Directional Resistivity Measurements in Exploration For Uranium Deposits on the Colorado Plateau

GEOLOGICAL SURVEY BULLETIN 1083-B

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By GEORGE V. KELLER

EXPERIMENTAL AND THEORETICAL GEOPHYSICS

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By George V. Keller

ABSTRACT

A study of the electrical properties of the Morrison formation in the Uravan mineral belt of the Colorado Plateaus province indicated that there is a significant correlation between electrical resistivity and the relative favorability for occurrence of ore. The differences in resistivity were not large enough to provide a recognizable target for standard resistivity field methods, especially where the ore-bearing sandstone member is more than a few hundred feet deep. Measurement of resistivity trends by placing one electrode in a drill hole and spreading the others out radially on the surface seemed to offer a means of exploiting the resistivity-favorability correlation.

Field tests of such directional-resistivity measurements were made in the Spud Patch area in San Miguel County, Colo., and the White Canyon district, San Juan County, Utah. In the Spud Patch area two methods were tried; in one a current electrode was placed in the drill hole, and in the other a potential electrode. The second method was the more tedious but provided the more readily interpretable results. A comparison of the resistivity trends thus determined with the favorability estimated from geologic indexes indicated that directional-resistivity methods could predict the location of favorable areas at distances of 600–1,000 feet with a high degree of success.

In the White Canyon district directional-resistivity measurements were made on the assumption that the conglomerate which is found in many channels filled with the Shinarump member of the Chinle formation has a high resistivity. The measurements were successful in tracing the channel conglomerate where surface conditions were favorable.

INTRODUCTION

The U.S. Geological Survey has carried on a research program to develop practical and economical methods of exploration for the uranium ores of the Colorado Plateau. Although ore occurs in many formations on the Colorado Plateau, most of the important deposits are in the Morrison formation of Late Jurassic age and in the Chinle formation of Late Triassic age. In the Morrison formation in the Uravan mineral belt, the ore bodies form irregular tabular masses within the Salt Wash sandstone member. In the Chinle formation in the White Canyon district, the ore is localized in the Shinarump member in channel scours that have been cut into the underlying Moenkopi formation of Early and Middle(?) Triassic age.

There are many guides to exploration, but the only positive method is drilling: first, at wide spacing to classify areas according to relative favorability for occurrence of ore on the basis of geologic information, followed by drilling at smaller spacing to locate and outline ore deposits.

In hopes of delineating favorable areas and locating ore more rapidly and at less expense, various geophysical exploration methods have been tested. Electrical-resistivity surveys over known ore deposits indicated that although ore cannot be located directly, thick sections of the Salt Wash sandstone member, which have been found to be the most favorable areas for ore occurrence (Weir, 1952), can be traced at depths of a few hundred feet (Davis, 1951). These results were confirmed by electric-logging studies (Keller, 1959) which showed a direct correlation between favorability and the product of sandstone thickness and electrical resistivity. It does not seem likely, however, that standard electrical-resistivity surveys can be of much assistance in exploration for deposits at depths of more than 200 feet. However, the existence of a small but significant resistivity anomaly associated with the favorable areas made it desirable to investigate the use of less conventional resistivity-exploration methods.

As a result of his work in southern Ohio, F. W. Lee (written communication, 1948) suggested that resistivity anomalies of the size of those associated with favorable ground could be detected to depths of 4,000 feet by tracing the direction of resistivity variations from measurements made with electrodes in a drill hole and on the surface around a drill hole. According to Lee, "there often is a decided advantage in making inhole potential observations where there is an underground condition which greatly modifies the electrical-potential distribution. It will be seen that such inhole measurements will assist in determining the location of the geologic body in question, whereas surface observations will produce an entirely different picture."

The use of directional-resistivity surveys in conjunction with wide-spaced drilling to delineate areas favorable for uranium and vanadium, if shown to be reliable, could reduce the number of drill holes necessary and thus reduce the cost and time involved.

Field tests of the method were made in the Spud Patch area, San Miguel County, Colo. (fig. 9), where the Morrison formation is widely exposed and also in the White Canyon district, San Juan County, Utah, where there are ancient channels. The Spud Patch area was chosen for the first tests because there is considerable geophysical information about the Spud Patch area available from earlier surveys

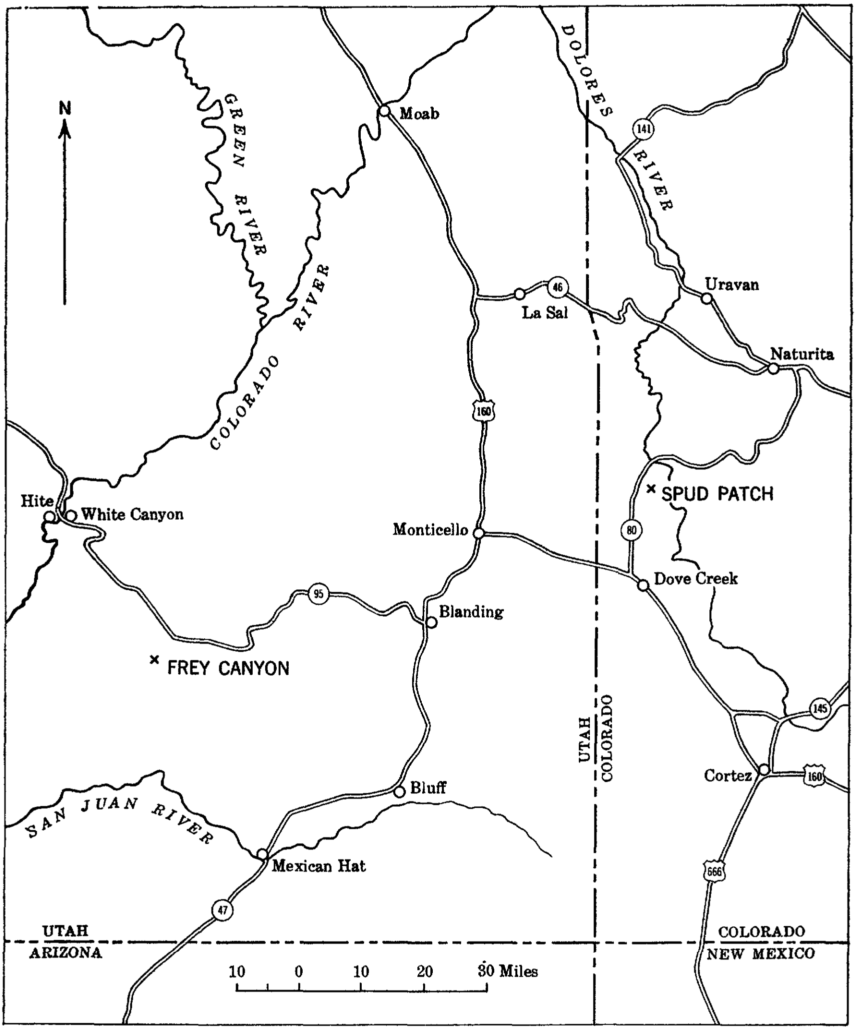


Figure 9.—Index map of Spud Patch and Frey Canyon areas of southwestern Colorado and southeastern Utah showing where field measurements were made.

(Davis, 1951; Keller, 1959); the terrain is flat, soil covered, and open; and there are many drill holes in the area ranging in depth from 100 to 300 feet.

ACKNOWLEDGMENTS

The work described in this report was part of a program carried on by the U.S. Geological Survey on behalf of the Division of Raw Materials, U.S. Atomic Energy Commission. The assistance of Leo J. Miller and other members of the Atomic Energy Commission at the Frey Canyon camp is gratefully acknowledged.

MEASUREMENTS IN THE SPUD PATCH AREA

LOCATION AND GEOLOGIC SETTING

The Spud Patch area is in the southernmost part of the Uravan mineral belt (Fischer and Hilpert, 1952) on the Egnar Plain about 5 miles north of Egnar, Colo. The Morrison formation is widely exposed in this region and dips about 10° northwestward into the Dolores and Disappointment Valleys. In the Spud Patch area the Salt Wash sandstone member is overlain by mudstones and conglomerates of the Brushy Basin shale member ranging in thickness from almost zero to several hundred feet.

PREVIOUS WORK

There are a number of worked-out mines along the exposed rim of the Salt Wash. In 1949, 137 exploratory holes were drilled in an attempt to trace the ore-bearing zones away from these mines. In 1950 and 1951 in a more detailed program of drilling, more than 400 holes were drilled in an area approximately 3 by 5 miles.

An electrical resistivity survey was made in part of the area in 1950 (Davis, 1951). The results indicated that the favorable areas could be determined fairly well by empirical methods of interpretation. In 1952, electrical well logs were made in 100 drill holes in the same area (Keller, 1959). Of these, 44 electric logs showed a complete thickness of the ore-bearing sandstone of the Salt Wash. These logs are summarized in Table 1.

On these logs the area under the resistivity curve through the sandstone member, which ordinarily is ore bearing, was planimetered to find the product of resistivity and thickness. The average resistivity was determined by dividing this area by the thickness of the sandstone. The classification according to favorability was made by geologists on the overall appearance of the cores taken from the drill holes. The semifavorable class, however, is not intermediate to the favorable and unfavorable classes necessarily but includes those drill holes which did not fit in with the geologic guides that were used in determining favorability. On the basis of these figures, it was believed that directional-resistivity variations could be used to predict favorability trends, at least in the Spud Patch area.

METHODS OF MEASUREMENT

A standard electric-logging unit was modified for use in measuring directional-resistivity variations. At first a single-pole electrode array (fig. 10) was used. This consisted of an inhole current electrode, C_1, and a current-return electrode, C_2, placed on the surface at a considerable distance from the hole. Potential-pickup electrodes, P_1, P_2, and P_3, were then placed along a radial line from the drill

TABLE 1.—*Summary of resistivities determined from electric logs in the Spud Patch area*

Drill hole	Depth interval of Salt Wash sandstone member (feet)	Resistivity-thickness product (ohm-m-feet	Average resistivity (ohm-m)
Favorable drill holes			
SP-142	87–160	29,600	405
151	84–184	25,400	254
210	64–172	22,700	210
357	83–138	21,100	293
293	71–119	20,100	303
245	14–74	19,700	270
254	41–109	19,200	283
68	25–104	18,200	179
153	54–131	17,400	285
123	60–124	16,800	220
251	14–58	14,900	229
348	142–195	14,900	207
131	64–210	14,400	108
33	90–164	14,400	232
1	26–64	14,300	223
262	21–69	14,200	214
60	56–148	13,700	167
284	110–186	13,600	179
323	32–60	13,300	221
306	12–50	13,200	330
42	76–132	13,200	236
117	89–149	10,400	173
80	54–113	10,200	172
38	32–80	7,620	136
Average values	----------	16,400	230
Semi-favorable drill holes			
SP-5	47–134	27,400	206
48	53–145	19,300	241
114	65–137	18,600	273
125	38–133	15,500	218
282	45–116	14,100	199
145	88–155	13,500	224
124	77–110	11,500	201
294	61–115	10,900	203
317	40–93	10,300	165
147	81–126	10,100	207
220	69–89	4,270	213
82	32–69	3,800	82
Average values	----------	13,300	203
Unfavorable drill holes			
SP-10	37–94	18,700	283
8	20–53	9,330	283
77	----------	8,520	196
12	32–58	7,460	287
201	24–128	4,770	46
28	35–104	4,600	75
118	36–57	4,260	203
	----------	4,030	176
Average values	----------	7,710	180

hole at distances of 50, 100, and 200 feet, as the ore-bearing sandstone in the Spud Patch area is at a depth of 50 to 150 feet. The electrodes were lead hemispheres, 5 inches in diameter, placed in shallow holes filled with a solution of sodium chloride. A constant current, com-

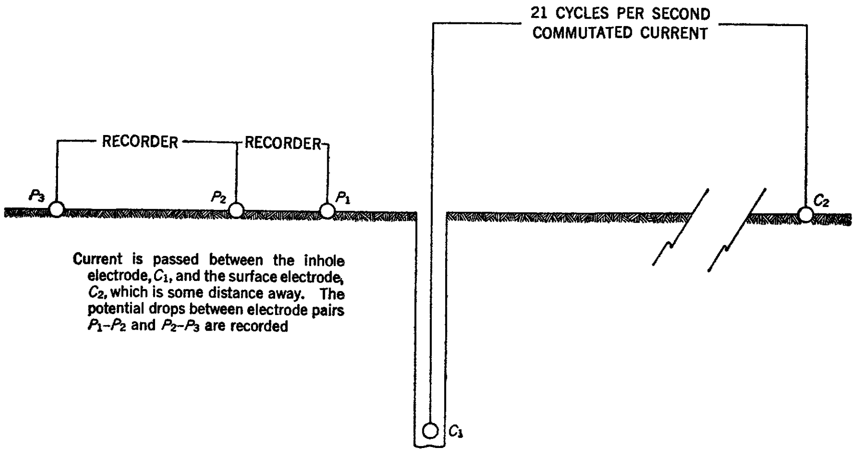


FIGURE 10.—Single-pole method of measuring directional variations in resistivity.

mutated at 21 cycles per second, was passed from the inhole electrode to the distant current-return electrode as the inhole electrode was raised through the drill hole. The potential drop between pairs of the surface electrodes was automatically recorded as this happened, first between the inner pair of electrodes (at 50 and 100 feet) and then between the outer pair of electrodes (at 100 and 200 feet). The measurements were repeated in 8 positions about the drill hole on lines 45° apart. These potential measurements closely resembled the curves ordinarily obtained in electric logging. The recorded potentials were large when the inhole electrode was opposite a sandstone of high resistivity and low when it was in a mudstone of low resistivity.

The relation between the recorded potential differences and ground resistivity varies as the electrode, C_1, is moved through the drill hole even where there is a uniform earth around the drill hole. If the inhole electrode were at the surface, the resistivity, ρ, and recorded potential difference, E, would be expressed by

$$E_{21}/I=\rho/4\pi a \tag{1}$$

where E_{21} is the potential difference from P_1 to P_2, I is the current, ρ is the electrical resistivity of the ground, and a is the spacing between the electrodes. When the electrode is lowered into the drill hole, the relative distances to the several surface electrodes vary, and the equation becomes

$$\frac{E_{21}}{I}=\frac{\rho}{2\pi a}\left[\frac{1}{\left(\frac{d^2}{a^2}+1\right)^{1/2}}-\frac{1}{\left(\frac{d^2}{a^2}+4\right)^{1/2}}\right] \tag{2}$$

where d is the depth of the inhole electrode below the surface. This means that as the inhole electrode is lowered in the drill hole, the potential difference generated at the pickup electrodes decreases, as shown in figure 11. The solid curve in figure 11 shows the relation between the apparent resistivity calculated by use of equation 1 and the true resistivity, as a function of the ratio of the depth of the inhole electrode to the distance between the drill hole and the inner potential electrode.

Because of the inverse relation between the potential about a single-pole current source and distance, the voltage drop between the 2 potential electrodes at 50 and 100 feet, and those at 100 and 200

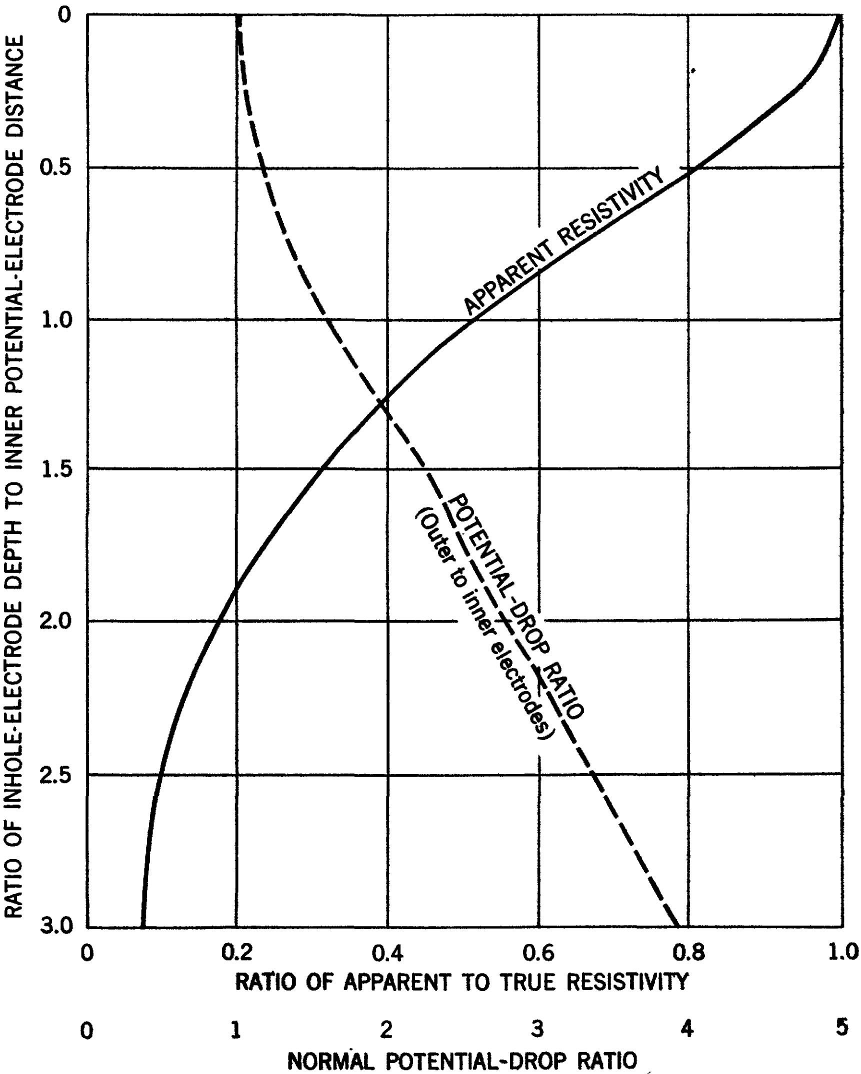


FIGURE 11.—Curves showing ratio of apparent to true resistivity and normal-potential-drop ratio.

feet would be the same in uniform ground when the current electrode, C_1, is at the surface. The ratio of the voltages between the outer and the inner pairs of pickup electrodes will ordinarily be somewhat greater than unity if resistivity increases with depth. As the current electrode is lowered in the drill hole, the voltage between the outer pair of electrodes should decrease more slowly than the voltage between the inner pair, so that the ratio of the outer to inner voltages should increase as indicated by the dashed curve in figure 11. The field data did not conform to these predictions even though resistivity increased with depth. In order to apply theoretical techniques to the interpretation of these data, it would be necessary to calculate curves for 2 or 3 layers rather than a uniform earth, and this would be a complicated procedure.

As there was not a theoretical basis for the interpretation of the single-pole data, an empirical approach was tried. The recorded data were plotted on polar graphs, and the results were compared with the distribution of favorability in the Spud Patch area. On any particular set of logs, a depth within the ore-bearing sandstone was chosen, and corresponding voltages were read for each pair of pickup electrodes and for each orientation. These voltages, and the ratio of the outer voltage to the inner voltage, were plotted as a function of direction on polar graphs. On many of these graphs a maximum direction can be inferred from the distance-resistivity patterns, but in general the results were discouraging. The directions shown by the graphs of the voltage between the outer electrodes, the voltage between the inner electrodes, and the ratio of the two voltages were not always consistent.

In spite of that fact, an attempt was made to correlate each set of data with favorability. Drill logs were available from each of the drill holes for comparison with the geophysical measurements, but only the qualitative indications of favorability such as "favorable," "semifavorable," and "unfavorable" had been assigned to these logs. Doris Weir (1952) has pointed out the advantages of a favorability scale consisting of weighted numerical values for each of the geologic factors used as ore guides, and I have followed her suggestion in determining favorability indexes for the drill holes in which directional resistivity measurements were made and for adjacent drill holes.

In the favorability scale as originally set up, quantitative measurements of sandstone thickness, thickness of the gray-green mudstone at the base of the sandstone, the ratio of red to green mudstone within the sandstone, and qualitative estimates of the relative amount of crossbedding and the carbon and iron oxide spotting the sandstone were used. For the present work only the summaries of the geologic logs were available, and the only factor known quantitatively was the sandstone thickness. For this reason the favorability indexes are subject to errors resulting from a shift in emphasis on the features recorded in the log summaries for each of the 3 drilling years. In assigning numerical values to the different factors, the following weights were used:

1. Sandstone thickness: Zero points for thickness of less than 30 feet to 8 points for thicknesses of more than 200 feet.
2. Thickness of gray-green mudstone at the base of the sandstone: Zero for none to 8 points for a "very thick" unit.
3. Color of the mudstone splits within the sandstone: Zero points for all red to 8 points for all green.
4. Radiation anomalies: Zero points for none, 4 points for a trace, 6 points for a trace to 0.1 percent eU, and 8 points for more than 0.1 percent eU.
5. Appearance of the sandstone: 1 point for "poor," 3 points for "fair," and 6 points for "good."
6. Presence of carbonaceous material: Zero points for none, 1 point for "scarce," 2 points for "some," and 4 points for "abundant."
7. Presence of iron-oxide spotting: 2 points, if mentioned.

Numerical indexes were determined in this way for 57 drill holes in which electric logs had been run. These indexes do not always agree with the geologist's qualitative estimate of favorability, but the correlation with electric log data is excellent (fig. 12).

In order to compare the favorability with the directional-resistivity patterns, a contour map of favorability was prepared from the numerical indexes (fig. 13), then a circle with a radius of 600 feet was drawn about each drill hole in which measurements had been made, and the highest value of favorability intersected by this circle was used to define the direction (or trend) toward maximum favorability (column 4, table 2).

It might be expected that the best correlation between favorability and resistivity would be obtained by using the favorability at about 200 feet, as 200 feet is the maximum electrode spread. However, the favorability contours cannot be determined on such a fine scale. The distance of 600 feet was selected because it is the average spacing of the drill holes considered in preparing the favorability map. As favorable areas probably have dimensions of several thousand feet, it is reasonable to expect that favorability trends controlling resistivity variations over distances of 200 feet will be reflected on the favorability map at 600 feet.

To estimate the reliability of the directions predicted by the resistivity data, the angle between the resistivity trend and the direction toward greatest favorability was measured for each set of data. If these two directions were randomly oriented with respect to each

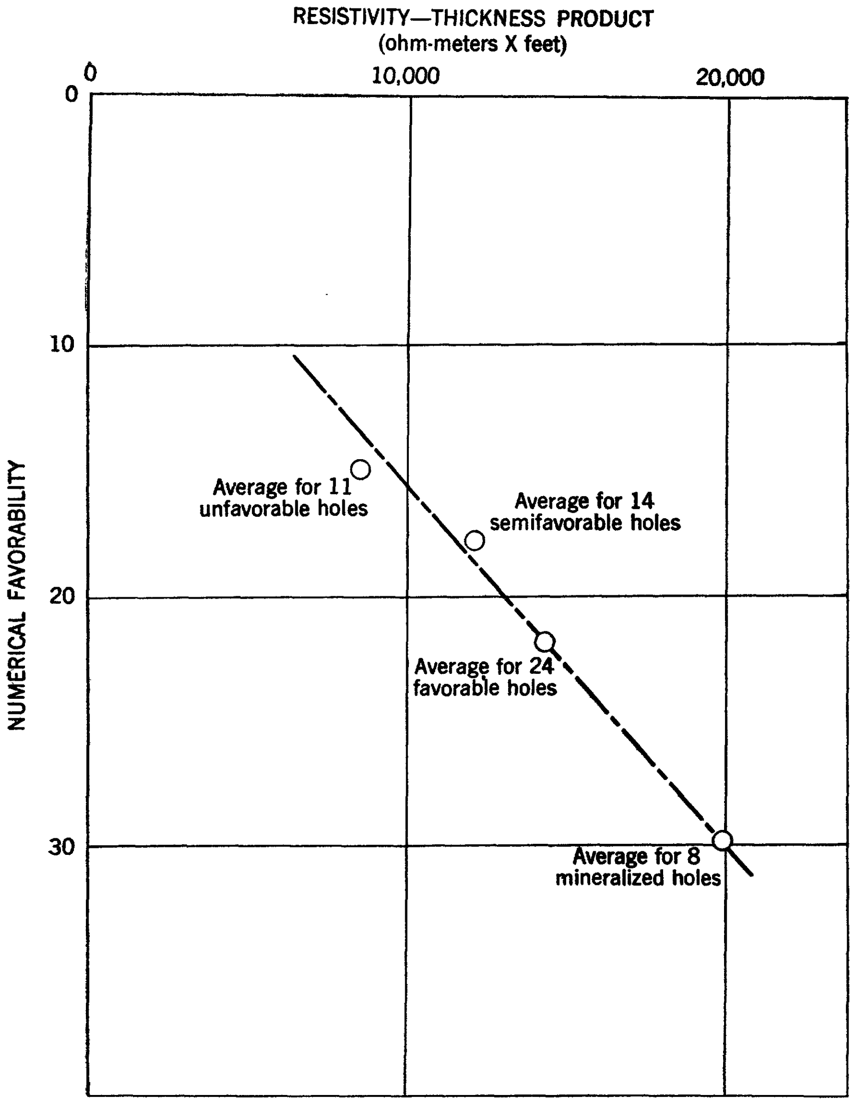


FIGURE 12.—Numerical favorability versus resistivity-thickness product.

other, then for large numbers of measurements the absolute value of the average angle of error would be 90°. An angle of less than 90° would indicate some correlation between the resistivity trend and direction of favorability. The results of such a study for the single-pole data are given in table 3.

The results of the single-pole group of measurements were negative. There is but 1 chance in 11 that any of the resistivity parameters

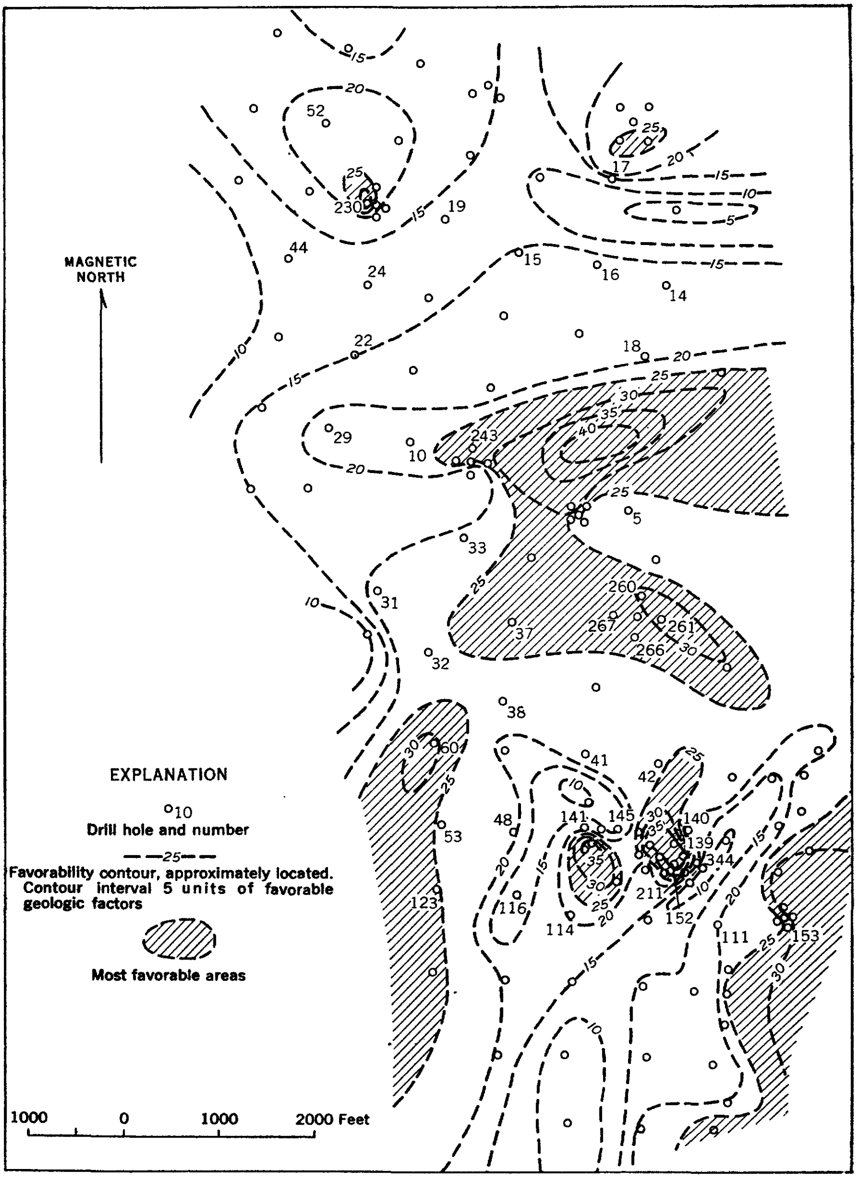


FIGURE 13.—Contour map showing favorability for the occurrence of uranium ore based on geologic factors in the Spud Patch area.

studied give any better than a random estimate of the direction toward maximum favorability.

Because of the discouraging results, the single-pole method was discontinued in favor of the Lee partitioning system. In this system, four equally spaced surface electrodes are placed on a line centered

TABLE 2.—*Resistivity trends determined from single-pole data*

[All trends are expressed as angles measured counterclockwise from magnetic north]

Drill hole	Maximum trend of E_{21}	Maximum trend of E_{32}	Maximum trend of ratio E_{32}, E_{21}	Maximum trend of favorability
SP-1	55	10	345	80
8	130 or 340	70	60	240
9	130	25	330	225
10	75	25	20	280
19	70	110	250	60
31	225	45	185	272
37	225	65 or 340	45	330
38	215	100	90	350
41	120	315	330	320
42	195	105	45	355
48	45	70 or 250	240	98 or 250
60	45	185	170	140
111	100	200	195	280
114	225	220	135	348
116	335	220	45	302
118	120	30	40	0
125	60	300	260	235
131	120	45	45	275
143	70 or 250	130	40	285
148	20	15	270	315
243	30	35	45	275
244	265 or 15	120	310	300
260	100 or 270	250	240	88

about a drill hole (fig. 14). A fifth electrode is then placed in the drill hole opposite the formation being studied. Current is passed between two of the surface electrodes, one on either side of the drill hole; and the potential drop is recorded between the inhole electrode and the remaining surface electrodes, first on one side of the drill hole and then on the other. Measurements are made at 6 electrode orientations, or on lines 30° apart around the drill hole, so that resistivities are obtained in 12 directions.

A group of 38 directional-resistivity measurements were made with this system in the Spud Patch area. The inner surface electrodes

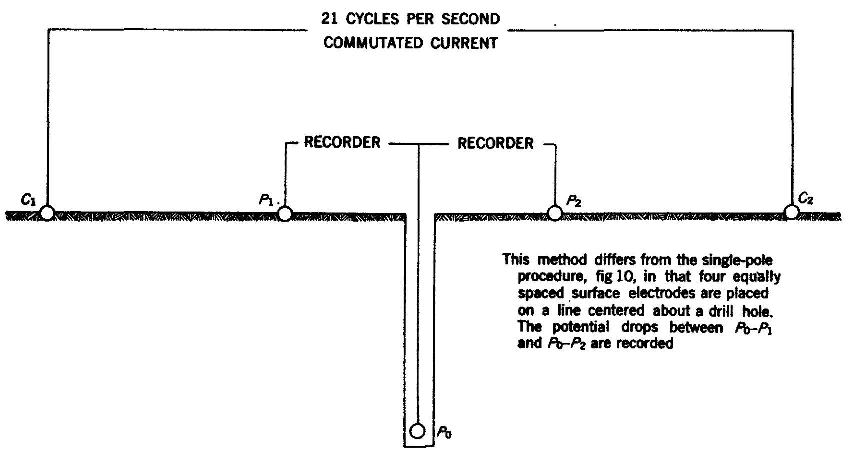


FIGURE 14.—Lee partitioning method of measuring directional variations in resistivity.

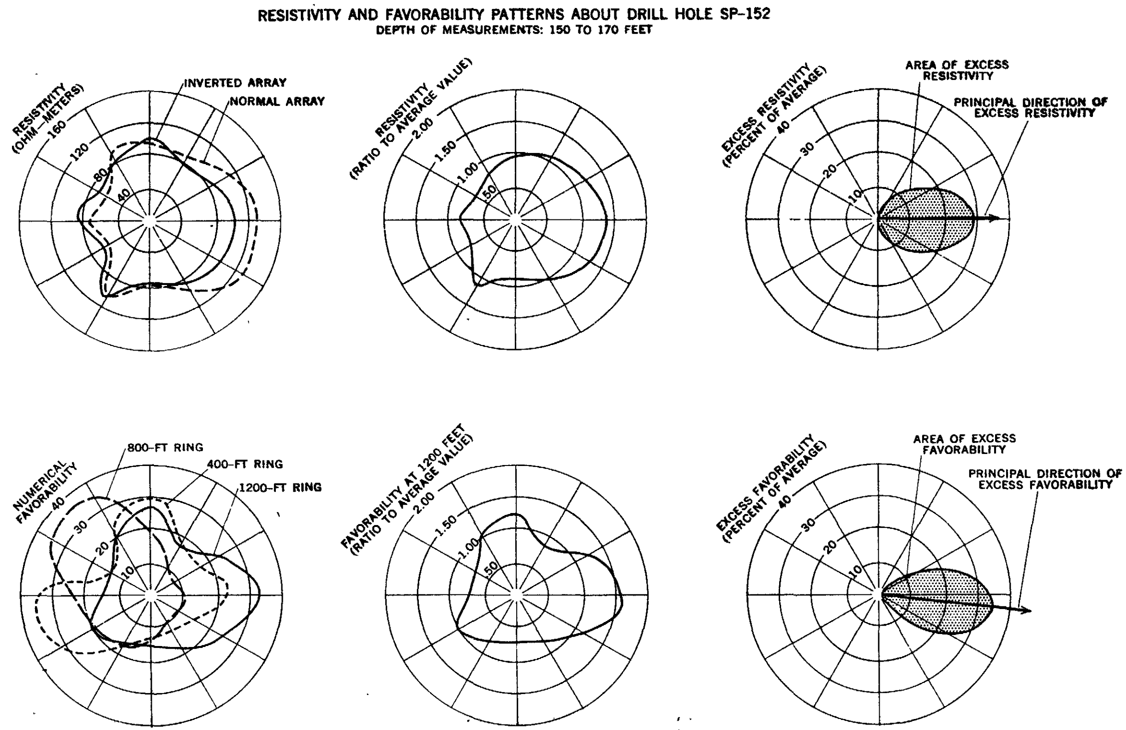
TABLE 3.—*Reliability of predictions by single-pole data*

	Mean error angle (degrees)	Standard deviation of error angle (degrees)	Standard deviation of mean error angle (degrees)	Probability of significant prediction success
Voltage measured between inner electrodes	95	110	23	0.173
Voltage measured between outer electrodes	94	108	23	.138
Potential-drop ratio	87	103	22	.107

were placed at distances of 67 feet on either side of the drill hole, and the outer electrodes were placed at 200 feet. The same electrode spacings were used about all 38 drill holes because the Salt Wash was at about the same depth throughout the area. During the measurements a constant current was passed first between the outer two surface electrodes C_1 and C_2, and the potential drop was measured from the inhole electrode P_0 to the inside surface electrodes P_1 or P_2. In many places a repeat set of measurements was made with the positions of the surface current and potential electrodes being reversed —that is, a constant current was passed between the inner two surface electrodes, and the potential drop was measured between the inhole electrode and the outermost surface electrodes. In all these logs it was found that the recorded voltage varied as the inhole electrode was raised through the drill hole, being high in zones of low resistivity and low in zones of high resistivity. As 2 measurements, oriented at 180° to each other, were made with 1 electrode spread, it would be expected that the sum of these 2 measurements would be constant, as it would be the potential drop between a pair of surface electrodes P_1 and P_2. This is not so; the sum is greater when the inhole electrode is in a zone of low resistivity than when it is in a zone of high resistivity. Considerable effort was spent during the fieldwork to determine the cause of this discrepancy in the data, but no instrumental cause, such as current leakage, could be found. Subsequent laboratory work (Keller and Licastro, 1959) has indicated that the cause lies in the high dielectric constant and very low conductivity of sandstone rocks in the Morrison. A commutator is used with the power supply to provide a 21 cycles-per-second square-wave current to the ground. The voltage between the pickup electrodes is rectified by a second set of commutator rings coupled mechanically to the current supply rings, before the signal is recorded. In this way the polarity of the pickup is reversed at the same instant the current polarity reverses. If there were no phase shift in the ground, as in ohmic conduction, the rectification by this procedure would be 100 percent efficient. However, if there is a phase shift in the ground, as there is when conductivity is low and the dielectric constant is high, then the commutator will reverse the pickup signal during a current surge. The average voltage after rectification will be less than it should be. This will be particularly noticeable if one of the electrodes is in sandstone, because sandstone rocks cause a larger phase shift than mudstone rocks.

Because of the variations in voltage caused by this phase shift, the average drop in potential over a 20-foot interval was used for interpretation rather than values at a single depth. The average drop was determined by planimetering the chosen area under the recorded curves. The manner in which these data were handled is shown in figure 15. The resistivities determined by planimetering were plotted against direction, as shown in the upper left hand diagram. Two curves are presented, one for each arrangement of surface current electrodes. The upper center plot shows the same data after averaging; that is, first, the 2 values for a given direction are averaged; second, these values are divided by the average for all 12 directions; and third, an average is formed for every set of 3 adjacent values. The first procedure is designed to eliminate baseline errors and reduce the errors caused by contact resistance at the surface electrodes. The second step is designed to reduce all the data to a comparable scale. The moving average used in the third step is intended to reduce the effect of one-point anomalies, which are probably due to instrumental errors. The upper right-hand plot shows the method which was used to determine the direction of maximum resistivity trend. As previous work had indicated that directions of high resistivity would be the ones most likely to be associated with favorability, only the amounts of resistivity in excess of the average for any one drill hole were plotted. These excess resistivities were used to define a direction of maximum resistivity.

For comparison of these data with favorability, the map shown in figure 13 was used. About each drill hole in which measurements were made, 4 circles with radii of 400, 800, and 1,200 feet were drawn. Then 12 radii were drawn in each of these circles to correspond to each of the directions for which resistivities had been measured. The numerical favorability was taken from the map at the intersection of each of the 12 radii with each of the 4 circles. These data were handled in the same manner as the resistivity data, as shown in the 3 lower diagrams of figure 15. The individual favorabilities were plotted as a function of direction, as shown in the lower left hand plot. Then, the data for the 1,200-foot ring were averaged in the same manner as the resistivity data, as shown in the lower center plot. Finally, the favorability in excess of the average was plotted separately, as shown in the lower right hand plot of figure 15. The graphs of excess-favorability plots and the excess resistivity for 20 drill holes are shown in figure 16.



STEP A.—VALUE OF RESISTIVITY OR NUMERICAL FAVORABILITY PLOTTED AS FUNCTION OF AZIMUTH

STEP B.—DATA AVERAGED AND PLOTTED AS RATIO TO AVERAGE VALUE

STEP C.—VALUES GREATER THAN UNITY PLOTTED TO FORM EXCESS GRAPH

FIGURE 15.—Example of the treatment of data obtained with the Lee partitioning method showing steps in reducing the data.

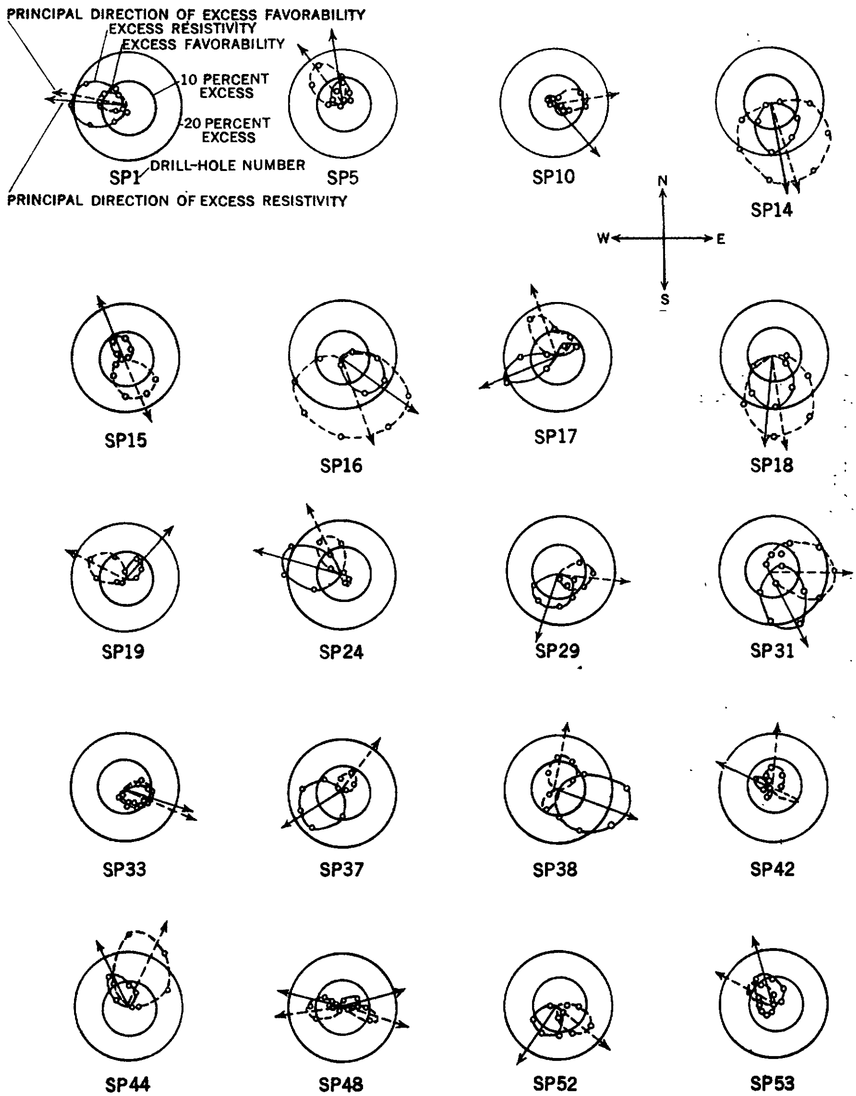


FIGURE 16.—Patterns of directional resistivity and favorability for typical drill holes.

The first step in the comparison of the resistivities with the favorabilities consisted of a statistical analysis of the correlation between individual values of both factors for each of the four rings on which favorability had been determined. The resistivity data were divided into seven groups, according to increasing magnitude. Then the average relative favorability corresponding to the groups of resistivity data was determined. The results are summarized in table 4.

TABLE 4.—*Summary of a statistical study of directional-resistivity data obtained with the Lee partitioning method*

Range of resistivity (ratio to average)	400-foot ring		600-foot ring		800-foot ring		1,200-foot ring	
	Cases	Average favor-ability	Cases	Average favor-ability	Cases	Average favor-ability	Cases	Average favor-ability
<0.80	51	1.009	50	0.970	41	0.954	59	0.968
0.80–0.89	48	.964	64	.957	67	.987	56	1.014
0.90–0.95	58	.980	51	.994	53	.961	54	.975
0.96–0.99	59	.958	55	.994	50	1.019	44	.969
1.00–1.04	49	1.065	33	1.040	40	1.009	48	.977
1.05–1.09	59	1.009	52	.986	58	1.031	49	1.035
1.10–1.19	52	1.014	56	1.031	58	1.005	49	1.013
>1.19	47	.992	56	1.024	51	1.035	59	1.031
Comparative probabilities [1]	0.9999		0.9996		0.9995		0.9992	

[1] Probability that the favorability corresponding to resistivity groups less than 1.00 is significantly less than that for resistivity groups greater than 1.00.

The last line of this table indicates that there is a highly significant increase in favorability in those directions which show higher-than-average resistivities. There is but one chance in several thousand that these results could have been obtained from a random set of data.

If the individual groups in the table are considered, the results are not so convincing. Only those groups of data with a resistivity 10 percent greater than, or less than, average correspond to significant variations in favorability. In other words, small increases or decreases in resistivity can be correlated with small increases or decreases in favorability, but large variations in resistivity cannot be correlated well with large variations in favorability.

The lower degree of correlation between the very large deviations from the average may be due to the fact that these large deviations are more likely to be errors, or that the errors involved may tend to be all in one direction. The frequency distributions of resistivities and favorabilities are shown in figure 17.

The difficulty of our problem is apparent when it is realized that the average variations in favorability or resistivity being considered are only 10 percent. As the favorability distribution is grouped so closely about unity, it is highly probable that if a resistivity considerably larger or smaller than the average is obtained because of a random error, the favorability associated with it will be close to unity. For this reason, errors will all tend to be in one direction when the end classes of the two distributions are compared. This may in part explain why there is a better correlation of small variations in resistivity and favorability than large ones.

In order to find at what distance from a drill hole that resistivity data best predict favorability trends, the data of table 4 were used to compute correlation coefficients between resistivities and favor-

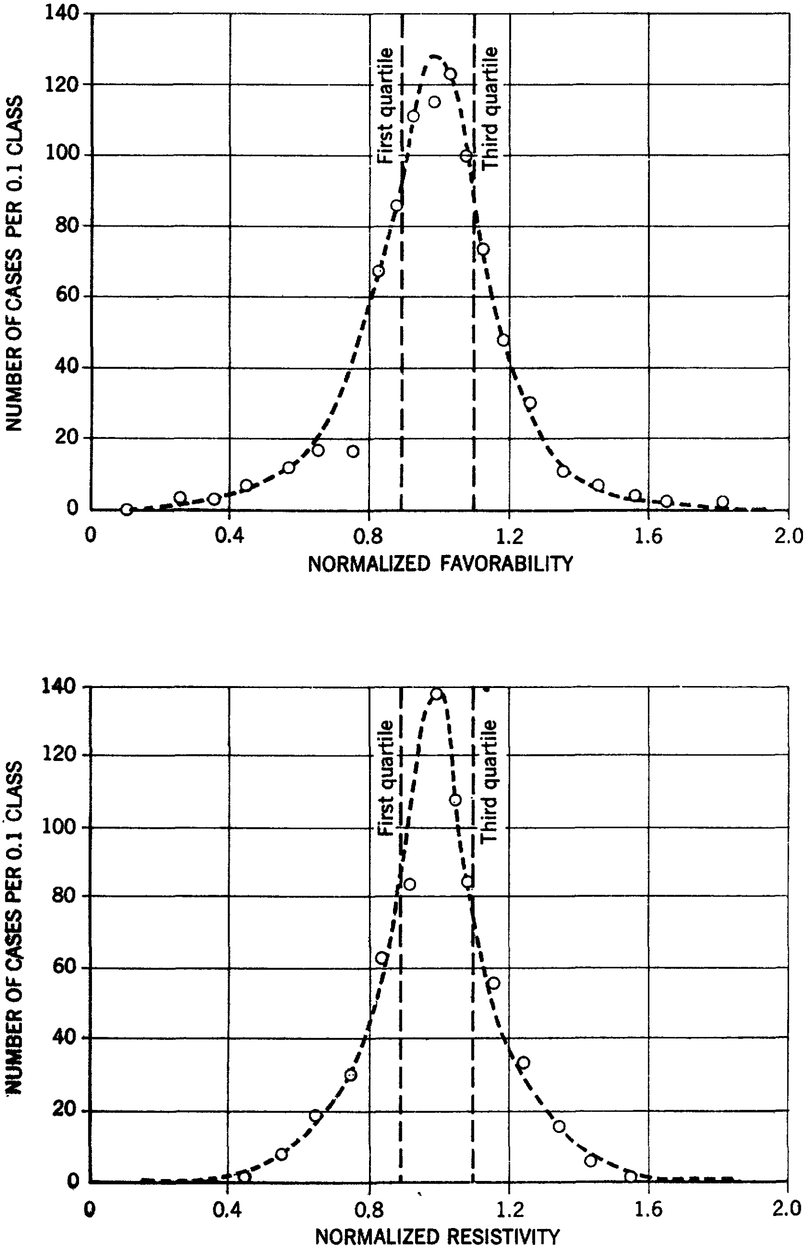


FIGURE 17.—Frequency distribution of favorability and resistivity.

abilities for each of the four rings. The results are presented graphically in figure 18. The correlation coefficients are less than 0.2 in four cases, indicating a very poor correlation. However, because there is a large amount of data involved (about 500 sets of values for each computation), these correlations are significantly better than zero.

The computations indicate that the best prediction from resistivity data is obtained at distances of 600 to 800 feet from the drill hole under study. A prediction cannot be tested very close to a drill hole and is very poor at distances of more than 1,500 feet. It might be expected that the prediction would be best at distances of a few hundred feet, the maximum electrode spacing that was used. Figure 18 merely illustrates that no fair estimate of correlation can be obtained on a scale finer than the grid used in contouring the favorability map of figure 13. The success of prediction of the resistivity data may actually be better at shorter distances, but the information to check this is not available.

As a more realistic measure of the ability to predict direction of favorability trends from the resistivity data, the direction of greatest excess resistivity, as defined in figure 16, was compared with the

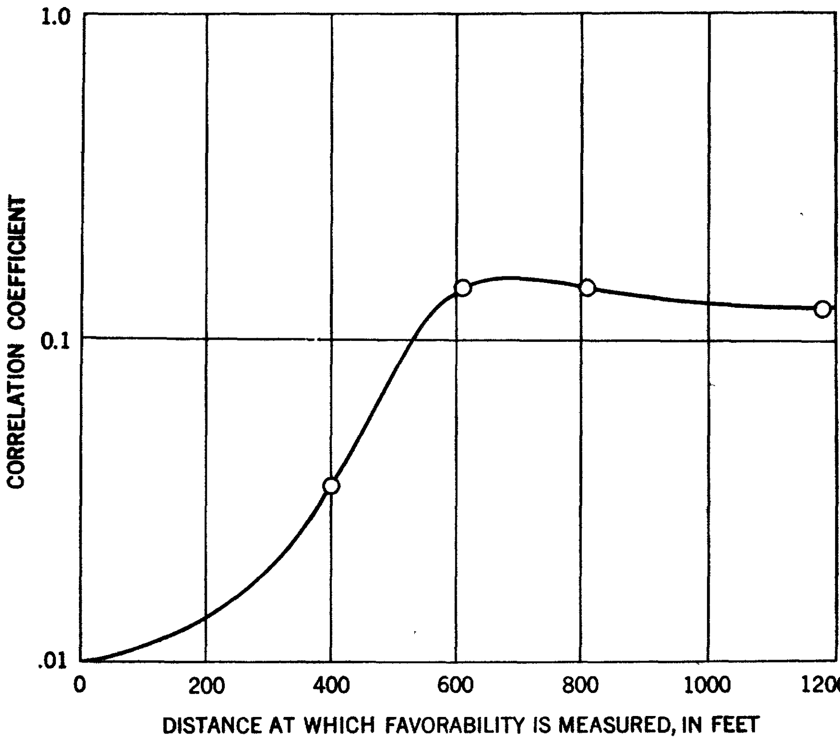


FIGURE 18.—Correlation coefficients between resistivity and favorability.

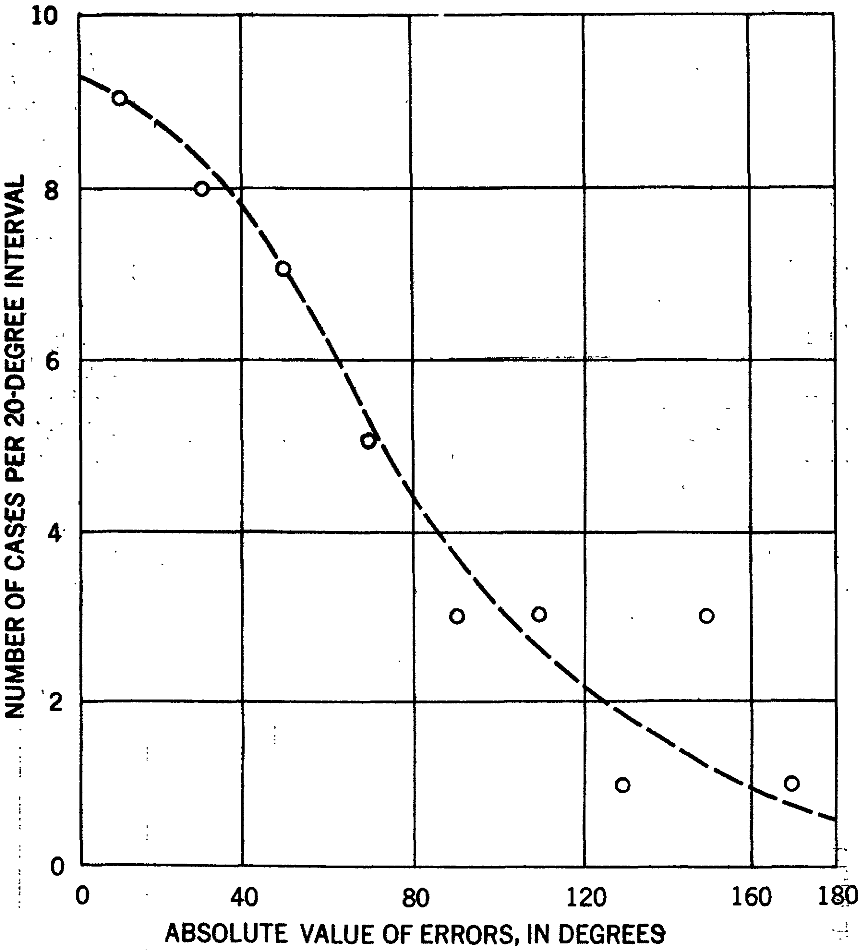


FIGURE 19.—Frequency distribution of the angle between direction of excess resistivity and favorability.

direction of greatest excess favorability for each of the 38 drill holes. Data from the 600-foot rings were used. Figure 19 shows a frequency-distribution graph for the angle between these two directions. These data are summarized in table 5.

The standard deviation of this distribution is 75°, and the mean absolute angle of error is 58°. If there were a uniform distribution of angles from −180° to 180°, as there would be if there were no correspondence between the directions of maximum resistivity and favorability, the average angle between the two would be near 90° for a large enough number of cases. The most probable standard deviation for the average angle was calculated to be 11.7°, so that the difference between 58° and 90° is 2.82 times as great as the standard deviation of the mean. Probability tables show that the chances are

TABLE 5.—*The angles, in degrees, between the directions of greatest favorability and greatest resistivity measured with the partitioning system*

Drill hole	Direction of excess resistivity	Direction of excess favorability	Angular error
SP-1	85	80	5
5	5	35	−30
10	215	280	−65
14	193	195	−2
15	22	200	−178
16	235	195	40
17	110	18	92
18	175	190	−15
19	320	60	−100
24	72	20	52
29	165	264	−99
31	206	272	−66
33	252	252	0
37	125	330	155
38	252	350	−98
42	60	355	65
44	22	340	42
48	72 and 285	98 and 250	−26 and 35
52	150	230	−80
53	15	55	−40
60	215	140	75
111	65	280	145
114	90	348	102
116	255	302	−47
123	355	100	−105
139	250	260	−10
140	70	28	42
141	260	285	−25
145	288	320	−32
152	267	257	10
153	40	267	133
211	308	265	42
230	78	30	48
243	130	275	−145
260	130	88	42
266	72 and 260	75 and 280	−3 and −20
267	38	45	−7
344	262	238	24
Average			−1.4

200 to 1 that this difference is caused by a significant correlation between resistivity and favorability rather than by chance.

An average error of 57° is large, but this may in part be owing to the errors involved in the determination of the directions of excess resistivity and favorability. The largest errors are probably those which enter into the determination of the direction of excess favorability. Favorabilities were estimated from qualitative geologic log summaries rather than from quantitative measurements; and as several of the factors involved were recorded in only a most general manner, errors could enter into the numerical values assigned to these factors. The magnitudes of the possible errors, given as estimated standard deviations, were probably as follows:

	Points
Thickness of sandstone	0
Thickness of basal mudstone	3
Color of mudstone splits	2
Radiation anomaly	0
Appearance of sandstone	2
Presence of carbonaceous material	1
Presence of iron oxide spotting	1

If it is assumed that these errors are not interrelated, the resultant numerical favorability should have an error with a standard deviation of 4⅛ points. From this factor the average error in the direction of excess favorability can be estimated. Ordinarily, the favorability pattern about a drill hole is determined by the 4 neighboring drill holes, even though 12 values of favorability were taken from the contour map of figure 13 in each case. From the frequency distribution of favorability values (fig. 17), it can be assumed that in the average case, one of these 4 drill holes will have a favorability of 32, two of them will have a favorability of 24, and the fourth will have a favorability of 16. This hypothetical case is illustrated in figure 20.

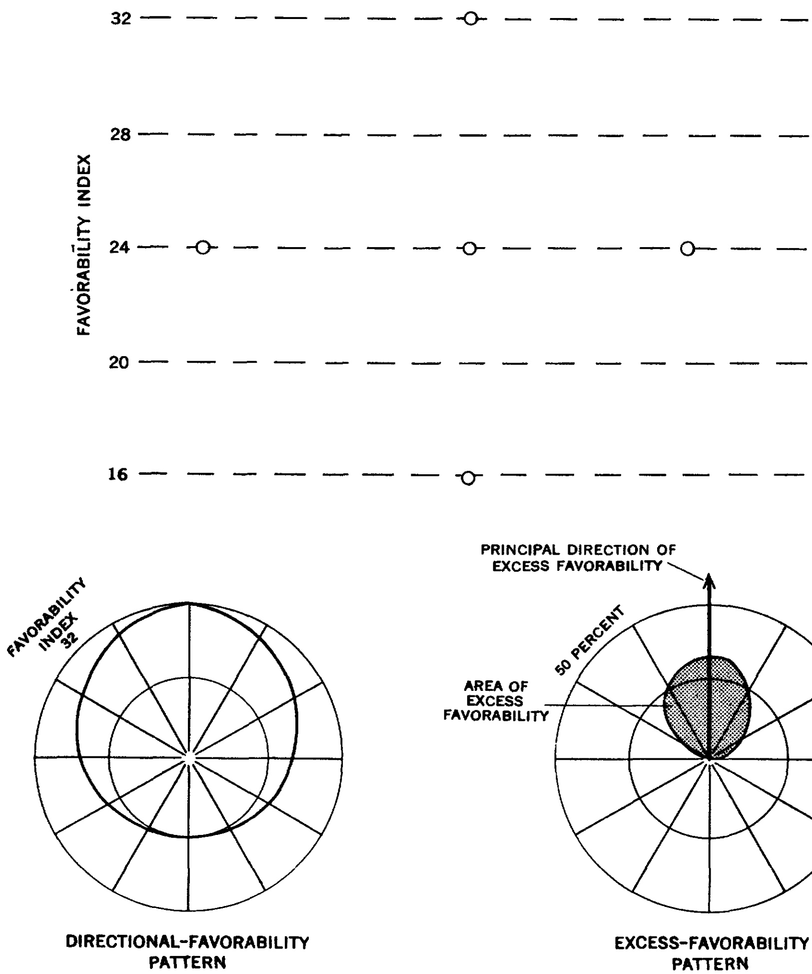


FIGURE 20.—Hypothetical favorability distribution about an average drill hole.

It is then assumed that these are the actual favorabilities pertaining to each of the drill holes; but that in the process of evaluating the core descriptions, an error with a standard deviation of 4¼ points is introduced. This means that the difference between any 2 favorabilities will have a standard deviation of 6 points (the square root of the sum of the squares of the 2 deviations). The excess favorability for the hypothetical case is 8 points, only slightly greater than the errors involved. The excess favorability equals the standard deviation at an angle of 73° from the direction of greatest favorability. This means that 68 percent of the time the favorability direction determined from the core logs differs by 73° or less from the actual direction of greatest favorability. This agrees closely with the standard deviation of 74° found between the experimentally determined resistivity and favorability trends.

If it could be said that the above figures are precisely correct, then the standard deviation of the angle between resistivity trends and the true direction of favorability increase would be only 12°. However, the estimation of the errors in favorability is not precise, and the figure "12°" has very little significance. Rather, it can only be said that the errors in prediction are on the average less than 57°, and possibly much less.

MEASUREMENTS IN THE WHITE CANYON DISTRICT

In addition to the fieldwork in the Morrison formation at the Spud Patch, 22 sets of directional-resistivity measurements using the Lee configuration were made in the Frey Canyon area of the White Canyon district in southern Utah.

LOCATION AND GEOLOGIC SETTING

The Frey Canyon area is 60 miles west of Blanding and 30 miles south of Hite, Utah (fig. 9). In this area the rocks are nearly flat lying, with a dip of a few degrees to the southwest, away from Monument uplift. The area is dissected by many canyons, and there are numerous mesas. The base of White Canyon, at an elevation of about 4,800 feet, is formed from the Cedar Mesa sandstone member of the Cutler formation. Above this lies a series of mesas known as the Moss Back, with the Moenkopi formation, the Chinle formation (including the Shinarump member), and the Wingate sandstone exposed on rims. The sandstones of the Chinle and Moenkopi formations are good cliff formers, so in many places there are ledges on the mesa rims a few hundred to some thousands of feet wide.

Uranium ore is found in the Shinarump in the ancient channels that have been cut into the old erosion surface of the Moenkopi formation. These channels range from a few to several tens of feet in depth and are several hundred feet wide. Individual channels may be traced for several miles. In exploration drilling, the holes are generally spaced at 200-foot intervals along a channel after its course has been predicted by drilling near an outcrop. If uranium minerals are found, the channel is outlined by close-spaced drilling about the discovery hole. Generally, from 20 to 50 drill holes are necessary to explore a channel, and these drill holes range in depth from about 20 feet near the outcrop of the Shinarump to 600 feet on the talus slopes of the overlying Chinle.

Electrical-resistivity and natural-potential surveys were carried out in the White Canyon district during 1953, but the results were difficult to interpret because of the complexity of the anomalies in the Chinle formation (W. H. Jackson, written communication). However, it seemed desirable to attempt directional-resistivity measurements in the Shinarump because although no electrical anomaly was known to be associated with the ore, it might be expected that the sandstone in the channel fillings would have a low water content and high resistivity, and it thus could be traced with directional-resistivity measurements. During part of August and September, 1953, measurements were made in 4 channel sections, 3 in the Ears claim drilling area, and 1 in the Bee claim drilling area of Frey Canyon.

A typical electric log through the channel filling of the Shinarump member and overlying Chinle is shown in figure 21. The cross-hatched area shows the channel filled with Shinarump. The resistivity of the channel is so great (about 1250 ohm-meters) that it would probably present an easy target to trace with directional-resistivity measurements. The channel would be easy to find if it were overlain only by mudstones of the Chinle, in which the resistivity is approximately 8 ohm-meters. However, drilling in much of the area was being carried out through the Moss Back member of the Chinle formation, which is about 80 feet thick and in which the resistivity is more than 1000 ohm-meters. The presence of this high-resistivity sandstone makes the interpretation of resistivity measurements uncertain.

In addition to the difficulties caused by the presence of the Moss Back member, the terrain was generally unfavorable for precise resistivity measurements. As the benches on which the drilling was being carried out are relatively narrow, many of the drill holes are close to rims. These rims would be expected to distort the directional-resistivity patterns. In much of the area the benches are steeply sloping, rather than flat, and covered by high-resistivity float. Not only did these factors make the field procedure difficult, but they also reduced the reliability of the measurements. Inasmuch as these conditions are typical of the areas in which the Shinarump is found, the utility of directional-resistivity measurements had to be evaluated from two points of view. First, it had to be established that there was

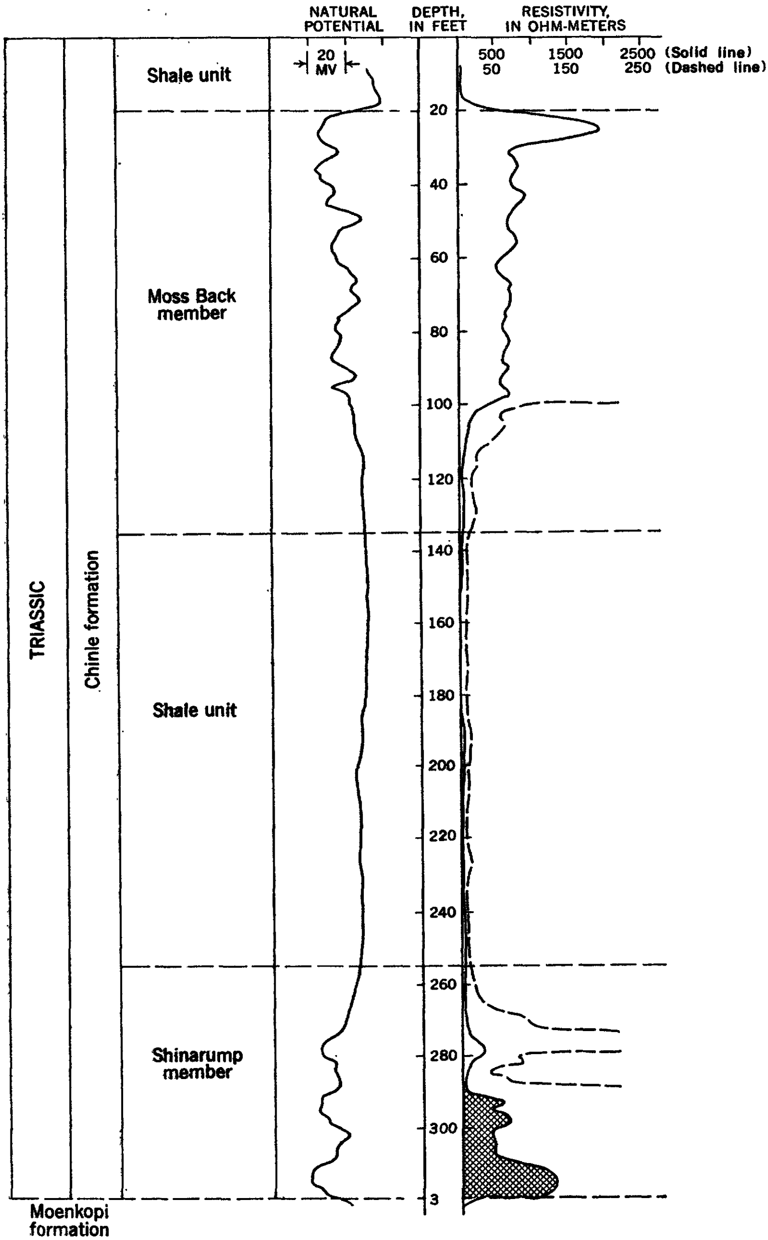


FIGURE 21.—Typical electric log of a section of the Chinle formation showing natural-potential and resistivity measurements. Cross-hatched pattern indicates part of resistivity curve corresponding to the Shinarump channel.

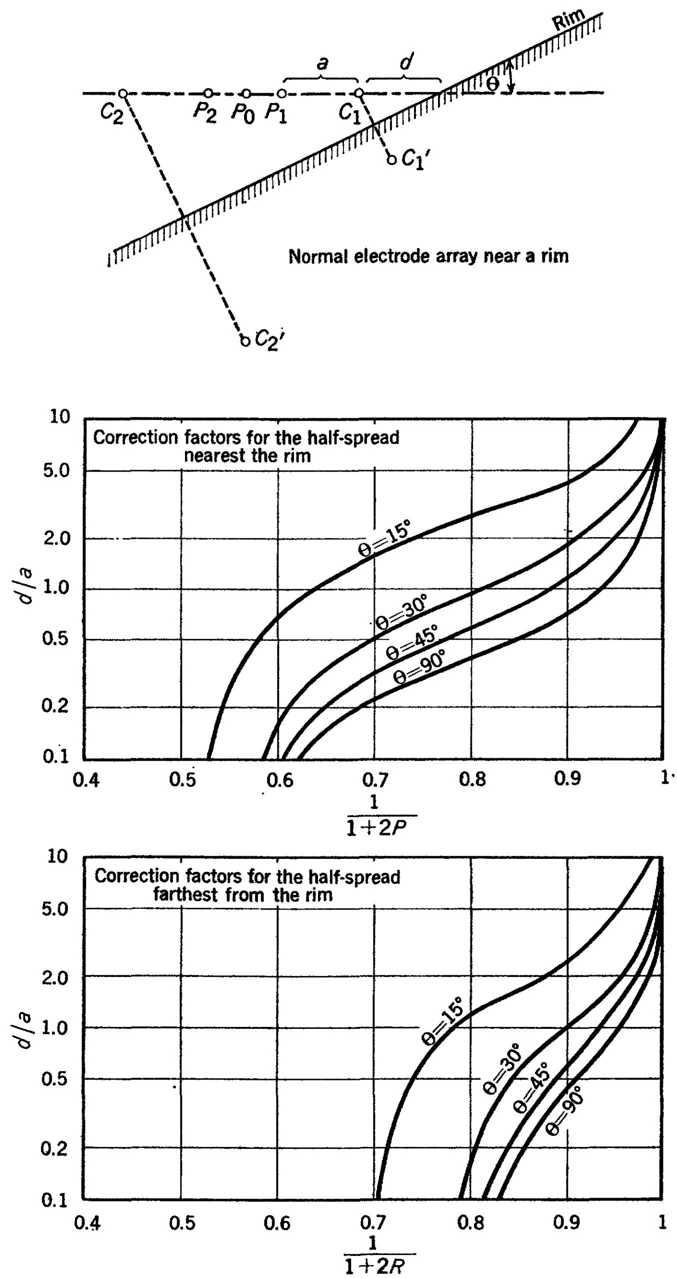


FIGURE 22.—Effect of a rim on the standard Lee arrangement.

a sufficiently large resistivity anomaly associated with Shinarump-filled channels to serve as a tracer; and second, it had to be shown that the disturbing terrain effects could be corrected or neglected.

The effect of rims can be studied analytically (fig. 22). The case of an infinite linear rim making an angle, Θ, with the electrode arrangement was considered for both a regular Lee array of electrodes and a Lee array with the current and potential electrodes interchanged. In the first case the earth resistivity would be given by

$$\rho=\rho_1 \frac{1}{1+2P};\ P=\frac{1}{C_2'P_1}+\frac{1}{C_1'P_0}-\frac{1}{C_1'P_1}-\frac{1}{C_2'P_0}$$
$$\rho=\rho_1 \frac{1}{1+2R};\ R=\frac{1}{C_2'P_0}+\frac{1}{C_1'P_2}-\frac{1}{C_1'P_0}-\frac{1}{C_2'P_2} \qquad (3)$$

where ρ_1 is the apparent resistivity calculated from the conventional formula for the half of the configuration closest to the rim; ρ_2 is the apparent resistivity for the half of the configuration farthest from the rim; and the quantities such as $C_2'P_1$ are the distances between the potential electrodes P_0, P_1, and P_2, the current electrodes C_1, and C_2, and the current electrode images C_1' and C_2'.

These equations are expressed so that the effect of the rim can be considered as a multiplying factor to the resistivity calculated from the observations under the assumption that no rims are present. These multiplying factors were calculated for four angles between the direction of the electrode lines and orientation of the rim. The results are presented in the graphs of figure 22. Calculations were carried out also for the inverted Lee arrangement; the results are shown in figure 23.

These correction curves were applied to the field observations where the distance between a drill hole and the rim was within several times the electrode spacing *a*. An example of these corrections is shown in figure 24.

The effect of a high-resistivity surface layer cannot be so readily evaluated. If there are lateral variations in resistivity in a surface layer, the effects of these variations may far outweigh the effect of variations in a layer at depth. In such a case the effectiveness of the Lee configuration of electrodes is doubtful. In order to check whether or not directional resistivity patterns were being controlled by the surface layer, patterns were determined about several drill holes with different electrode separations in areas where the 80-foot thick Moss Back member crops out. The results of these experiments are shown in figure 25. Somewhat different patterns are obtained with different electrode spacings; hence there must be some doubt about those patterns determined in areas with high-resistivity surface layers.

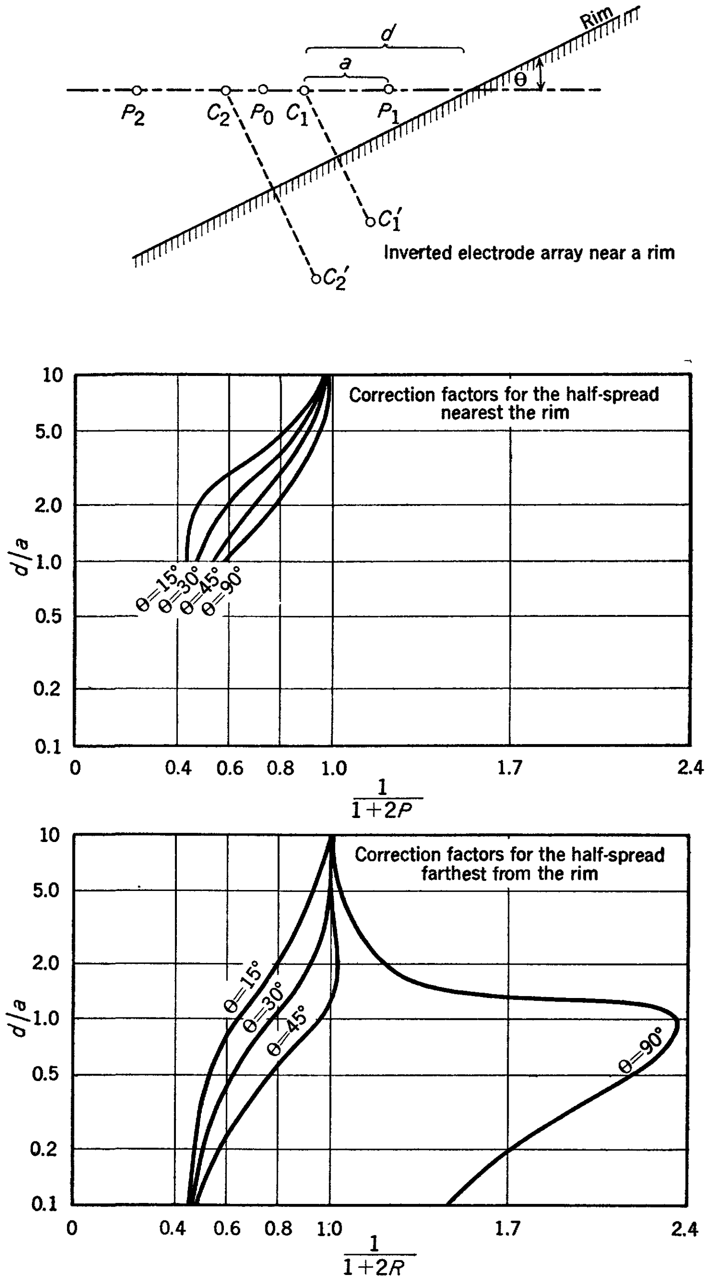


FIGURE 23.—Effect of a rim on the inverted Lee arrangement.

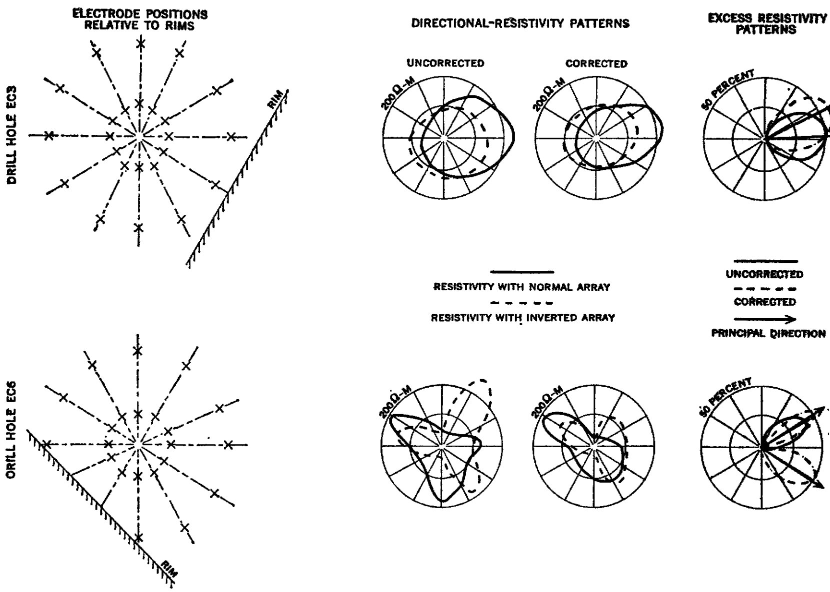


FIGURE 24.—Examples of resistivity patterns corrected for rim effects.

The field data obtained in the Frey Canyon area should be con sidered in the light of these various disturbing factors. Excess resistivity patterns over a channel with favorable surface conditions are shown in figure 26. Here the channel sediments are overlain by 25 to 125 feet of low-resistivity mudstone of the Chinle formation. The channel could be outlined by following the resistivity trends.

In other areas there is a much poorer correlation between direction of the channel and resistivity trends. In some places the discrepancy may be the result of irregular surface conditions, as there was very poor correspondence between the resistivities measured with the normal and the inverted Lee arrays. In other places the surface layer is the Moss Back member, and the resistivity trends are probably controlled by channels within the Moss Back. These channels in general overlie channels in the Shinarump, and thus, even though there is some correlation between the resistivity patterns, the correlation must be viewed as inconclusive.

CONCLUSIONS

The success of the initial experiments using resistivity trends to trace favorability patterns in the Morrison, and the channel sediments filled with the Shinarump member of the Chinle, indicates that further work could profitably be carried out, particularly on the development of methods of measuring directional-resistivity trends. The goal of such work should be the development of a reliable method of locating

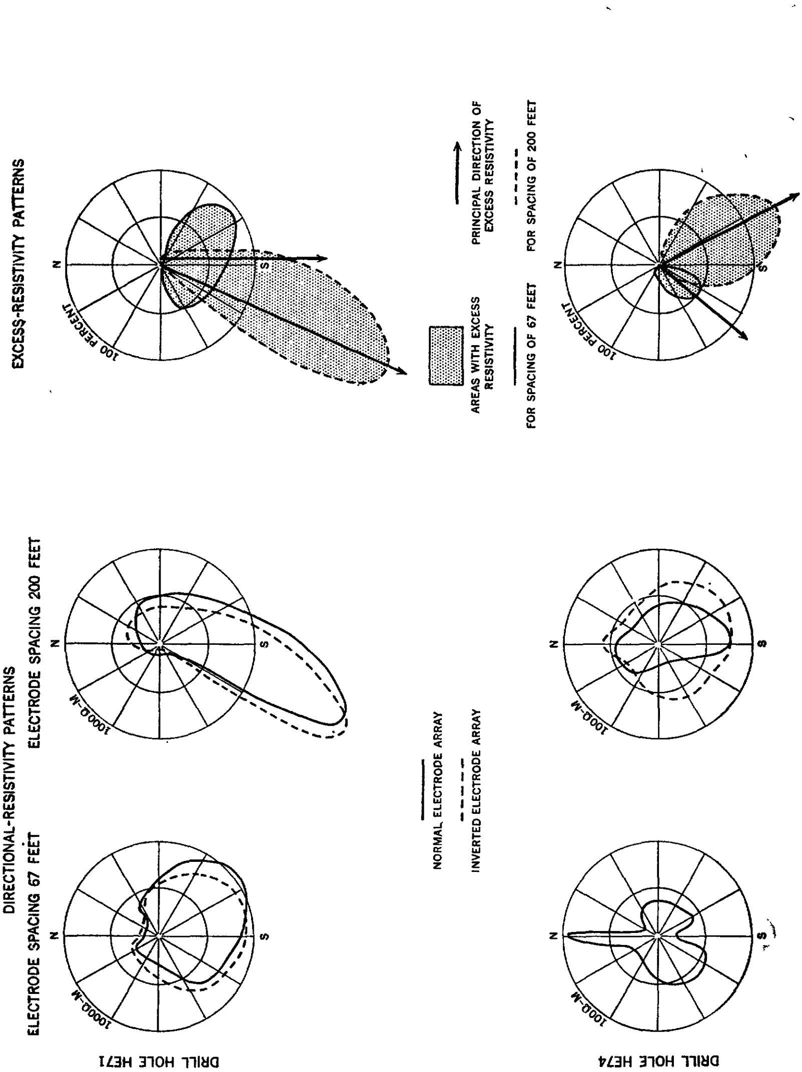


FIGURE 25.—Resistivity patterns obtained with various spacings about the same drill hole.

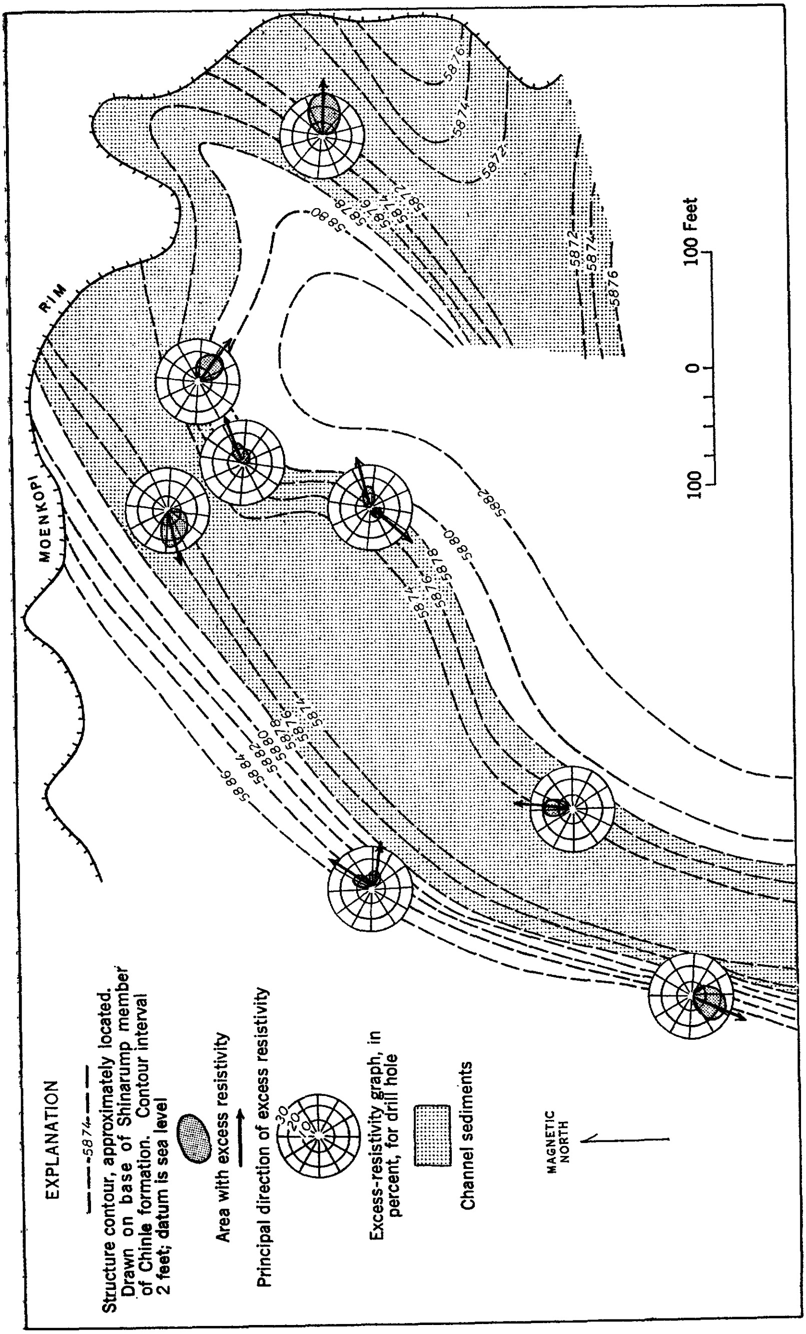


FIGURE 26.—Directional-resistivity patterns for a channel in the B-claim area, White Canyon district.

drill holes most judiciously during an exploration drilling program. The use of directional-resistivity measurements during the primary wide-spaced phase of exploration drilling could conceivably reduce by 75 percent the number of drill holes necessary to locate favorable areas. The saving in drill holes would be accomplished by eliminating generally unfavorable areas and by permitting drill holes to be spaced farther apart than is now the custom, without missing favorable areas. The ability of the method to predict favorability trends in the Spud Patch area at distances of from 600 to 800 feet would permit the spacing of drill holes to 1,500 feet without risking missed favorable areas. This is double the spacing used in the original drilling program at Spud Patch.

The results of the present work indicate the method could be used in areas of the Morrison formation where a suitable correlation has been established between resistivity and favorability by electric logging. The method could also be used in areas of the Shinarump member of the Chinle where the channel sediments are not overlain by the Moss Back member or an equivalent high-resistivity sandstone.

The present equipment is limited to use at a maximum electrode spacing of from 300 to 500 feet by its low sensitivity. These considerations indicate that further development should be directed towards increasing the sensitivity of the present equipment and to devising methods of minimizing the disturbing effects of surface irregularities. The first problem is primarily one of instrument design, while the second deals with field technique and methods of interpretation.

The nature of the second problem may best be seen by considering the resistivity patterns that would be associated with several hypothetical conditions of the ground. Figure 27 shows the potential distribution in a uniform ground. The equipotential surfaces are symmetric about the center of the electrode spread. The potential difference between P_0, the inhole electrode, and either P_1 or P_2 is the same, and there is no directional pattern. This illustrates also why it is desirable to have the current electrodes equidistant from the drill holes. In a uniform earth there is no variation in potential as the inhole electrode is moved through the drill hole. This simplifies interpretation, as any deviation from this condition must be caused by directional variations in resistivity.

Figure 27 also illustrates the conditions being sought—an area of high resistivity, such as a favorable sandstone lens, to one side of a drill hole. Here the equipotential traces are warped in the vicinity of the resistant zone, and the field is no longer symmetric about the drill hole. The voltage recorded in the direction of the resistant zone will be greater than normal, and the voltage in the opposite direction

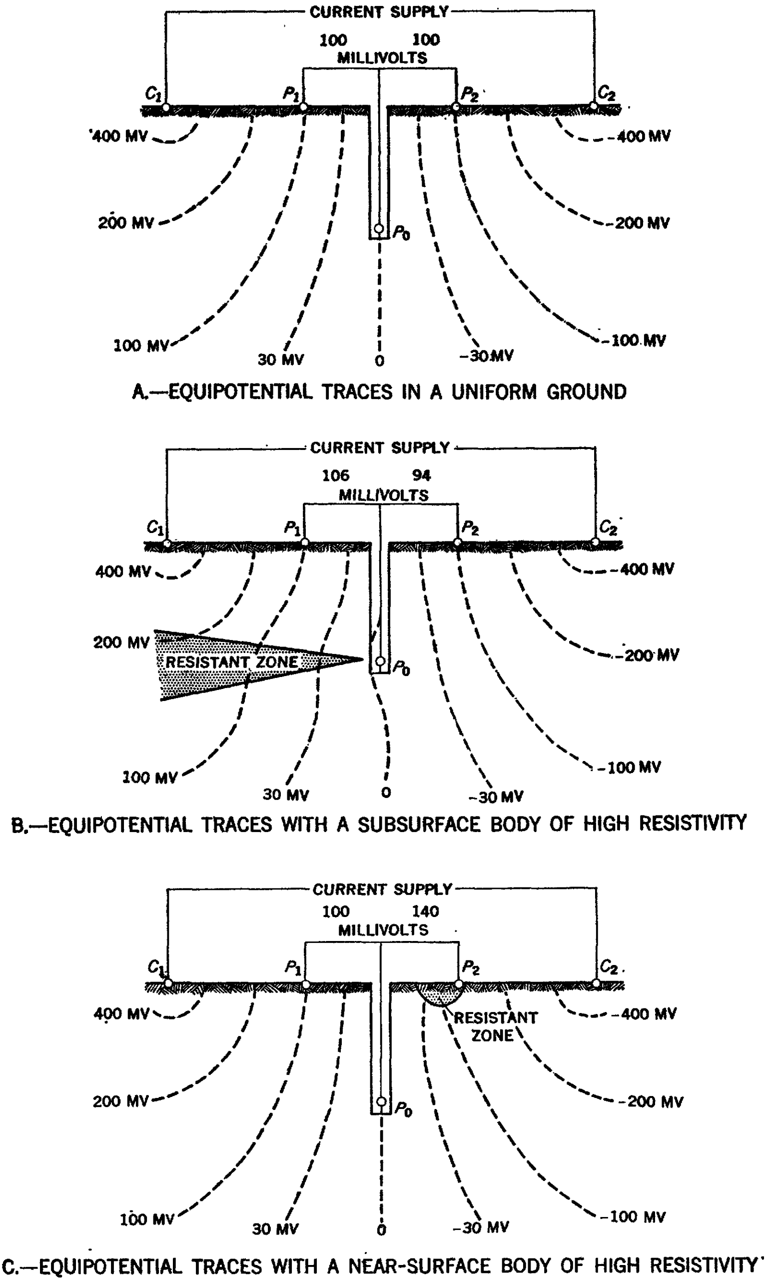


FIGURE 27.—Equipotential traces under different assumed conditions in a uniform ground.

will be less than normal. This diagram also illustrates how the use of an inhole electrode can detect anomalies too small to be noted with surface electrodes alone.

Figure 27 shows how surface discontinuities in resistivity can adversely affect directional-resistivity measurements. A small resistant body near one of the surface potential electrodes can alter the potential distribution enough to provide a distinct directional-resistivity effect. A resistant body near the surface electrode causes a larger effect than the same body near the inhole electrode as the current density is much higher near the surface electrode. Because of the difference in current densities in the 2 places, a typical range of variation that might be expected at the 2 electrodes would be 20 millivolts per ampere at the inhole electrode and 200 millivolts per ampere at the surface electrode. Thus, surface discontinuities in resistivity are more effective in establishing resistivity trends than subsurface variations.

To overcome this effect the surface electrodes must be placed at positions that always have the same potential. Various methods of doing this have been considered, but all involve an impractical amount of labor in the choice of a spot with the correct potential each time the electrode spread is rotated. Rather, it seems that the solution to the difficulty may lie in comparing the potential of the inhole electrode with an arbitrary external potential not related to the flow of current through the ground. Such a circuit is illustrated in figure 28.

The purpose of this circuit is to obtain a reference potential exactly equal to the potential of the partitioning plane in a homogeneous earth. This is done by shunting the ground circuit between the two current electrodes with a pair of series resistors exactly equal in size. The midpoint of these two resistors will have the same potential as the partitioning plane, and any variation in potential between this point and the inhole electrode must be caused by warping of the potential field near the inhole electrode.

This method will be subject to errors if the contact resistances at the two current electrodes are not approximately equal. The equalizing of these resistances presents no problem in field operations. In the work described here, they were equalized by pouring salt water about the current electrodes.

Better results might also be obtained if directional variations in electrical properties other than volume resistivity were studied. As was pointed out in the first section of this report, the resistivities associated with favorable ground are only one-third greater than those associated with unfavorable ground. It is possible that anomalies in other electrical properties such as dielectric constant or capacity for induced polarization may be of larger relative magnitude.

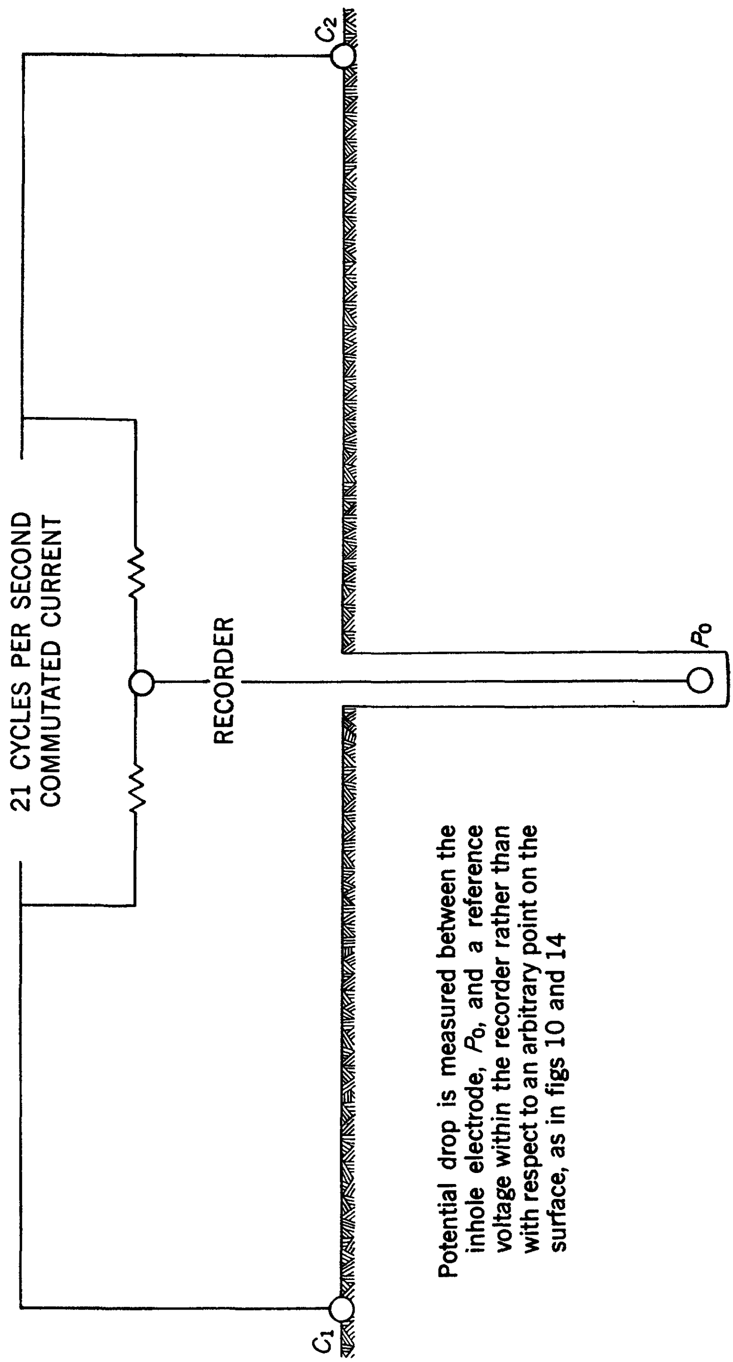


FIGURE 28.—Proposed method of determining directional-resistivity variations.

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