The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics

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The usefulness of the electrical resistivity log in determining reservoir characteristics is governed largely by: (1) the accuracy with which the true resistivity of the formation can be determined; (2) the scope of detailed data concerning the relation of resistivity measurements to formation characteristics; (3) the available information concerning the conductivity of connate or formation waters; (4) the extent of geologic knowledge regarding probable changes in facies within given horizons, both vertically and laterally, particularly in relation to the resultant effect on the electrical properties of the reservoir. Simple examples are given in the following pages to illustrate the use of resistivity logs in the solution of some problems dealing with oil and gas reservoirs. From the available information, it is apparent that much care must be exercised in applying to more complicated cases the methods suggested. It should be remembered that the equations given are not precise and represent only approximate relationships. It is believed, however, that under favorable conditions their application falls within useful limits of accuracy.

Introduction

The electrical log has been used extensively in a qualitative way to correlate formations penetrated by the drill in the exploitation of oil and gas reservoirs and to provide some indication of reservoir content. However, its use in a quantitative way has been limited because of various factors that tend to obscure the significance of the electrical readings obtained. Some of these factors are the borehole size, the resistivity of the mud in the borehole, the effect of invasion of the mud filtrate into the formation, the relation of the recorded thickness of beds to electrode spacing, the heterogeneity of geologic formations, the salinity or conductivity of connate water, and, perhaps of greatest importance, the lack of data indicating the relationship of the resistivity of a formation *in situ* to its character and fluid content.

On the Gulf Coast it is found that the effects of the size of the borehole and the mud resistivity are generally of little importance, except when dealing with high formational resistivities or extremely low mud resistivities. Fortunately, little practical significance need be attached to the exact values of the higher resistivities recorded. Low mud resistivities are not common, but when this condition is encountered it may be corrected by replacing the mud column. With the present advanced knowledge of mud control, invasion of mud filtrate into sands can be minimized, thereby increasing the dependability of the electrical log. The effect of electrode spacing on the recorded thickness of a bed is often subject to compensation or can be sufficiently accounted for to provide an acceptable approximation of the true resistivity of the formation. As development of a field or area progressively enhances the knowledge of the lithologic section, the resistivity values of the electrical log take on greater significance, ultimately affording acceptable interpretations. The salinity, and

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therefore the conductivity, of the connate water associated with the various producing horizons may be determined with sufficient accuracy by the usual sampling procedure.

Determination of the significance of the resistivity of a producing formation as recorded by the electrical log appears, for the present at least, to rest largely with the application of empirical relationships established in the laboratory between certain of the physical properties of a reservoir rock and what may be termed a formation factor. It should be stressed at this point that numerous detailed laboratory studies of the physical properties of the formations in relation to the electrical measurements in question are essential to a reliable solution of the problems dealing with reservoir content. The purpose of this paper is to present some of these laboratory data and to suggest their application to quantitative studies of the electrical log. It is not intended to attempt to discuss individual resistivity curves and their application. The disturbing factors (borehole, bed thickness, and invasion) are discussed briefly only to indicate instances when they are not likely to affect the usefulness of the observed resistivity.

Resistivity of Sands when Pores Are Entirely Filled with Brine

A study of the resistivity of formations when all the pores are filled with water is of basic importance in the detection of oil or gas by the use of an electrical log. Unless this value is known, the added resistivity due to oil or gas in a formation cannot be determined.

The resistivities of a large number of brine-saturated cores from various sand formations were determined in the laboratory; the porosity of the samples ranged from 10 to 40 per cent. The salinity of the electrolyte filling the pores ranged from 20,000 to 100,000 milligrams of NaCl per liter. The following simple relation was found to exist for that range of porosities and salinities:

$$R_o = FR_w \qquad [1]$$

where R_o = resistivity of the sand when all the pores were filled with brine, R_w = resistivity of the brine, and F = a "formation resistivity factor."

In Figs. 1 and 2, F is plotted against the permeabilities and porosities, respectively, of the samples investigated. The data presented in Fig. 1 were obtained from consolidated sandstone cores in which the cementing medium consisted of various amounts of calcareous as well as siliceous materials. The cores had essentially the same permeability, parallel to and perpendicular to the bedding of the layers. All of the cores were from producing zones in the Gulf Coast region. Cores from the following fields were used: Southeast Premont, Tom Graham, Big Dome-Hardin, Magnet-Withers, and Sheridan, Texas; also La Pice, and Happytown, La. Fig. 2 presents similar data obtained from cores of a widely different sandstone; that is, one that had extremely low permeability values compared with those shown in Fig. 1 for corresponding porosities. These cores were from the Nacatoch sand in the Bellevue area, Louisiana.

From Figs. 1 and 2 it appears that the formation resistivity factor F is a function of the type and character of the formation, and varies, among other properties, with the porosity and permeability of the reservoir rock; many points depart from the average line shown, which represents a reasonable relationship. Therefore, individual determinations from any particular core sample may deviate considerably from the average. This is particularly true for the indicated relationship to permeability. Further, although the variation of F with porosity for the two groups of data taken from sands of widely different character is quite consistent, the effect

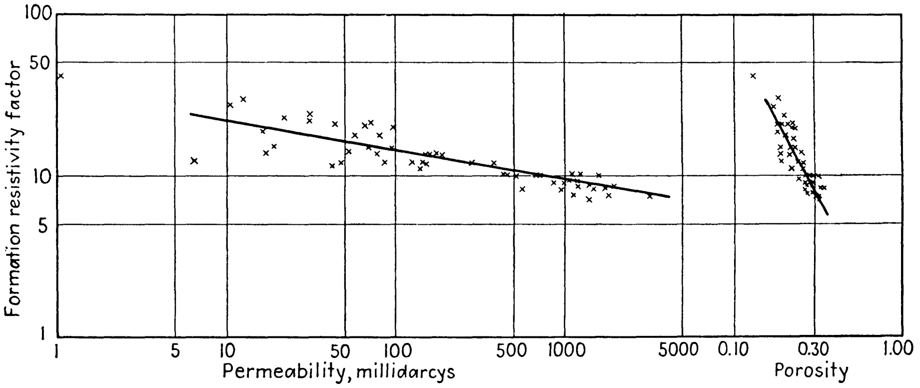

FIG. 1.—RELATION OF POROSITY AND PERMEABILITY TO FORMATION RESISTIVITY FACTOR FOR CONSOLIDATED SANDSTONE CORES OF THE GULF COAST.

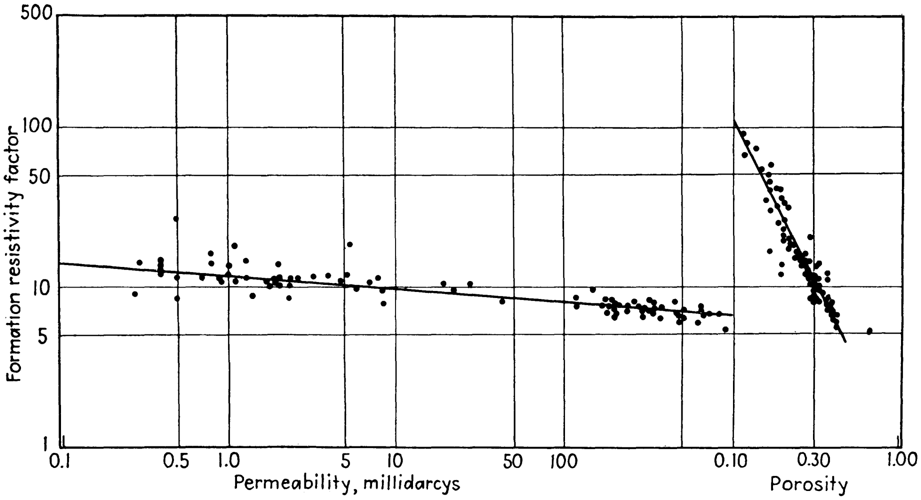

FIG. 2.—RELATION OF POROSITY AND PERMEABILITY TO FORMATION RESISTIVITY FACTOR, NACATOCH SAND, BELLEVUE, LA.

Permeabilities below 0.1 millidarcy not recorded.

of variations in permeability on this factor is not so evident. Naturally the two relationships could not be held to apply with equal rigor because of the well established fact that permeability does not bear the same relation to porosity in all sands. From close inspection of these data, and at the present stage of the investigation, it would appear reasonably accurate to accept the indicated relationship between the formation resistivity factor and porosity. Thus, knowing the porosity of the sand in question, a fair estimate may be made of the proper value to be assigned to F, based upon the indicated empirical relationship

$$F = \theta^{-m} \qquad [2]$$

or from Eq. 1,

$$R_o = R_w\theta^{-m} \qquad [3]$$

where θ is the porosity fraction of the sand and m is the slope of the line representing the relationship under discussion.

From a study of many groups of data, m has been found to range between 1.8 and 2.0 for consolidated sandstones. For clean unconsolidated sands packed in the laboratory, the value of m appears to be about 1.3. It may be expected, then, that the loosely or partly consolidated sands of the Gulf Coast might have a value of m anywhere between 1.3 and 2.

Resistivity of Formations when Pores Are Partly Filled with Brine, the Remaining Voids Being Filled with Oil or Gas

Various investigators—Martin,[1] Jakosky,[2] Wyckoff,[3] and Leverett[4]—have studied the variation in the resistivity of sands due to the percentage of water contained in the pores. This was done by displacing varying amounts of conducting water from the water-saturated sand with nonconducting fluid. Fig. 3 shows the relation which the various investigators found to exist between S (fraction of the voids filled with water) and R (the resulting resistivity of the sand) plotted on logarithmic coordinates. For water saturations down to about 0.15 or 0.20, the following approximate equation applies:

$$S = \left(\frac{R_o}{R}\right)^{\frac{1}{n}} \quad \text{or} \quad R = R_oS^{-n} \qquad [4]$$

For clean unconsolidated sand and for consolidated sands, the value of n appears to be close to 2, so an approximate relation can be written:

$$S = \sqrt{\frac{R_o}{R}} \qquad [5]$$

or from Eq. 1,

$$S = \sqrt{\frac{FR_w}{R}} \qquad [6]$$

Since in the laboratory extremely short intervals of time were allowed for the establishment of the equilibrium conditions compared with underground reservoirs, there is a possibility that the manner in which the oil or gas is distributed in the pores may be so different that these relations derived in the laboratory might not apply underground.

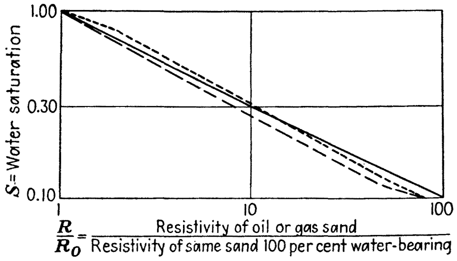

Fig. 3.—Relation of S to $\frac{R}{R_o}$

Legend and Data

Curve	Investigator	Type Sand	Salinity of Water, Grams NaCl per Liter	Oil or Gas	Porosity Fraction
———	Wyckoff	Various		CO_2	Various
———	Leverett	Uncons.	8 approx.	Oil	0.40
— — —	Martin	Cores	130	Oil	0.20 and 0.45(?)
-------	Jakosky	Friable	29 approx.	Oil	0.23

Considerable encouragement on this point is established, however. For example, Eq. 4 appears to hold even though gas or oil is the nonconducting phase. Each probably assumes a different distribution in the pores, yet the resulting resistivity is not appreciably changed. Also, no great change is found in the average relation between the formation resistivity factor and porosity for changes in types of consolidated sandstones. This indicates that even though the oil or gas underground may fill the pore space in a different manner from that in the short-time laboratory experiments, the relationship expressed by Eq. 4 should apply equally well underground.

Basic Resistivity Values to Be Obtained in Estimating Fluid Content of a Sand

The foregoing discussion indicates that the basic values to be obtained are: (1) the resistivity of the sand in question under-

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[1] References are at the end of the paper.

ground (R), and (2) the resistivity of the same sand when its pores are entirely filled with connate water (R_o).

The first value can be obtained from the electrical log when all factors can be properly weighed. The latter may also be obtained from the log when a log is available on the same horizon where it is entirely water-bearing. Of course, this is true only when the sand conditions, particularly porosity, are the same as at the point in question and when the salinity of the connate or formation water throughout the horizon is the same.

In a water-drive reservoir, or any reservoir where the connate water is in direct contact with the bottom or edge water, there should be no appreciable difference in the salinities through the horizon, at least within the limits set forth for the operation of Eqs. 1 and 4; that is, when the salinity of the connate water is over 20,000 mg. NaCl per liter and the connate water is over 0.15. In depletion-type reservoirs, or when connate water is not in direct contact with bottom or edge water, special means may have to be devised to ascertain the salinity of the connate water.

When it is not possible to obtain R_o in the manner described above, the value can be approximated from Eq. 3, θ and m having been determined by core analyses and R_w by regular analyses.

Calculation of Connate Water, Porosity and Salinity of Formation Water from the Electrical Log

The resistivity scale used by the electrical logging companies is calculated assuming the electrodes to be points in a homogeneous bed.[5] Therefore, the values recorded must be corrected for the presence of the borehole, thickness of the layers in relation to the electrode spacing, and any other condition different from the ideal assumptions used in calculating the scale.

Consider a borehole penetrating a large homogeneous layer, in which case the electrode spacing is small in comparison with the thickness of the layer. If the resistivity of the mud in the hole is the same as the resistivity of the layer, there will be, of course, no correction for the effect of the borehole. If the resistivity of the mud differs from the resistivity of the layer, there will be a correction. Table 1 shows approximately how the presence of the borehole changes the observed resistivity for various conditions. The third curve, or long normal, of the Gulf Coast is considered because this arrangement of electrodes gives very nearly a symmetrical picture on passing a resistive layer and has sufficient penetration in most instances to be little affected by invasion when the filtrate properties of the mud are suitable.

TABLE 1.—*Effect of Borehole on Infinitely Large Homogeneous Formation*

True Resistivity of Formation, Meter-ohms	Observed Resistivity on Electric Log			
	In an 8-in. Borehole		In a 15-in. Borehole	
	Resistivity of Mud in Hole (at Bottom-hole Temperature) of		Resistivity of Mud in Hole (at Bottom-hole Temperature) of	
	0.5 Meter-ohms	1.5 Meter-ohms	0.5 Meter-ohms	1.5 Meter-ohms
0.5	0.5	0.5	0.5	0.5
1	1	1	1	1
5	6	5	5	5
10	12	11	11	11
50	65	65	50	55

The values in Table 1 have been calculated assuming a point potential "pick-up" electrode 3 ft. away from a point source of current, other electrodes assumed to be at infinity, and it has been found that the table checks reasonably well with field observations. Checks were made by: (1) measuring the resistivity of shale and other cores whose fluid content does not change during the coring operation and extraction from the well; (2) measuring the resistivity of porous cores from water-bearing formations after these cores were resaturated with the original formation water. Adjustment due to temperature difference, of course, is necessary before the laboratory measurement is compared with the field measurement.

TABLE 2.—*Effect of Formation Thickness, No Borehole Present*

True Resistivity	Observed Resistivity		
Layer between Large Shale Bodies Having Resistivity of 1.0 Meter-ohms	Thickness of Layer		
	24 Ft.	16 Ft.	8 Ft.
1	1	1	1
5	5	5	3
10	10	9	6
20	20	19	11

The correction at the higher resistivities appears to be appreciable. However, in the Gulf Coast when the value of R_o is low the correction is not so important. For example, assume a friable oil sand whose true resistivity is 50 meter-ohms and whose resistivity when entirely water-bearing is 0.50 meter-ohms; the connate water would occupy about 0.10 of the pore volume (Eq. 5). However, if the observed value on the log, 65 meter-ohms, were used without correcting for the borehole, the connate water would be calculated to occupy 0.09 of the pore volume. Therefore, although the effect of the borehole size and mud resistivity on the observed resistivity readings may be appreciable, the resultant effect on the calculated connate-water content of the sand is not important.

When the thickness of the formation is very large in comparison with the electrode spacing, there will, of course, be no correction to make for the thickness of the layer. However, when the thickness of the formation approaches the electrode spacing, the observed resistivity may be very different from the true value. Table 2 shows approximately what the third curve (long normal) of the Gulf Coast would read for certain bed thicknesses and resistivities. It is assumed that large shale bodies are present above and below the beds, at the same time neglecting the presence of the borehole and again assuming point electrodes.

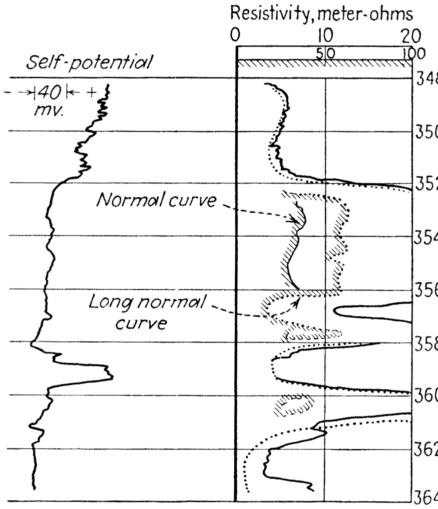

FIG. 4.—ELECTRICAL LOG OF AN EAST TEXAS WELL.

Diameter of hole, 7⅞ in.; mud resistivity, 3.4 at 85°F.; bottom-hole temperature, approximately 135°F.

Tables 1 and 2 assume ideal conditions, so if the sand is not uniform, or if invasion affects the third curve, the observed resistivity values may deviate farther from the true value. The magnitude of the influencing factors, of course, will limit the usefulness of the observed resistivity value recorded on the log. Invasion of the mud filtrate is probably the most serious factor; however, as previously mentioned, it can often be controlled by conditioning the mud flush for low filtrate loss.

Fig. 4 shows a log of an East Texas well. The observed resistivity on the long normal curve for the interval 3530 to 3560 ft. is 62 meter-ohms, or, from Table 1, approximately 50 meter-ohms after correcting for the borehole. In this instance the mud resistivity at the bottom-hole temperature of 135°F. is approximately 2.2 meter-ohms.

The interval is thick enough so that there should be no appreciable effect due to electrode spacing. The formation is more or less a clean friable sandstone, so Eq. 5 can be used to approximate the connate-water content. The formation resistivity factor for this sand is approximately 15, using Eq. 2 where $\theta = 0.25$ and $m = 1.8$. The resistivity of the formation water by actual measurement is 0.075 meter-ohms at a bottom-hole temperature of 135°F. Therefore, from Eq. 1, R_o for this sand is $15 \times 0.075 = 1.1$ meter-ohms. This value checks reasonably well with the value recorded at 3623 to 3638 ft. on this log as well as on the many logs from this pool where the Woodbine sand is water-bearing; i.e., 0.9 to 1.5 meter-ohms. The close check obtained between the calculated and recorded resistivity of the water sand indicates that invasion is not seriously affecting the third curve. Solving Eq. 5, the connate water of the zone 3530 to 3560 ft. occupies approximately $\sqrt{\frac{1.1}{50}} = 0.15$ of the pore volume. The accepted value assigned for the connate-water content of the East Texas reservoir is 17 per cent.

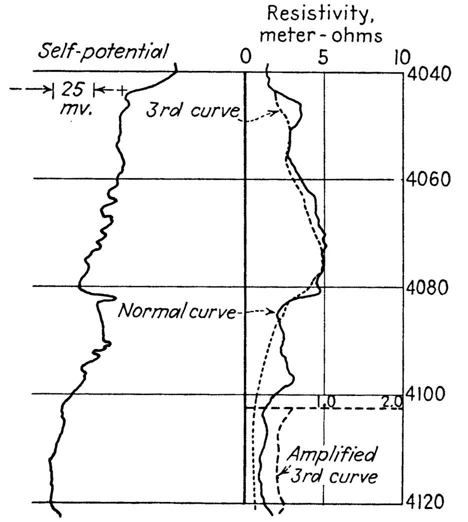

FIG. 5.—ELECTRICAL LOG OF A SAND IN EAST WHITE POINT FIELD, TEXAS.
Diameter of hole, 7⅞ in.; mud resistivity, 1.7 at 80°F.; bottom-hole temperature, 138°F.

An electrical log of a sand in the East White Point field, Texas, is shown in Fig. 5. The observed resistivity at 4075 ft. is approximately 5 meter-ohms. The value of F for this sand by laboratory determination is 6. The sand is loosely consolidated, having 32 per cent porosity average. The resistivity of the formation water by direct measurement is 0.063 meter-ohms at the bottom-hole temperature of 138°F. Therefore, $R_o = 6 \times 0.063$ or 0.38 meter-ohms. This checks well with the value obtained by the electrical log between the depths of 4100 and 4120 ft., which is 0.40 (see amplified third curve). Therefore, invasion probably is not seriously affecting the third curve. From Tables 1 and 2 it appears that the borehole and electrode spacing do not seriously affect the observed resistivity at 4075 ft. The connate water is approximately $\sqrt{\frac{0.38}{5.0}}$, or 0.27.

Other uses of the empirical relations may have occurred to the reader. One would be the possibility of approximating the maximum resistivity that the invaded zone could reach (when formation water has a greater salinity than borehole mud) by Eq. 1, where R_w would now be the resistivity of the mud filtrate at the temperature of the formation and F the resistivity factor of the formation near the borehole. By knowing the maximum value of resistivity that the invaded zone could reach, the limits of usefulness of the log could be better judged. For example, assume that a porous sand having an F factor of less than 15 was under consideration. If the mud filtrate resistivity were 0.5 meter-ohms, the resistivity of the invaded zone, if completely flushed, would be $15 \times 0.5 = 7.5$. Thus the observed resistivity values of this sand up to approximately 7.5 meter-ohms could be due to invasion.

ACKNOWLEDGMENT

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DISCUSSION

(H. F. Beardmore presiding)

S. W. WILCOX,* Tulsa, Okla.—This paper recalls some of my own observations on the correlation of the electrical resistance of earth materials with their other physical properties. While Geophysical Engineer for the Department of Highways, of the State of Minnesota, from 1933 until 1936, I was primarily engaged in conducting earth-resistivity surveys prospecting for and exploring sand and gravel deposits. This work was done by two field parties using equipment of the Gish-Rooney type, and was carried out in every part of the state, both winter and summer.

In brief, when a sand or gravel prospect was discovered, in any way, it was detailed by the resistivity survey to outline its extent and to locate test holes for field and laboratory sample analysis. This survey consisted of a grid of "steptraverses" of one or more electrode separations, and for each an "iso-ohm," or equal resistance contour plan map, was drawn.

Several thousand earth-resistivity readings were taken over more than one hundred prospects. In some instances the test pitting was started before the completion of electrical survey and their findings were soon available for checking any suspected correlation theory and confirming what subsurface factors were being measured and how effectively.

From accepted earth-resistivity theory, it follows that within a definite sphere surrounding the electrodes the apparent resistance measurement is uniquely determined from the specific resistance and position of each and all of the particles making up the sphere. Any rational interpretation of these apparent resistance measurements is possible only for the simplest combinations of particles and their specific resistances. Fortunately, soils, subsoils and subsurface rocks, with their embodied fluids and gases, vary greatly in this property among themselves. For example, clay appears to have an average specific resistance of approximately 50 to 150 foot-ohms, whereas for sand and gravel the specific resistance is roughly from 2000 to 5000 foot-ohms. The important feature is the great absolute differences in resistance, consequently a resistance profile across a buried lens of sand or gravel surrounded by clay produces a striking response.

In spite of the amount of control available and the freedom for selecting various electrode intervals, no reliable quantitative predictions could be made that were not related to boundary surfaces. The probable depth to the first discontinuity—namely, the clay-sand contact—could be determined fairly accurately if the thickness of the sand body was considerable. When the depth to the sand was known from independent data, or could be assumed to be constant, it was possible to predict its thickness. If both were known, a good guess might be made regarding the depth to the water table; and, in addition, if all these were known, a surmise could be made about the quality of the sand; i.e., whether it contained organic material or was weathered. Perhaps if the degrees of control were sufficient the porosity of the sand, its grain size, or even its temperature might be predicted.

I observed that few of these variables, even the ones that generally contribute to the bulk of the readings, could be quantitatively separated without additional independent data; therefore my interpretation was necessarily empirical and based on experience. Fortunately, in sand and gravel prospecting the economically most important factors contribute their effects in the same direction. A high apparent resistance indicates either a thin body of highly resistant gravel near the surface, or a thicker one overlain with more clay stripping. Clean gravel is more resistant than weathered, and hard gravel more so than soft.

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* Seismograph Service Corporation.

In practical terms, I found that an apparent resistance reading of 500 foot-ohms for a 20-ft. electrode separation recorded over ground or glacial moraines of southern Minnesota reliably suggested a deposit of sand or gravel worth further investigation. As a matter of record, prospecting in the part of the state where these materials are very scarce, less than 3 per cent of the test holes located on the geophysical information failed to yield granular materials of commercial quality and quantity for at least highway subgrade treatment. Varying the electrode interval gave additional confirmation as to the thickness of the deposit and very little else.

In connection with our field work, we made extensive laboratory studies, attempting to work out the relation between the moisture content of sand and gravel and its specific resistance. These apparently simple experiments were not of much help in clearing up my field interpretations. Several variables were very hard to control in the laboratory.

The analogy between this type of earth-resistivity mapping and electrologging is close. The first measures electrical impedance along a surface generally parallel to the bedding planes; the latter, up a borehole more or less perpendicular to them. The same general limitations and possibilities appear to be common to both methods. Obviously, controls for checking are easier to obtain for plan mapping than for well logging within the depth of effective penetration.

My interpretation problems appeared to be essentially similar to those of electrical well logging where the operator, after observing the character of the resistance and the self-potential curves, tells his client whether pipe should be set. The accuracy of his prediction is based largely on experience and not on slide-rule calculations.

Mr. Archie's paper suggests an experimental attack for expanding and improving the interpretation technique of electrical well logging. Any contribution of this nature that increases its effectiveness is of great value to the petroleum industry. I offer my own experiences and observations to emphasize that he has tackled a difficult research problem and wish him luck.

Dr. A. G. LOOMIS,* Emeryville, Calif.—In the laboratory, we take into account the variations in measured resistivities of sands and tap water by finding out the cause of the variations in resistivity. That is, if the tap water itself varied from day to day, its electrolyte content must vary from day to day and chemical analysis would indicate the change. If sands did not give consistent resistivity readings, the character of the sands (in other words, the formation resistivity factor) probably changed or the kind and amount of water contained in the sand must have varied.

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* Shell Development Co.