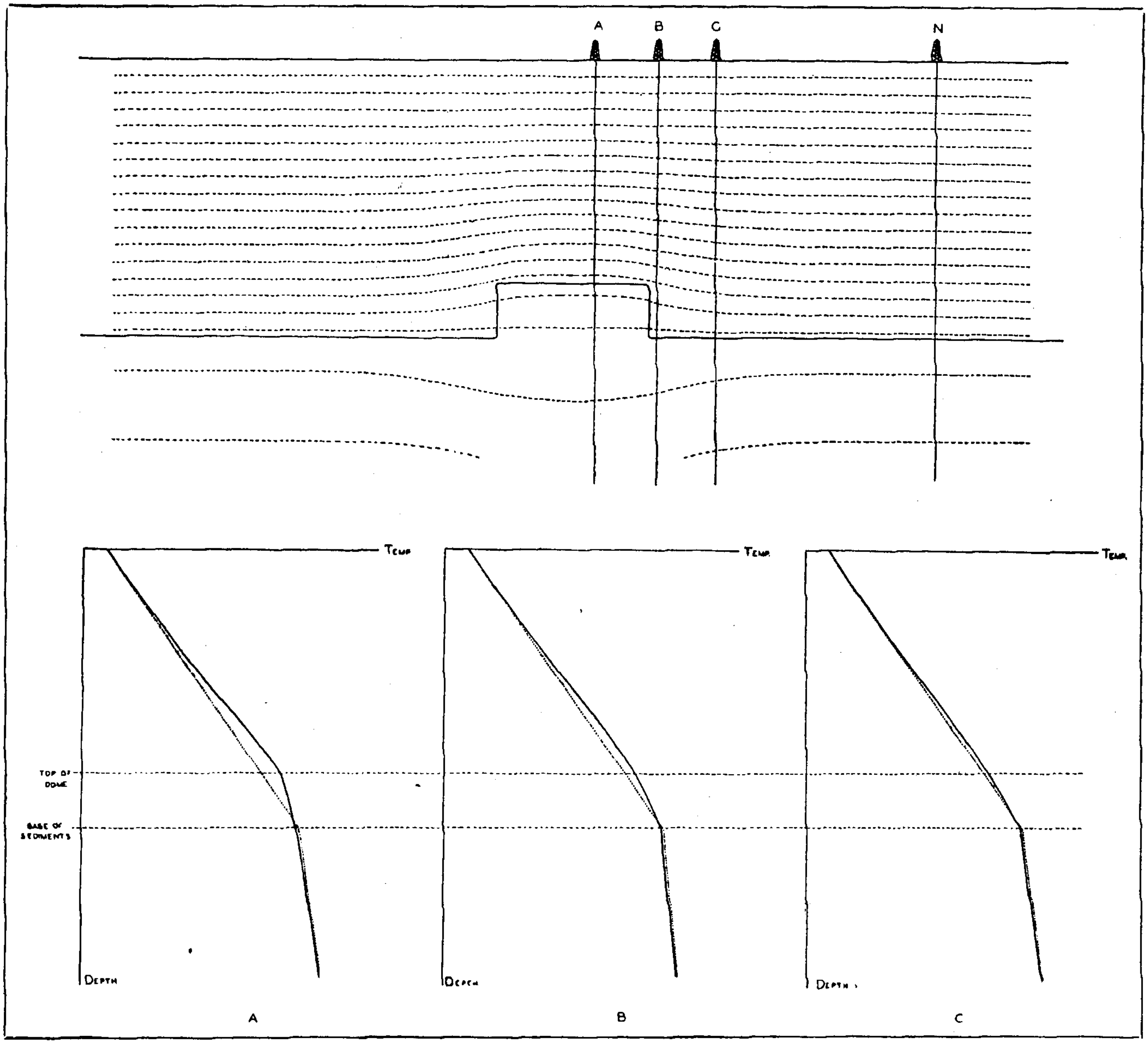


Figure 2-2. Isogeotherms and depth-temperature graphs in the vicinity of a deep-seated salt dome (scale model data).

of the dome is D_3. The same temperature graph represents also the temperature in a similar formation in which the dimensions of the salt dome are nD_1, nD_2 and nD_3, n being any number greater or smaller than unity. The only modification to bring to this graph is to multiply the depth and temperature scales by the factor n. A similar remark can be made regarding the heat conductivity of the formations. If graph G was obtained for sediments and salt having conductivities K_1 and K_2 respectively, the same graph represents the temperature distribution in geometrically similar formations whose heat conductivities are mK_1 and mK_2. The only change to make on the graph is to divide the original temperature scale by the factor m.

The geometrical and thermal homologies are absolutely independent of each other and the principle applies if, for instance, the dimensions are increased n times and the conductivities decreased m times, or conversely.

This, of course, facilitates considerably the investigation of the earth's temperature because it makes it possible to use, for a given set of conditions, the data obtained previously for different but homologous conditions. A few examples of application of this principle will be given later.

Symmetrical Structures

Frequently the structures found in petroliferous provinces are roughly symmetrical about an axis (intrusions) or about two planes at right angles (anticlines, ridges). To simplify this work, only symmetrical structures will be considered. The basic information obtained in this manner may be applied, with a few minor modifications, to actual formations whose asymmetry is not excessive.

Each type of formation and structure modifies the temperature distribution in its own way. For example, the effect of a salt intrusion is different from that of an anticline. Also, the influence of a thick lime bed is different from that of a shale bed. Because there are so many possible geometrical and petrographical combinations of formations, it is necessary to understand the influence of each factor separately before the resulting effect of a combination of factors can be considered.

Intrusions

The effect of an intrusion on the temperature distribution of the associated sediments is relatively simple and, for this reason, will be discussed first.

Most intrusions have a greater thermal conductivity than sediments. For example, salt conducts heat about five times as well as shales, and approximately three times as well as sands. Granite is also a better heat conductor than shales and sands, although its conductivity is only ½ to ⅔ that of salt. On the other hand, there are also intrusions whose conductivity is less than that of the associated formations, in particular those of igneous origin having a relatively large amount of gas filled vesicles. However, such cases are probably rare.

The temperature distribution in and about conductive intrusions is illustrated in Figures 2-2 through 2-5. These figures

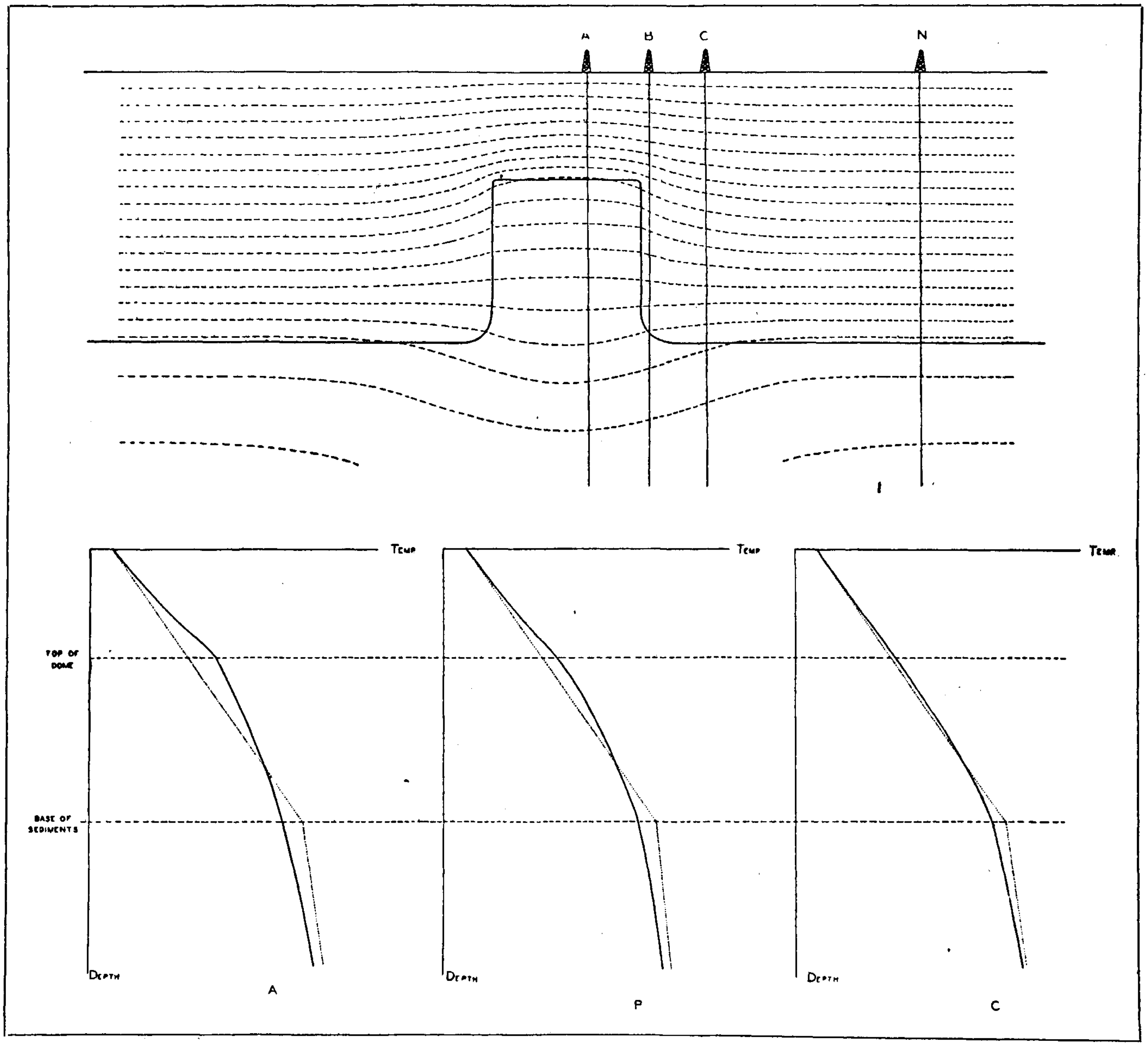


Figure 2-3. Isogeotherms and depth-temperature graphs in the vicinity of a salt dome of intermediate depth (scale model data).

represent, in vertical cross-section, the four following conditions:

Figure 2-2: a deep-seated dome (depth: 15 units)

Figure 2-3: a deep piercement-type dome (depth: 7.5 units)

Figure 2-4: a shallow piercement-type dome (depth: 2 units)

Figure 2-5: a mushroom-type dome (depth: 4 units).

The cap-rock conductivity is assumed to be equal to the salt conductivity.

The diameter of these domes is assumed equal to ten units, while the diameter of the overhang of Figure 2-5 equals 15. The depth of the top of the salt, far from the domes, is assumed to be 20. The actual value of the units used for the foregoing dimensions is immaterial for the following discussions, and it can be 1000 feet if the reader so wishes.

The formation overlying the salt is supposed to be uniform and its heat conductivity is one fourth as great as that of the salt, except for Figure 2-5, for which it is a little less (1/5).

The isogeotherms are represented by dash-lines. The temperature interval between them is constant. The plain line graphs situated below each section of the domes are the depth-temperature curves which would be obtained in vertical wells drilled at the following locations:

A, above the salt intrusion,

B, close by the intrusion,

C, at a relatively short distance from the intrusion,

D, through the overhang.

These wells are supposed to be drilled in such a manner that the temperature of the ground is not modified by the drilling operations.

The dotted lines represent the depth-temperature graphs which would be obtained far from the intrusions, at N for example, or farther. These lines give therefore the normal temperature of the formation in the non-disturbed areas.

The first remark which can be made regarding these figures is that the isogeotherms are raised above and around the domes. This corresponds to the frequently reported fact that sediments associated with salt intrusions are warmer than normal. It should be noted, on the other hand, that the isotherms are slightly depressed near the lower part of the domes, with the result that the sediments are slightly colder than normal in this particular zone. This has probably never been observed or reported before, very likely because temperature measurements have not been taken at such points as yet.

Another interesting feature of the figures is that the rate of temperature increase is greater above and near shallow domes than near deeper plugs. More exactly, the smaller the ratio D_1/D_2 (see Figure 2-1), the greater the rate of temperature increase in the vicinity of the salt.

If the diameters of the intrusions are different from those assumed in the figures, the temperature distribution above the dome or near it is not appreciably changed, unless the diameter becomes

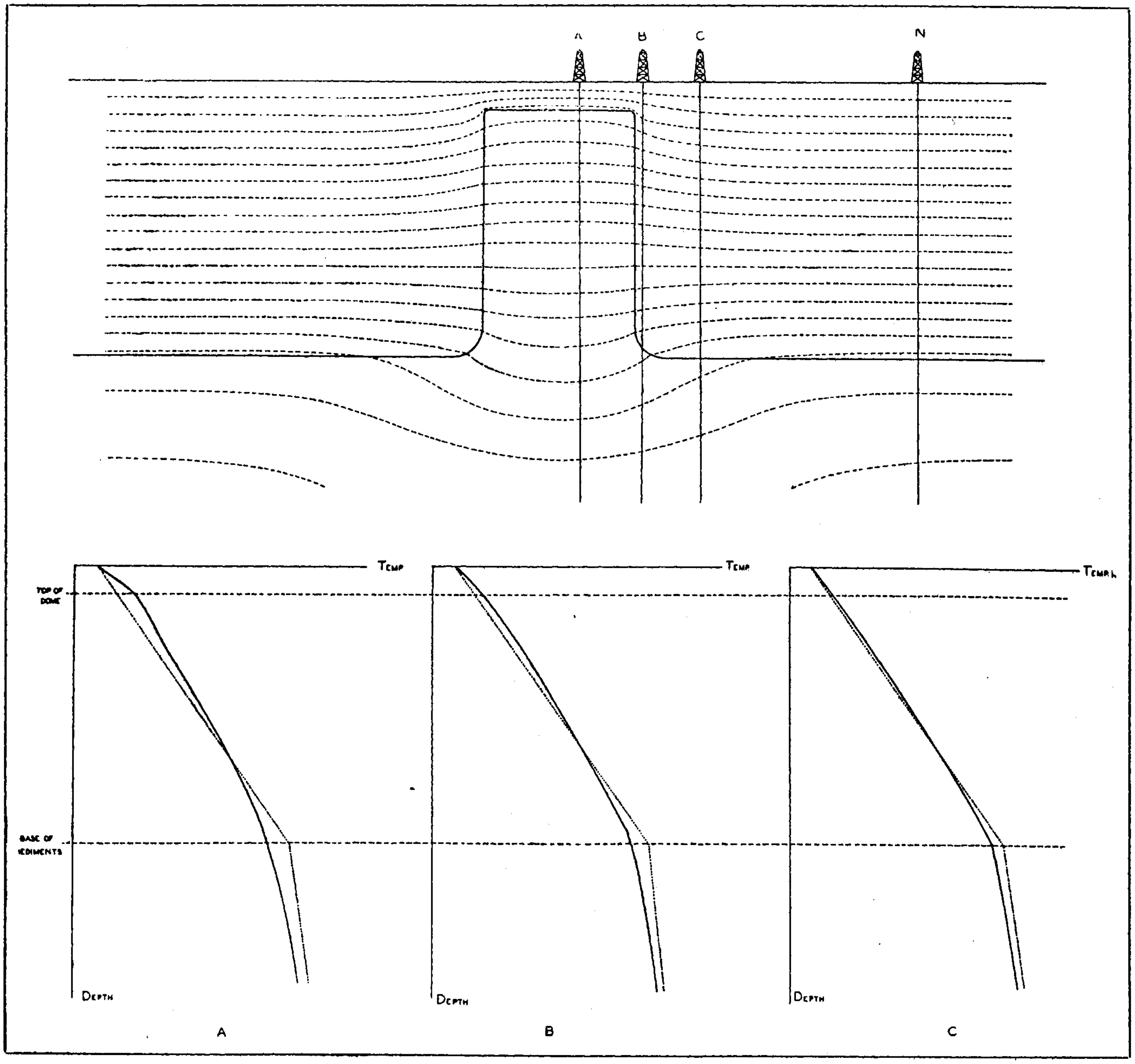


Figure 2-4. Isogeotherms and depth-temperature graphs in the vicinity of a shallow piercement-type salt dome (scale model data).

very small, in which case the temperature anomalies are reduced.

Inside the intrusions, the isogeotherms are spread apart much more than in the sediments. This is evidently caused by the relatively high conductivity of the salt. The temperature is greater than normal in the top section of the dome, but less than normal in its bottom section as well as in the undisturbed basement rock near the roots of the plug.

To summarize, a conductive intrusion modifies the temperature distribution of the ground in an area comprised within a vertical cylinder centered at the intrusion and whose radius equals about four times the radius of the intrusion. Outside this area, the temperature is not appreciably modified.

It will be observed that the depth-temperature graphs of Figures 2-2 through 2-5 are calibrated neither in degrees nor in feet. This is because they have been established according to the homology principle mentioned previously: they are therefore, in certain ways, universal curves that can be used to fit many different conditions. For instance, suppose that it is desired to determine the temperature of the ground immediately above a salt dome whose top is 8000 feet deep, while the top of the nonintrusive salt bed is 20,000 feet deep. This particular dome is represented on Figure 2-3. Graphs A and N of this figure are the curves which have to be used for the determination, and they are reproduced as Figure 2-6 for convenience. The point whose temperature is desired is marked Z on this figure. Graph N, which is the normal depth-temperature curve in nondisturbed formations, is the yardstick which will allow calibrating curve A.

It will be assumed that the average reciprocal gradient in the non-disturbed areas of the ground is known and equal, for instance, to 64 feet per degree, and that the mean surface temperature is 60°. Point X of graph N represents the mean surface temperature. Therefore, its coordinates are:

depth: 0′
temperature: 60°.

Point Y of graph N represents the normal temperature at the top of the salt, far from the intrusion. Its coordinates are:

depth: 20,000′

temperature: $60 + \frac{20{,}000}{64} = 372°$.

These two sets of coordinates permit calibrating the depth and temperature scales of the graphs of Figure 2-6. From this calibration the desired temperature at point Z is readily obtained: 223°. It is interesting to note that the normal temperature at that depth (Point Z′) is 180°.

If the temperature at other points of the ground in the vicinity of the same intrusion is desired (graphs A, B, C, or N) the same temperature and depth scales have to be used.

If similar temperature determinations are desired near a homologous salt dome, the same graphs have to be used (Figure 2-3) using the adequate numerical values.

If a depth-temperature graph is de-

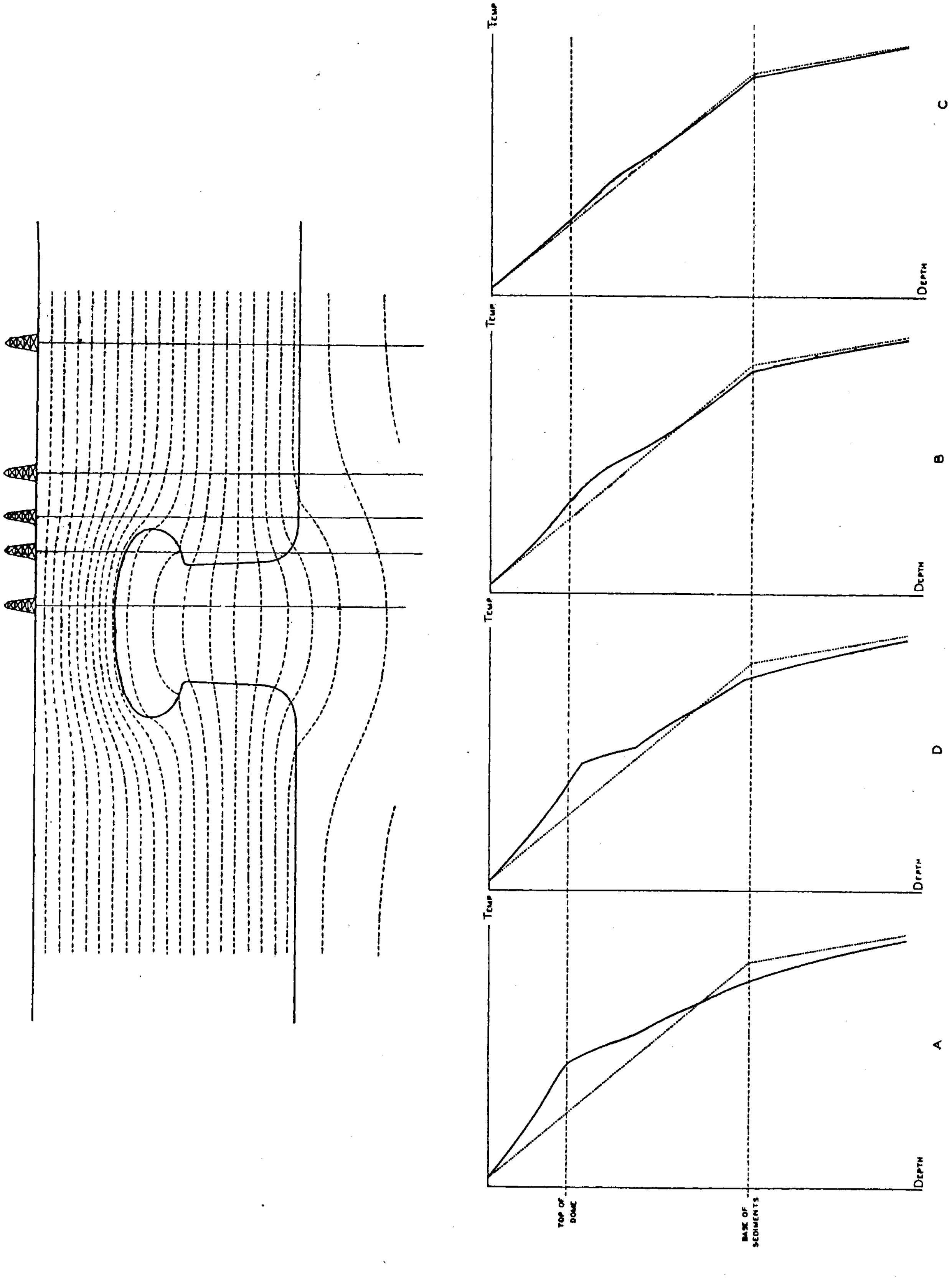


Figure 2-5. Isogeotherms and depth-temperature graphs in the vicinity of a mushroom-type salt dome (scale model data).

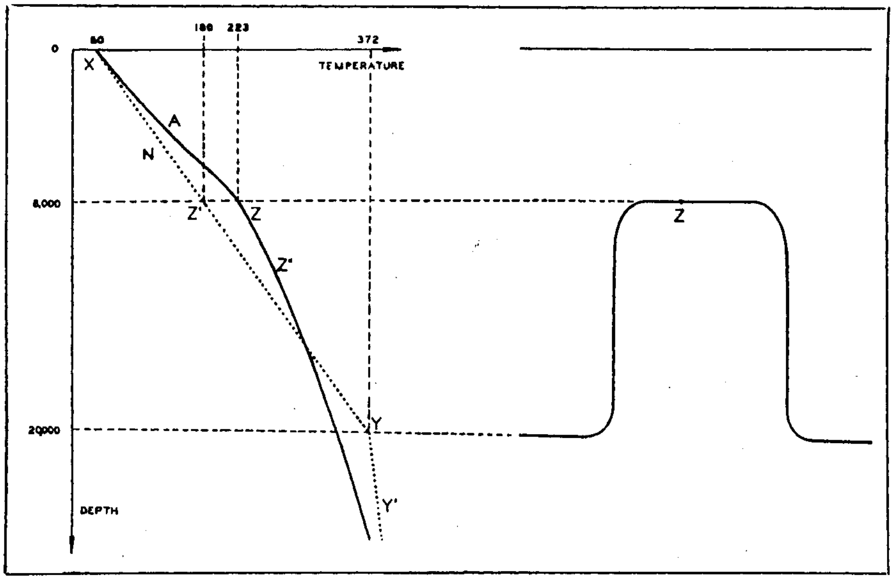


Figure 2-6. Calibration of temperature data.

sired on a vertical profile different from those given as examples, such profile can be readily established from the isogeotherms shown on the figures.

If the approximate temperature distribution is desired near a salt dome whose dimensions are different from those given as examples the corresponding graphs can be obtained by interpolation or, if facilities are available, by constructing an electrolytic model of proper dimensions and making the necessary electrical measurements.

Temperature Correction Chart

Figures 2-2 through 2-5 were established for intrusions whose heat conductivities are four times greater than the associated sediments. In practice it is probable that much greater conductivity ratios will almost never be found, while smaller ratios—down to two or three—will be common, for instance if the sediments contain a high proportion of sands or limes. Under such conditions the temperature anomalies are less than those exhibited by the preceding figures, and they can be estimated by using the chart of Figure 2-7. This chart is basically similar to those used for the computation of true resistivity from the apparent resistivity data given by an electric log.[3] It gives a correction factor in terms of the relative depth of the intrusion and of its relative conductivity. Suppose for example that it is desired to determine by this method the temperature T_z at the point Z of Figure 2-6. Let $T_{z'}$ designate the normal temperature at the same depth (point Z') and T represent the mean surface temperature. The procedure is as follows:

1. Determine the relative depth (or depth ratio) $D_r = D_1/D_2$ of the point whose temperature is desired.

   In the present example:

   $D_1 = 8000'$
   $D_2 = 20{,}000'$

   therefore $D_r = 0.4$, giving point D on the abscissa axis of the chart.

2. Determine the relative conductivity (or heat conductivity ratio) $K_r = K_2/K_1$ of the plug, K_2 being the intrusion conductivity and K_1 the sediments conductivity. This ratio will be assumed to be equal to 4 in this example. Curve 4 of the chart must therefore be used.

3. The vertical passing through point D intersects curve 4 at point L whose ordinate is 1.35.

This means that from the surface of the ground to point Z the temperature increase is 1.35 times greater than between the surface and point Z'. In other words:

$$T_z - T_x = 1.35\,(T_{z'} - T_x)$$

and

$$T_z = T_x + 1.35\,(T_{z'} - T_x)$$

Assuming for $T_{z'}$ and T_x the values mentioned previously, namely, 180° and 60°, respectively, it is found from the foregoing relation that $T_z = 222°$.

An examination of the graphs of Figures 2-2 to 2-5 shows that the temperature anomaly is maximum in the zone situated immediately above the salt dome. The correction chart was established for this particular zone. Elsewhere, the anomalies are usually less. Therefore, if the correction chart is used for estimating the temperature at other points, the values will be too high. Temperatures can nevertheless be reasonably estimated anywhere in the vicinity of a salt dome by using different correction charts. These are not given here in order not to complicate this discussion, and because good results can usually be obtained by simply estimating from the graphs available in this article the "correction" which should be made to the correction factor given by Figure 2-7.

The correction chart refers to conductivity ratios comprised between one and five. Greater ratios are probably not found in petroleum provinces.

When the intrusion is a salt dome, the conductivity ratio varies according to the nature of the sediments approximately as follows:

Sediments	Ratio
Only shales	5
Predominantly shales	4.5
Shales and sands (roughly in equal amounts)	4
Predominantly sands	3.5
Only sands	3
Shales and hard formations (roughly in equal amounts)	2.5
Predominantly hard formations	2

If the intrusion is of igneous origin the conductivity ratios are approximately half as great as indicated in the foregoing table.

All these figures are based on a relatively small number of reliable observations. They will have to be corrected when additional accurate measurements made under controlled conditions are available.

The dearth of accurate data is caused by the fact that the few observations made on salt sections in wells which are in thermal equilibrium are usually at stations situated very close to the sediments. These measurements give figures which cannot be used for accurate determinations of conductivity. Referring for example to graph A of Figure 2-7 it will be seen that in the top section Z Z" of the dome the slope of the temperature graph is different from that which is ob-

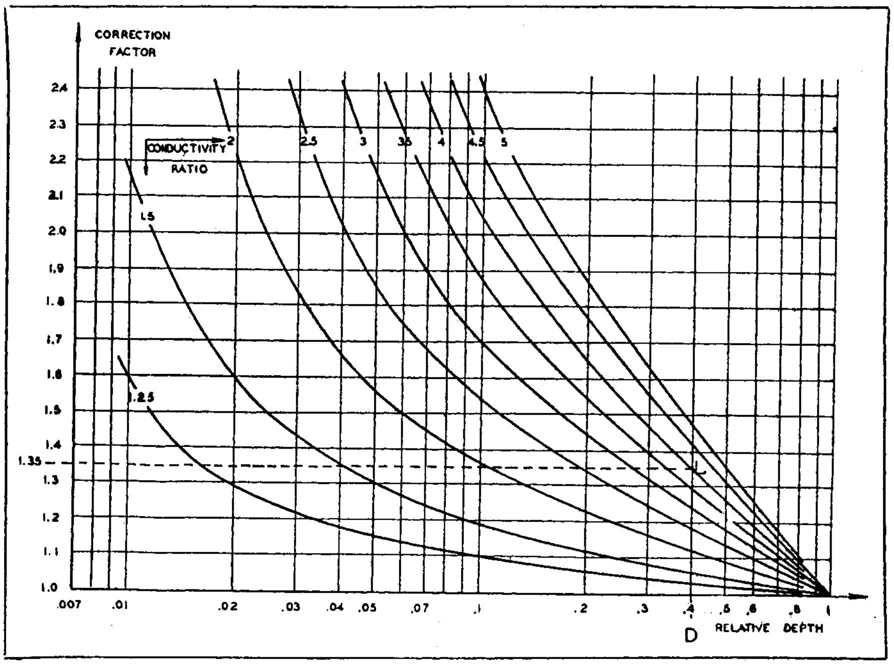
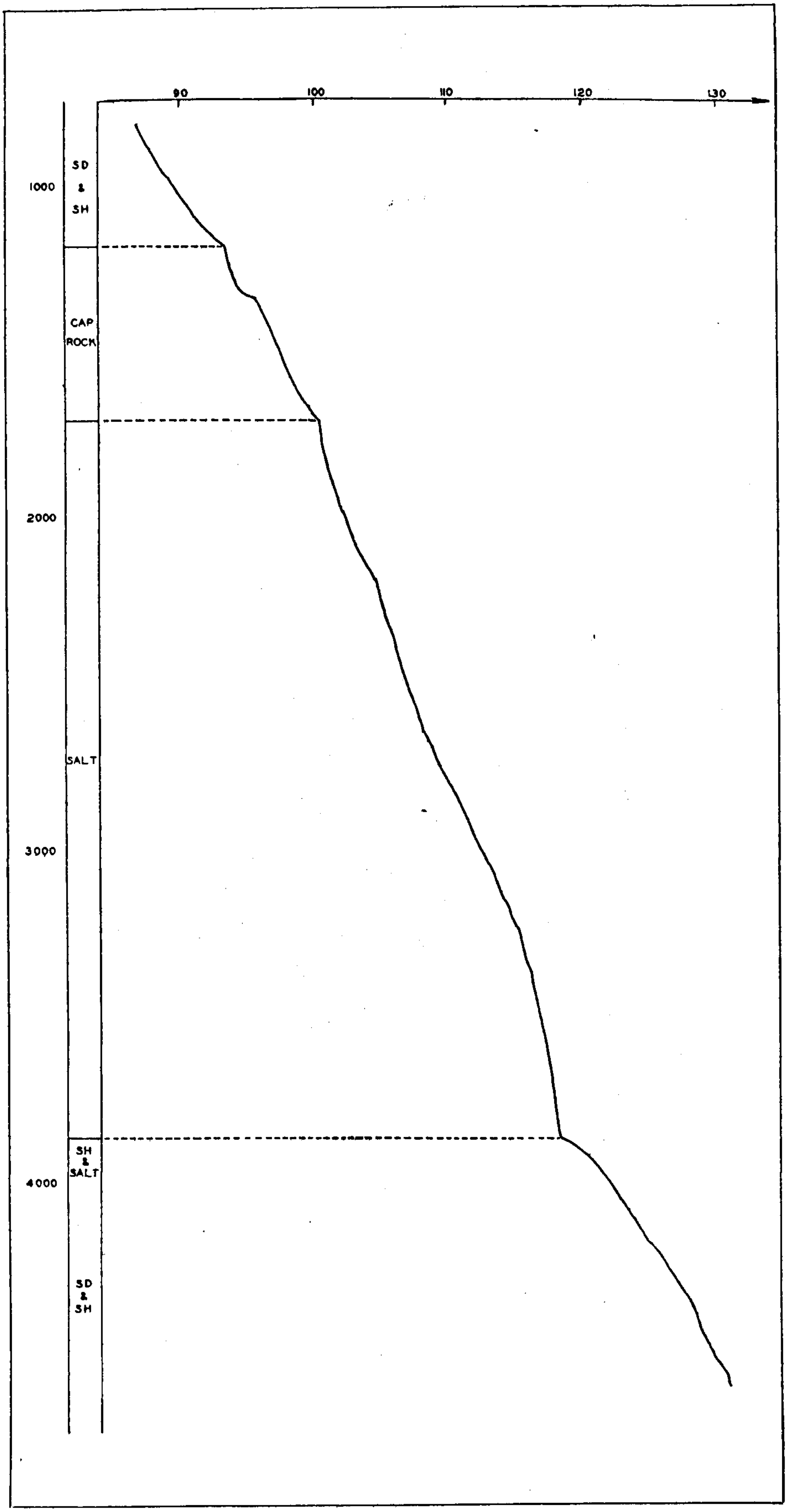


Figure 2-7. Chart giving correction factor for estimating temperature above a heat-conductive intrusion.



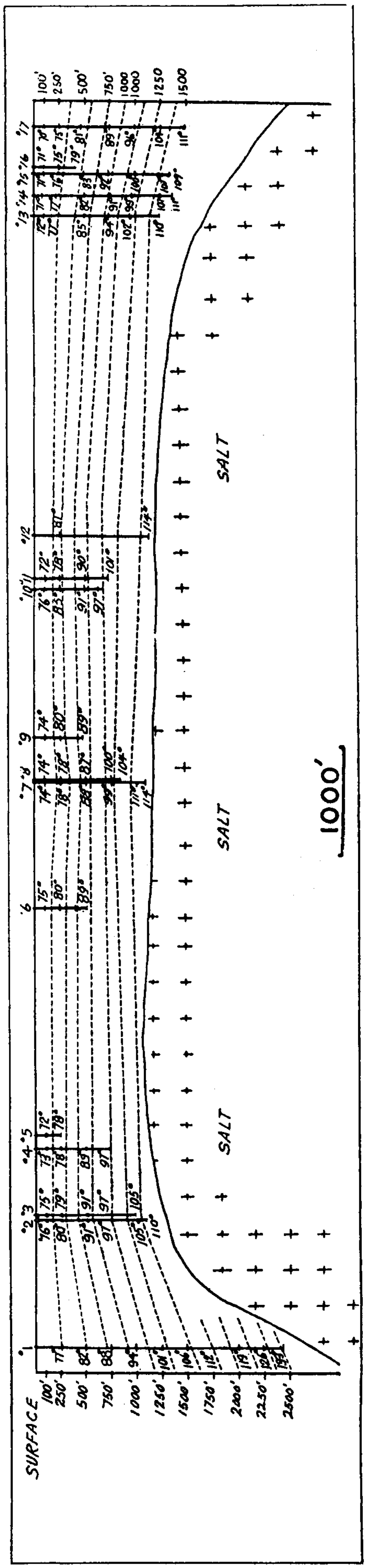


Figure 2-8 (above). Temperature graph obtained in a Gulf Coast well having penetrated a salt overhang.

Figure 2-9 (right). Isogeotherms above Humble salt dome, Harris County, Texas. Temperature interval between isogeotherms: 5° F. (From Hawtof, API Production Bulletin 205.)

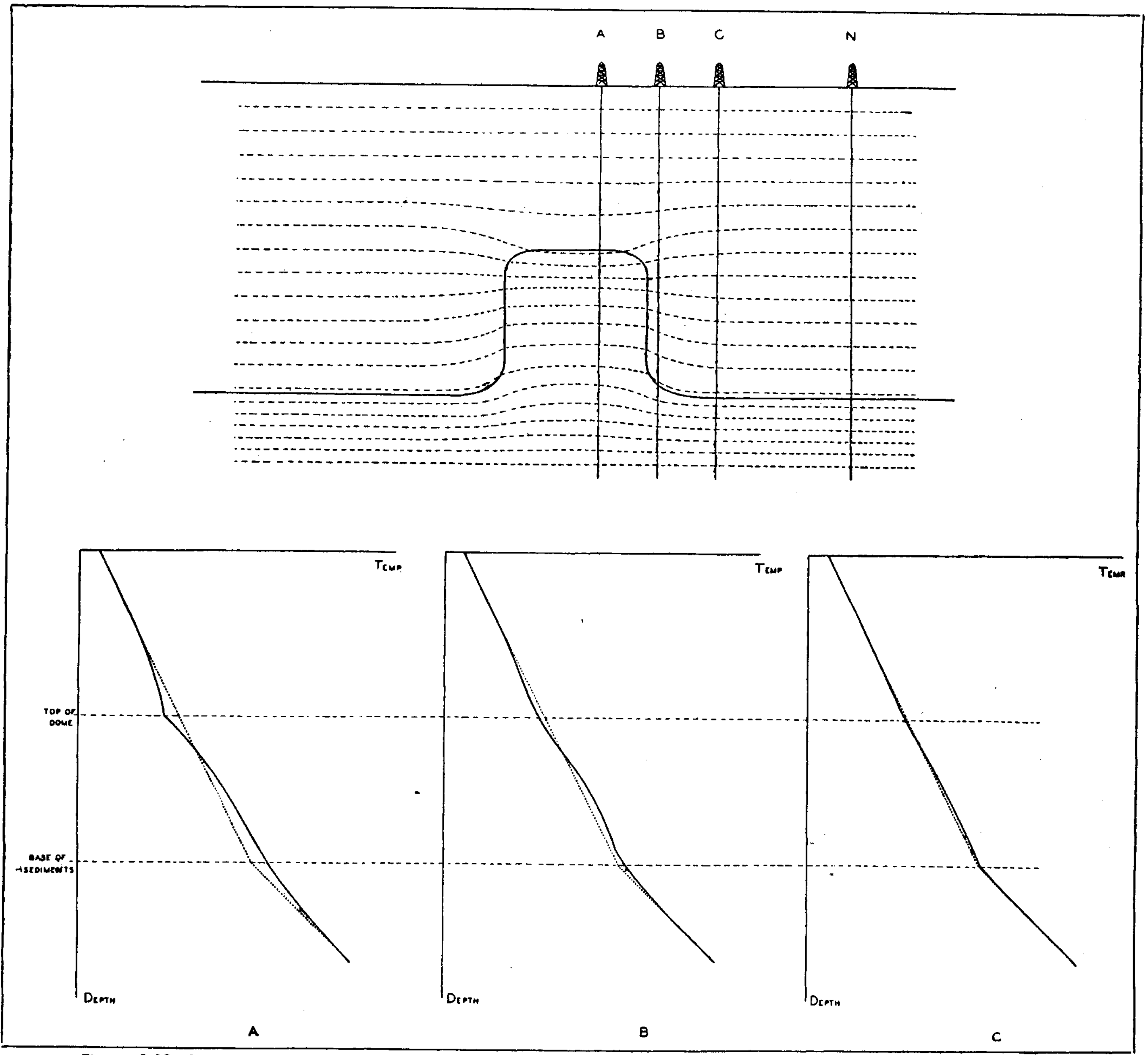


Figure 2-10. Isogeotherms and depth-temperature graphs in the vicinity of a heat-resistant intrusion (scale model data).

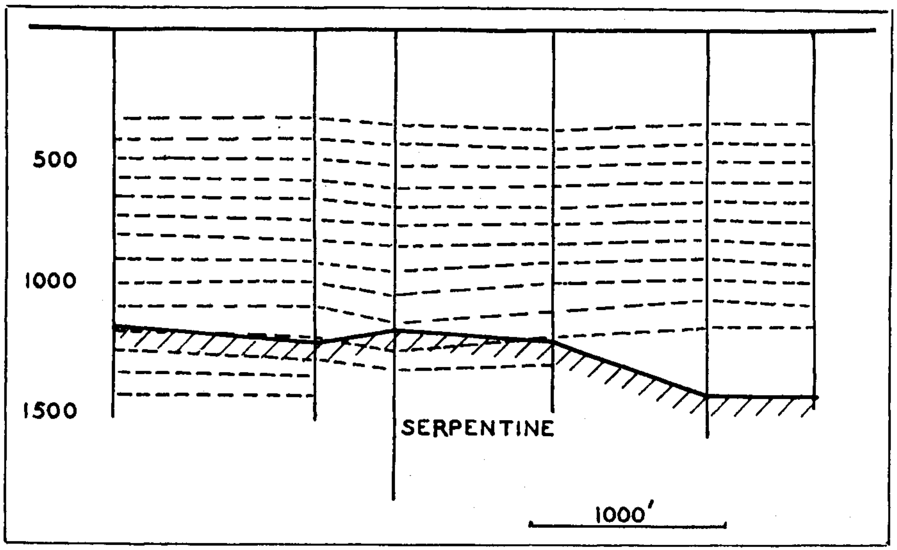


Figure 2-11. Isogeotherms in and above a serpentine plug, Lytton Springs oil field, Caldwell County, Texas. Temperature interval between isogeotherms: 2° F. (Data from Hawtof, API Production Bulletin 205, 1930.)

tained in an undisturbed section (Section Y Y′ of Graph N). Therefore, the reciprocal gradient obtained from temperature readings taken in Section Z Z″ does not give an exact value of the salt conductivity, and this erroneous value cannot be corrected unless all the pertinent data are at hand. This is due to the fact that the sediments modify the temperature distribution in the dome, just as the dome modifies the temperature of the sediments.

Figure 2-8 represents an actual temperature graph obtained in a salt overhang. The formations were reasonably in temperature equilibrium at the time the measurements were taken.

Figure 2-9 gives an interesting illustration of the isogeotherms obtained near a shallow dome from actual temperature measurements. The pattern is strikingly similar to that obtained on scale models.

The discussion offered in this section shows that the abnormally high temperatures associated with salt or granite intrusions are fully accounted for by considering the conductivity and geometry of the formations involved.

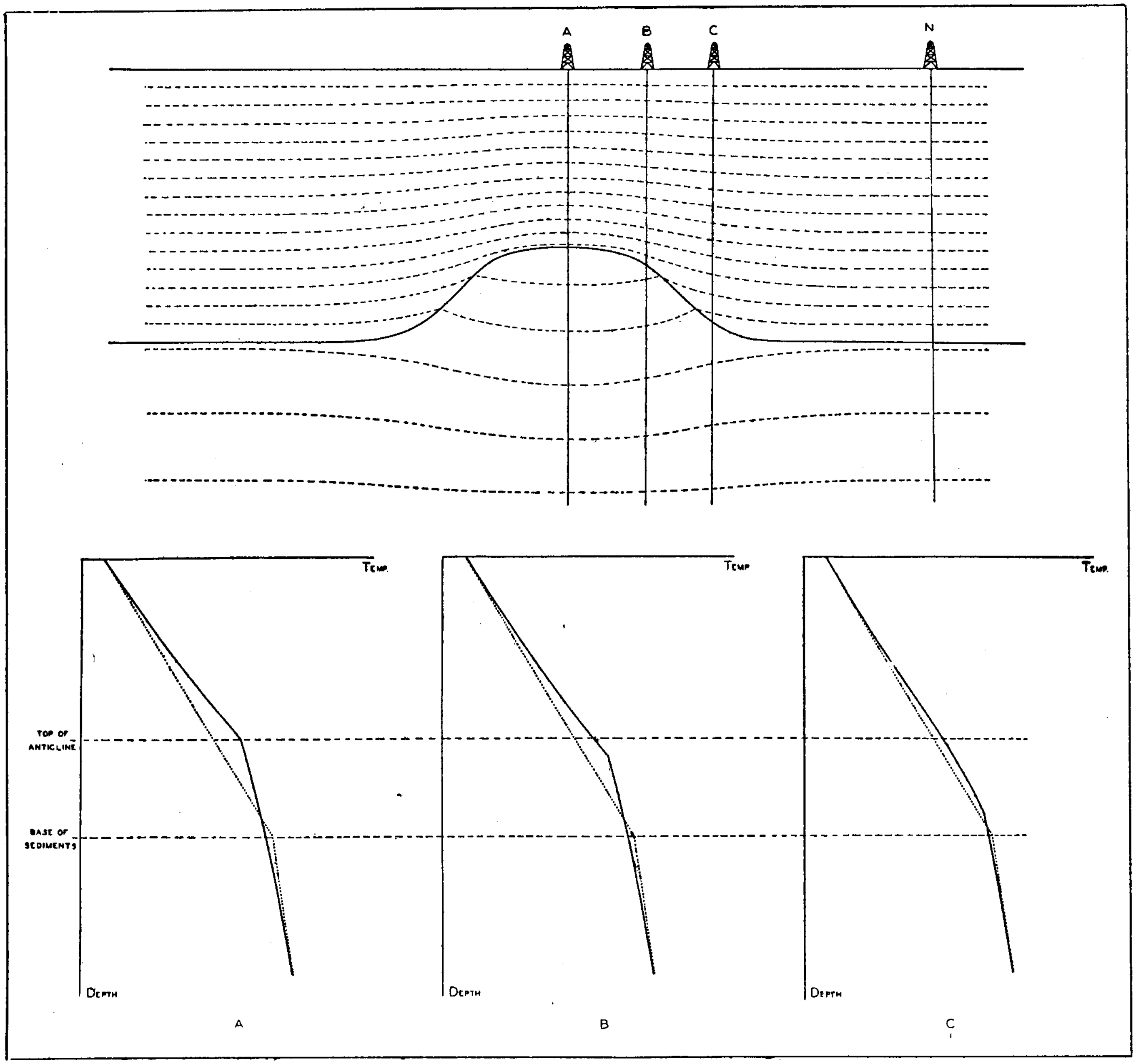


Figure 2-12. Isogeotherms and depth-temperature graphs in the vicinity of a salt anticline (scale model data).

The preceding discussion referred to intrusions having a higher heat conductivity than the associated sediments. Intrusions from rocks whose thermal conductivity is less than that of sediments are rarely found and will be only briefly discussed here.

Figure 2-10 represents an intrusive rock only one half as conductive as the associated formation. As should be expected, the isogeotherms (dash lines) are depressed above the top of the plug and around it (except near its bottom where they are raised). This means that near the top of the dome the temperature is less than normal.

Typical depth-temperature graphs in hypothetical bore holes A, B and C are shown in plain lines in the lower half of the Figure. The dotted lines represent the normal temperature distribution (well N) far from the intrusion.

Figure 2-11 represents isogeotherms obtained from actual temperature measurements near an intrusion which appears to be less conductive than the associated formation.

Salt Anticlines

The effect of a salt anticline on the temperature distribution in the ground is evidently very similar to that of a salt dome. Figure 2-12 represents the section of the isogeothermal surfaces by a plane perpendicular to the major axis of the anticline. A few typical depth-temperature graphs are also given.

Measurements made on a model representing a dome whose section is the same as that of the anticline shown on Figure 2-12 have shown that the temperature anomalies are slightly less than those of a similar anticline, all other factors remaining the same. This was to be expected since, in a salt dome less salt is lifted above its normal level than in a salt anticline: the effect of the salt must therefore be somewhat less.

Evidently the foregoing remarks apply not only to salt but also to granitic ridges, or other similar structures whose core is more conductive than the sediments.

More discussions on conductive ridges are unwarranted here. Satisfactory data on conditions different from those of Figure 2-12 can be secured by the reader by simply comparing Figure 2-12 to the previous figures representing the temperature distribution in domes.

Non-Uniform Sediments

The typical depth-temperature graphs and isogeotherm patterns discussed above were obtained on scale models for which the materials simulating the sediments were uniform. In practice, such uniformity is never found. The data offered above can nevertheless be used without major modifications when the sediments consist of horizontal or nearly horizontal beds. In such cases, the average conductivity has to be considered instead of the conductivity of any particular bed. It should be noted, however, that in non-uniform sediments the

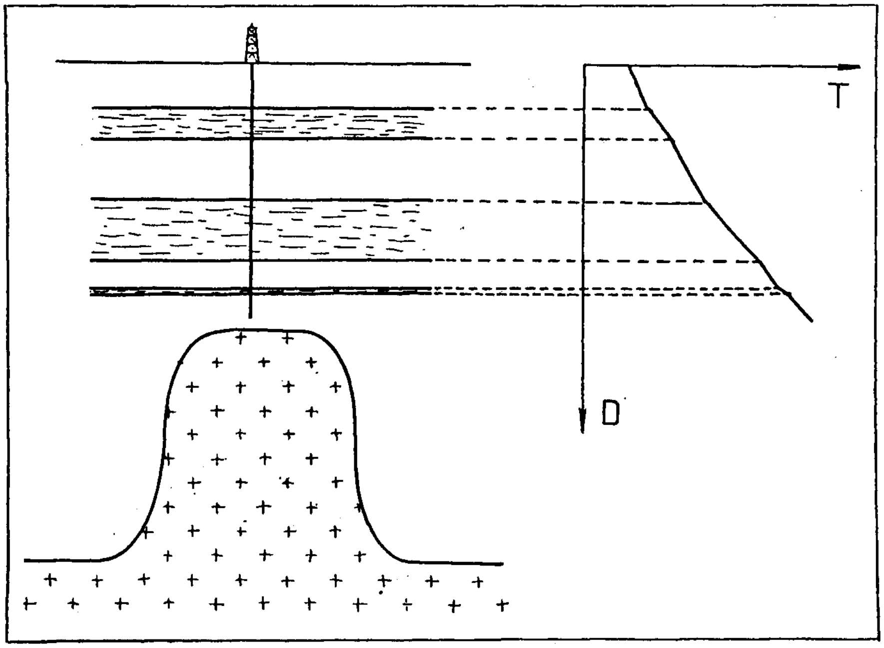


Figure 2-13. Depth-temperature graph in horizontal sediments above a salt dome (estimated).

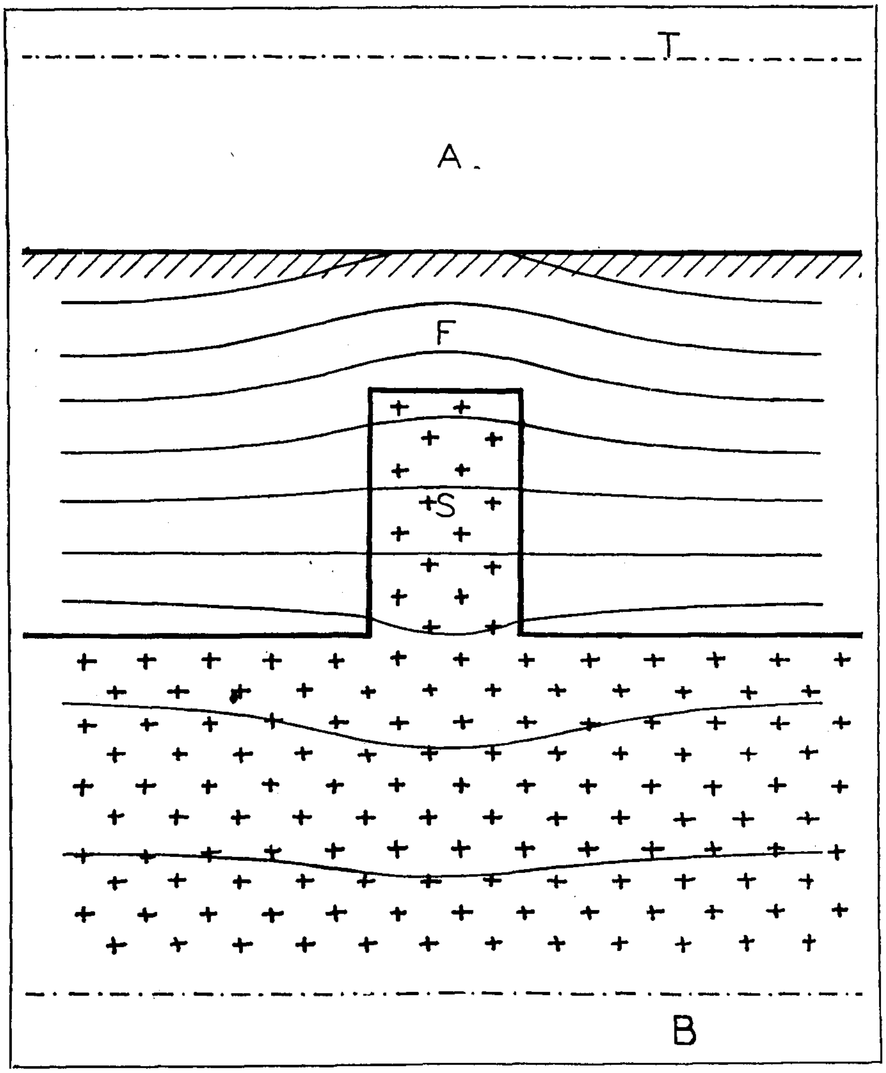


Figure 2-14. Temperature distribution in the vicinity of a salt intrusion when the influence of the atmosphere is taken into account (estimated).

depth-temperature graphs are not as smooth as shown on the preceding figures: breaks are observed at each formation boundary, but the general slope of the curves is not appreciably changed.

Figure 2-13 illustrates the case of a dome whose heat conductivity is four times as great as the average conductivity of the sediments, the latter consisting of an alternation of horizontal shale and sand beds of various thickness.

If the sediments are not approximately horizontal the temperature distribution is further modified. This condition will be discussed in the next article.

Accuracy of the Method

The use of scale models for the study of flow problems gives excellent results when the boundaries of the models simulate accurately the corresponding surfaces of the ground. This result is obtained without difficulty as far as the geometry of the systems is concerned. Less satisfactory results may be obtained for the boundary temperatures. For example, in the examples given above it was assumed that the surface of the ground is an isogeotherm. This is not entirely true, and it would have been more correct to assume that, above the ground, the nearest isogeotherm is situated perhaps at T, several thousand feet in the air (Figure 2-14). The isogeotherms obtained in the ground with this modified model would be found to be raised a little higher above he dome, as shown by the dash lines. These better patterns are obtained by constructing models comprising three different media instead of two, namely: S for the salt, F for the sediments, and A for the air.

Also, instead of considering line B as representing an isogeotherm 4000 or 5000 feet below the salt plug, it would have been more accurate to move this line perhaps 10,000 feet deeper. The result would be to depress the isogeotherms a litle lower in the neighborhood of B, as shown by the figure.

It has not been thought necessary to introduce all these refinements to secure the data required for this work. However, for a really accurate quantitative treatment of the problem it would be desirable to construct more elaborate models. This does not offer any difficulty.

Miscellaneous Applications of Data

The foregoing quantitative discussions were restricted to the estimation of temperature anomalies caused by intrusions when the approximate depth of the salt is known. It is evident that the same charts can be used to estimate the depth of a salt intrusion if the correct temperature data are available. Also, the approximate shape of a salt mass can be sometimes inferred if depth-temperature graphs such as C., Figure 2-5, can be obtained.

To solve these problems with good accuracy more data and more accurate figures than those offered in this work are necessary. These will probably be available at a later date. At present, the data offered in this work should be considered as being more an illustration of the possibilities of the scale model method, rather than the result of a very accurate and complete qualitative investigation.

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[1] Hubert Guyod, "Electrical Well Logging, Part 5," The Oil Weekly, September 4, 1944.

[2] Hubert Guyod, "Electric Log Interpretation, Part 3," The Oil Weekly, December 17, 1945.