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# AN EVALUATION OF THE RESISTIVITY AND SEISMIC REFRACTION TECHNIQUES IN THE SEARCH FOR PLEISTOCENE CHANNELS IN DELAWARE

by

WILLIAM E. BONINI

Newark, Delaware

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By

WILLIAM E. BONINI

Professor of Geophysics and Geology
Department of Civil and Geological Engineering
Princeton University
Princeton, New Jersey

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# INTRODUCTION

## Purpose and Scope of Study

In March, 1965, Dr. Johan J. Groot, State Geologist of Delaware, requested that I make an evaluation of the electrical resistivity and seismic refraction geophysical methods as possible techniques for use in the exploration for Pleistocene channels. In order to accomplish this objective, it was decided that a field program should be undertaken in several areas where these channels are known from well data. Three areas were selected for these studies by the staff of the Delaware Geological Survey: (1) the Smyrna area, where the State Welfare Home well is located in a channel; (2) the New Castle area, about one mile west of the town on School Lane near several recent wells; and (3) the Bear area, where there are several wells with high water production presumed to be in a Pleistocene channel.

Pleistocene channels along the margins of the Atlantic Coastal Plain are developed in crystalline and Triassic sediments (Bonini and Hickok, 1958), or into the Cretaceous and Tertiary coastal plain sediments (Widmer, 1965). Deposits in these channels consist of sand and gravel with amounts of silt and clay. For example, the Bear area channel is 50 to 70 feet deep and contains up to 30 feet of sand and gravel overlain by sandy clay. Because they are usually more permeable than the older deposits into which the channels are developed, Pleistocene deposits are important in ground water studies for several reasons: (1) where they are thick enough they may be used as aquifers, as in the case of the Bear channel, and (2) these beds can effectively increase the recharge into the underlying aquifers by absorbing precipitation and transmitting the water to them.

Experience by me and my students in an area of similar geology in the New Jersey Coastal Plain near Princeton, had indicated that the seismic technique, while highly successful in determining depths to the crystalline bedrock, is not successful in differentiating geologic units in the unconsolidated Coastal Plain sediments above bedrock. In general, where depth to bedrock is less than 300 feet, only the position of water table within the unconsolidated sediments and depth to bedrock could be determined by the seismic refraction technique. Although chances of success were poor, it was decided to make seismic measurements in the Smyrna area. Six reversed seismic refraction spreads were shot there.

It was felt that the resistivity technique offered the best chance of success and a total of 18 spreads were observed in the three test areas. Additional resistivity data was available from a 1955 U. S. Geological Survey report in New Castle County for study and possible re-interpretation (Spicer, McCullough, and Mack, 1955).

The scope of study was not exploration for new Pleistocene channels, but rather to make measurements over known channels in order to be able to evaluate the geophysical results over the known geologic situation. Unfortunately, in the areas selected well data was limited and the channels were not too well known. There is only one well at Smyrna, near which data could be observed, along School Lane in the New Castle area, only one well had been drilled prior to the resistivity survey, and at Bear two good producing wells were located such that the channel was defined within some limits.

This report is written as a companion report to the U. S. Geological Survey manuscript (Spicer, McCullough, and Mack, 1955) and therefore, frequent reference will be made to that data.

## GENERAL STATEMENT ON RESISTIVITY OF ROCKS

The resistivity of a given rock unit is related to three variables: the amount of fluid present, the fluid resistivity, and the resistivity of the solid constituents of the rock.

### Amount of Fluid Present

The amount of fluid present is determined by the porosity and the degree of saturation. With a saturated rock and all other factors equal, a more porous rock will have a lower resistivity. As saturation decreases, the resistivity will increase. With a clearly defined water table, i.e. dry above water table and saturated below, one should have a major resistivity discontinuity. In general, as has been shown in a number of cases in Illinois, gravel beds show up as resistivity highs in comparison with surrounding till, mainly because of the lower porosity (but higher permeability) of the gravels and the smaller quantity of water present.

## Resistivity of Fluid Present

The more saline (or higher mineral content in the water), the lower the resistivity. Thus, in a rock of uniform porosity, the salt or brackish water zone will exhibit a much lower resistivity than the fresh water zone. This has been shown in the field in Hawaii, where the fresh water-salt water interface has been mapped in basalt flows (Swartz, 1940).

## Resistivity of Solid Constituents

Feldspars, quartz and micas, are all good insulators, thus, a dry rock composed of these minerals will give high resistivity values because conduction is mostly through these materials. However, small percentages of water will greatly lower the resistivity such that most of the flow of current will be through the fluid.

Thus, with three variables present, it is almost impossible to uniquely determine subsurface geology by resistivity techniques. To increase reliability of the interpretation, most successful resistivity work is tied closely to field and drill hole observations of geology. The best rule is simply to work from the known to the unknown. The evaluation of the resistivity data in this survey attempts this by use of multiple interpretations and the comparison with existing knowledge of geology, mostly from well data.

# GENERAL STATEMENT ON THE SEISMIC VELOCITIES OF ROCKS

The velocity of propagation of compressional seismic waves is given by the following formula:

$$V_p = \sqrt{\frac{k + 4/3\ u}{d}}$$

where k is the bulk modulus, u the shear modulus, and d the density.

In geological terms, velocity is directly related to the degree of consolidation of earth materials. Unconsolidated deposits vary from about 1200 feet per second (fps) to about 5000 fps; semi-consolidated materials from about 5000 fps to near 10,000 fps; and consolidated and crystalline rocks, normally thought of as bedrock, are above 10,000 fps. Consolidation in sedimentary rocks is a function of degree of compaction or cementation or a combination of both. Thus, soils and loose sedimentary materials have low velocities whereas sandstones and shales have velocities above 10,000 fps.

The velocity of water is near 5000 fps. When an unconsolidated material is saturated, that is, below water table, its velocity will be that of water, even though its dry velocity may be quite low. The velocity of a material with a dry velocity above 5000 fps will not be affected appreciably by saturation. Thus, there is ambiguity in interpretation of velocities that fall between about 4500 and 6000 fps. Sediments that fall in this range could be either unconsolidated material below water table, or semi-consolidated rock without reference to saturation.

## ACKNOWLEDGMENTS

I am grateful for the initiative and encouragement of Dr. Johan J. Groot, State Geologist of Delaware, and Robert D. Varrin, Director of the Water Resources Center at the University of Delaware. Mr. Kenneth D. Woodruff supplied well data, and important assistance in the field on various days was given by W. Wayne Baker, Michael W. Allen, and Jeffrey N. Fischer, all in the employment of the Delaware Geological Survey at the time. The geophysical equipment and truck, licensed to transport explosives, was made available by the Department of Geological Engineering (now Department of Civil and Geological Engineering), Princeton University. Mr. Steven J. Leech, General Superintendent, Artesian Water Company, Wilmington, supplied logs for four wells in the Bear area.

## GEOPHYSICAL EQUIPMENT AND TECHNIQUES USED

### Seismic

A twelve-channel Century shallow-zone seismic-refraction unit was used in the survey. All spreads were reversed, that is, shots were fired at each end of a 650 foot spread, with a 50 foot geophone interval. Shots were 1-1/2 to 2 pounds of 40 per cent dynamite placed at a depth of 3 feet. Depth and true velocity calculations for multiple-sloping beds were made according to formulas given by Ewing, Woollard, and Vine (1939). Depth determinations are generally good to within 10 per cent (Bonini and Hickok, 1958).

### Resistivity

These observations were made with a Gish-Rooney type instrument with motor-driven commutator. All measurements were made using the Wenner configuration with equal electrode spacing (a-spacing), and were carried out to an a-spacing of 200 feet.

In the interpretation of the resistivity measurements several methods were used:

### Curve Matching

In this technique field curves are plotted on log-log paper and are compared to theoretical curves (Mooney and Wetzel, 1956). When a match is made the depth and resistivity values can be obtained.

### Empirical Methods

These methods have no theoretical basis, but experience has shown that they can be of value.

Moore Cumulative Technique: In this method, described by Moore (1945), resistivity values are cumulated on an equal a-spacing increment. Intersections of straight lines drawn through the plotted points indicate depths. No resistivity values are calculated.

Horizontal Resistivity Traversing: This is a method in which one compares the resistivity measured at one location with that at another. This is done for a family of a-spacings, say 25, 50, 75, and 100 feet, where the a-spacing is presumed to be related to the depth of effective current penetration. The comparisons from place to place can be used to locate zones of anomalous resistivity. The method is qualitative and in the present survey this technique appeared to give the most interesting results.

## SMYRNA AREA RESULTS

### Well Data Available

There are numerous wells in the area, principally located northwest and southeast of Lake Como. Because much of the area near these wells is built-up, it was necessary to move the line of cross-section about one mile south of the Welfare Home well. Six wells are located close enough to the geophysical data to provide some comparisons. These wells are located on the Smyrna Map (Figure 1) and are as follows: Hc34-1, 0.4 mile NE of DGS 3; Hc34-5, 0.6 mile E of DGS 3; Hc44-1, 0.25 mile SE of DGS 6; and Hc34-25, 0.1 mile W of DGS 7. Logs of two other

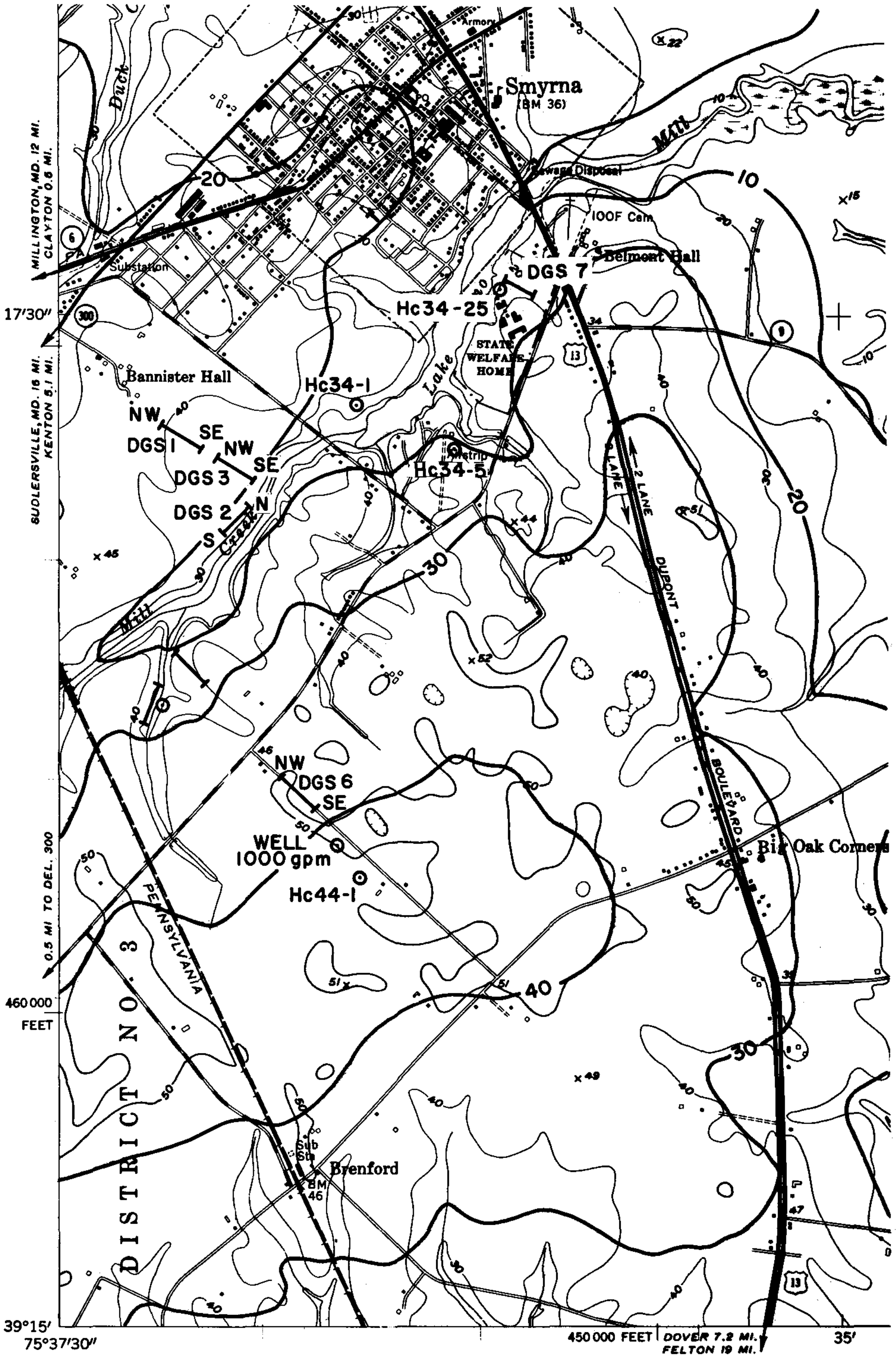


Figure 1. Location of seismic and resistivity stations in Smyrna Area with 10-foot water-table contours (9/1958); after Boggess et al. (1964).

wells were not yet available, but these are located near DGS 4 and 6. Local information indicates that these are good production wells for irrigation. Logs available are given in Appendix A, and several are shown on Figure 2.

## Seismic Survey

Six reversed seismic-refraction spreads were shot at sites DGS 1 through 6. Travel time curves are given in Appendix B. Results are tabulated in Table 1. In all cases the first layer has an assumed velocity of 1500 feet per second (fps). This value is consistent with observations at spread DGS 1, and with experience in similar areas. It was not possible to shoot on the State Welfare Home lawn, so no spread is available near the well at the Home.

Table 1

Smyrna Seismic-Refraction Data

| Spread | End | Seismic Velocities in feet/second | | | Depth to top of layer in feet | |
|---|---|---|---|---|---|---|
| | | $V_1$ | $V_2$ | $V_3$ | $V_2$ | $V_3$ |
| DGS 1 | NW | 1500 | 4800 | 5500 | 18 | 52 |
| | SE | | | | 18 | 62 |
| DGS 2 | NE | 1500 | 5600 | | 9 | |
| | SW | | | | 9 | |
| DGS 3 | NW | 1500 | 4970 | 5675 | 14 | 34 |
| | SE | | | | 9 | 75 |
| DGS 4 | N | 1500 | 5200 | | 9 | |
| | S | | | | 10 | |
| DGS 5 | NW | 1500 | 5150 | | 8 | |
| | SE | | | | 9 | |
| DGS 6 | NW | 1500 | 5150 | | 15 | |
| | SE | | | | 14 | |

It can be noted that the highest velocity group has a range of 5150 to 5675 fps. Spreads DGS 1 and 3, which are the two spreads on the northwest end of the cross-section, were the only ones on which an intermediate velocity is found (4800-5000 fps).

Velocities are interpreted as follows: (1) 1500 fps - unconsolidated material above water table; (2) 4700-5700 fps - unconsolidated material below water table, or semi-consolidated material. Thus, water table is located at the top of the 4700-5700 fps layer. Seismic interfaces and water table positions for October 1958 (Boggess et al., 1964) are shown on Figure 2.

In 21 spreads in the Coastal Plain of New Jersey, where the Pleistocene Pensauken gravels are known to overlay the Cretaceous, the velocity range for the section above the Precambrian bedrock is 4760-6000 fps range, averaging 5230 fps. In that area it is not possible to differentiate between the Pleistocene gravels and the Cretaceous sediments on the basis of velocity in the upper 300 feet of section.

Although the 4800-5000 fps velocities possibly could be correlated with gravel, they are not significantly different from the other values observed along the line of traverse to permit a certain interpretation.

Generally, the depth of investigation is one-third the cross-over distance. In these cases with a 650-foot spread, we might expect that we have investigated to a depth of about 220 feet. To check this, a hypothetical layer was assumed to be present with a velocity of 7500 fps, but was deep enough to miss being recorded at the spread distance. The calculations of the depth to this hypothetical layer give an appraisal of the minimum depth that such a higher layer could exist. These minimum depths are as follows: DGS 1 - 153 feet; DGS 2 - 126 feet; DGS 3 - 154 feet; DGS 4 - 132 feet; DGS 5 - 139 feet; DGS 6 - 144 feet. Any layer with a lower velocity than that assumed could be shallower.

It is concluded that it is NOT possible in the Smyrna area to differentiate between Pleistocene gravels and the Tertiary sediments on the basis of velocity, assuming that the line of seismic data did in fact cross a channel.

## Resistivity Survey

Resistivity spreads were made at the seven localities plotted on Figure 1. Resistivity versus "a" spacing plots and the Moore cumulative data are included for each spread in Appendix B.

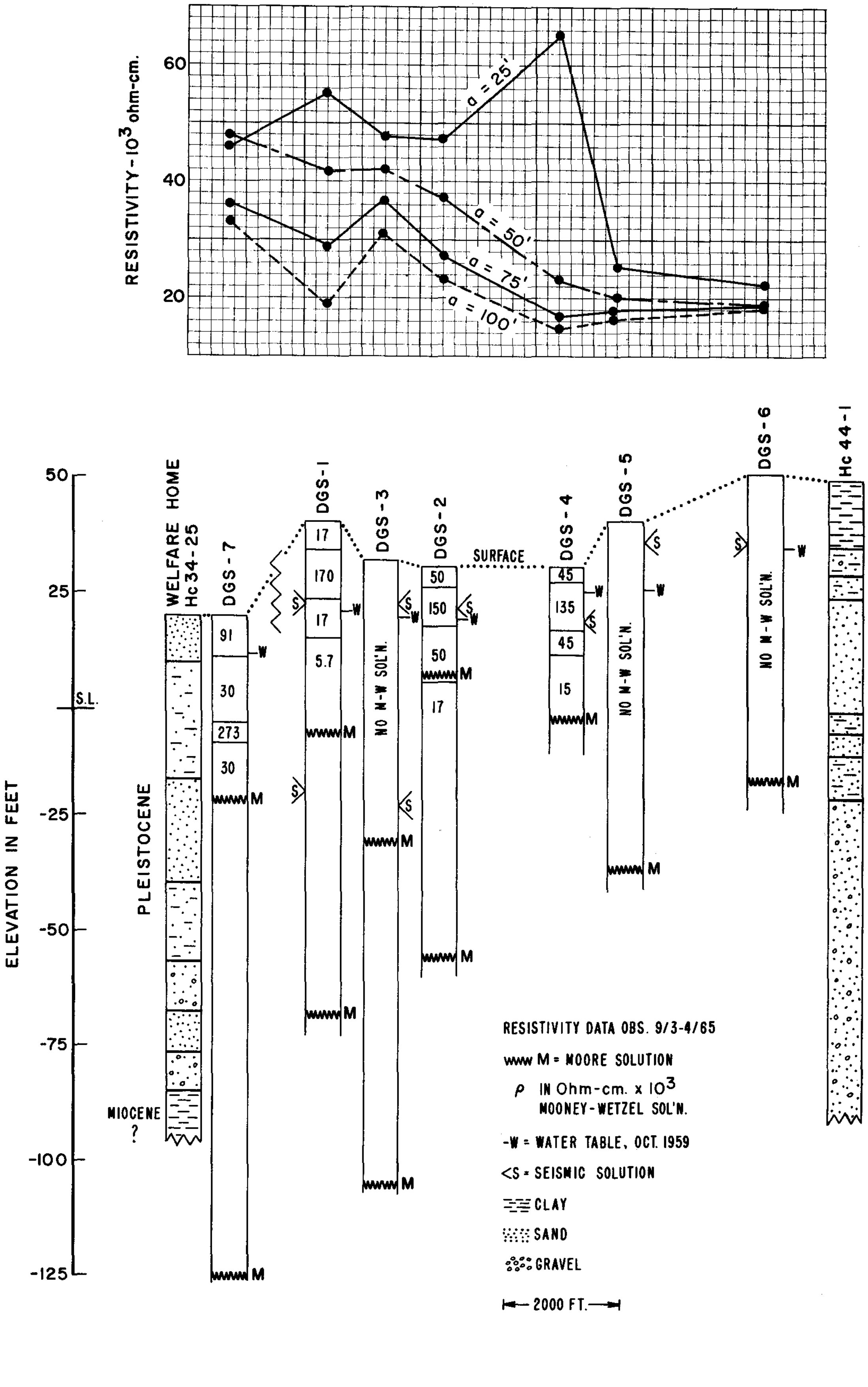


Figure 2. Smyrna Area cross-section.

## Comparisons Against Wells

Only well Hc34-25 at the State Welfare Home is close enough to provide a direct comparison. At this well clay and silt (Miocene ?) is reached at a depth of 103 feet, and the overlying sand, pebbles, clay, and mud, is presumed to be in the Pleistocene channel. Resistivity depth predictions (Figure 2) using the Moore cumulative technique give depths of 40 and 147 feet. Mooney and Wetzel curve-matching solutions give depths of 9, 23, and 26 feet. Both interpretations do not appear to give solutions consistent with the 103 foot channel depth, unless the channel changes markedly within the 0.1 mile distance between the well and resistivity spread location.

## Horizontal Resistivity Traversing

Table 2 and Figure 2 give the traversing data for "a" spacings of 25, 50, 75, 100, 150 and 200 feet. Resistivity values greater than 30,000 ohm-cm are underlined in the Table. Empirically, the resistivity spread at the State Welfare Home (DGS 7) gives consistently higher resistivity values to a depth of 100 feet. Spread DGS 3 is very similar to DGS 7. Well Hc34-1 is located between these two spreads (Figure 1) and bottoms in coarse sand at 60 feet. This suggests on a qualitative basis that all three locations may be in the Pleistocene channel. Spread DGS 6 appears not to be located in the channel, although at well Hc44-1, 0.25 mile southeast of DGS 6, indicates sand, clay and pea gravel to depths of 137 feet. Spreads DGS 4 and 6 are near two wells for which logs are not available, but good production for irrigation is obtained. Resistivity data suggests that they are not in a deep channel. DGS 4 does have a high resistivity at an "a" spacing of 25 feet. Perhaps the production is shallow in this area.

## Summary for the Smyrna Area

Moore cumulative and curve-matching predictions do not correlate with well data. The horizontal traversing technique suggests that the State Welfare Home channel has been located at DGS 3. Seismic data indicate that it is not possible to differentiate on the basis of velocity between the Pleistocene and Miocene deposits.

Table 2

Smyrna Horizontal Traverse Data

(Resistivity values in ohm-cm x $10^3$ versus "a" spacing)

| Profile No. | "a" spacing in feet 25 | 50 | 75 | 100 | 150 | 200 | |
|---|---|---|---|---|---|---|---|
| DGS 1 | 55.0 | 41.5 | 28.5 | 19.7 | 10.4 | 9.1 | |
| DGS 2 | 47.0 | 37.0 | 27.0 | 23.0 | 19.1 | 18.4 | |
| DGS 3 | 47.0 | 42.0 | 36.5 | 31.0 | 25.1 | 19.3 | |
| DGS 4 | 63.5 | 23.0 | 16.6 | 15.0 | 14.2 | 14.4 | |
| DGS 5 | 24.3 | 19.3 | 16.5 | 13.8 | 10.5 | 8.8 | |
| DGS 6 | 22.0 | 17.2 | 17.4 | 18.0 | 16.0 | 14.5 | |
| DGS 7 | 46.4 | 40.8 | 36.0 | 33.0 | 29.0 | 22.0 | SWH Well |

## SCHOOL LANE (NEW CASTLE) RESULTS

### Well Data Available

Three wells were drilled near the resistivity traverse, Cc55-10, 11, and 12 (Figure 3). These are located 50 to 100 feet southwest of School Lane in field positions. Resistivity spreads SR 1 and SR 5 are within 50 feet of the well sites 10 and 12, respectively, and SR 2 is located on the School Lane right-of-way about 100 feet north of Cc55-11. Spread locations given are the centerpoint of the spread, all of which were expanded in a direction parallel to School Lane. Well Cc55-5 is located on Route 40-13 and is about 800 feet northwest of spread SR 4. Well logs are shown in Figure 4 and Appendix A and resistivity data in Figure 4 and Appendix B for the section from well Cc55-12 northwest to well Cc55-5. This includes the entire resistivity survey in the School Lane area.

### Resistivity Results

Mooney and Wetzel curve-matching analyses give poor fits to the field curves and all give shallow solutions at best. A 20-foot depth solution for SR 1 does not compare with anything on the lithologic log (Figure 4). The other spreads are such poor matches to the theoretical curves that they are not reported.

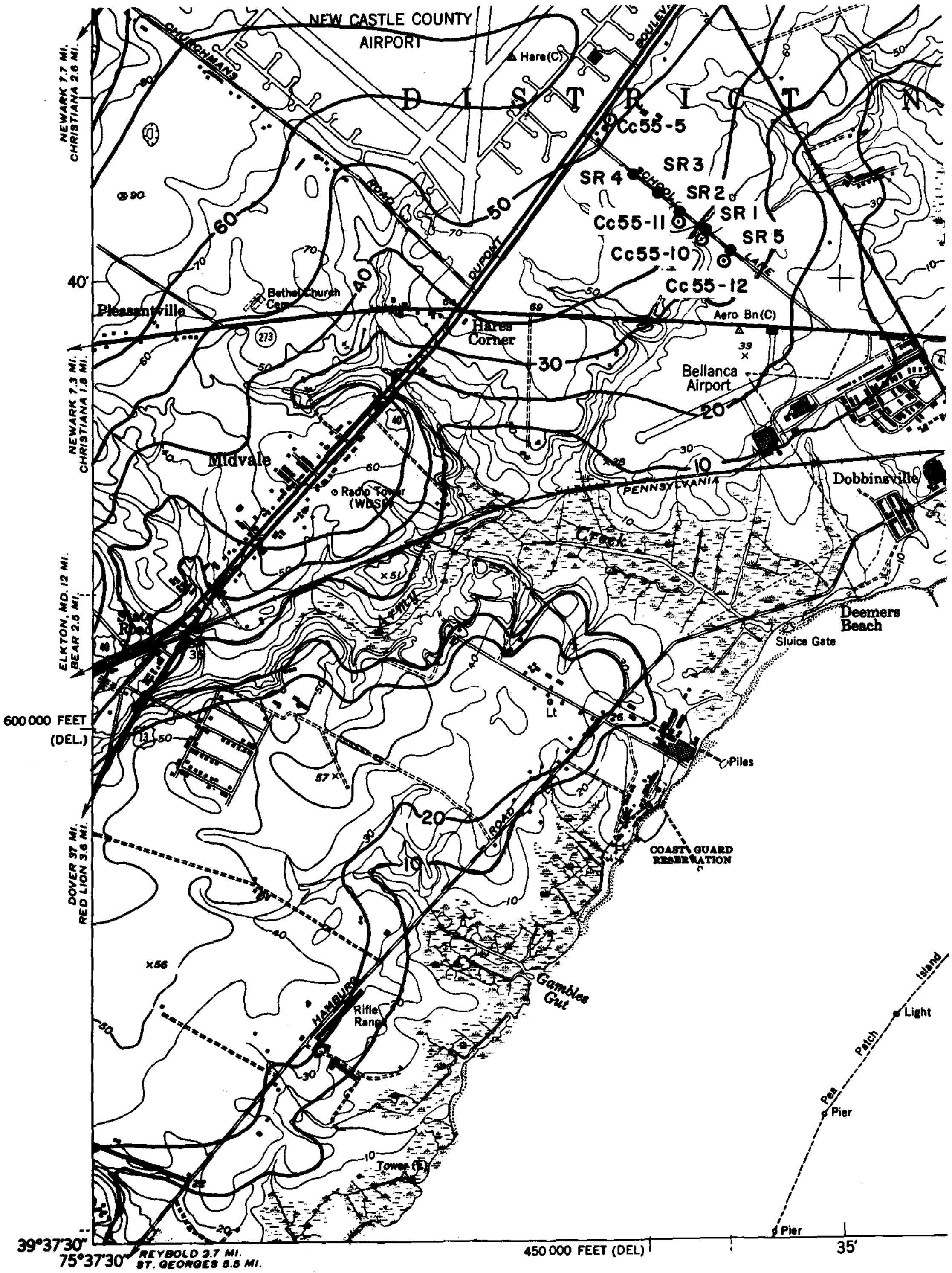


Figure 3. Location of resistivity stations, School Lane (New Castle) Area with 10-foot water-table contours (9/1958); after Adams et al. (1964).

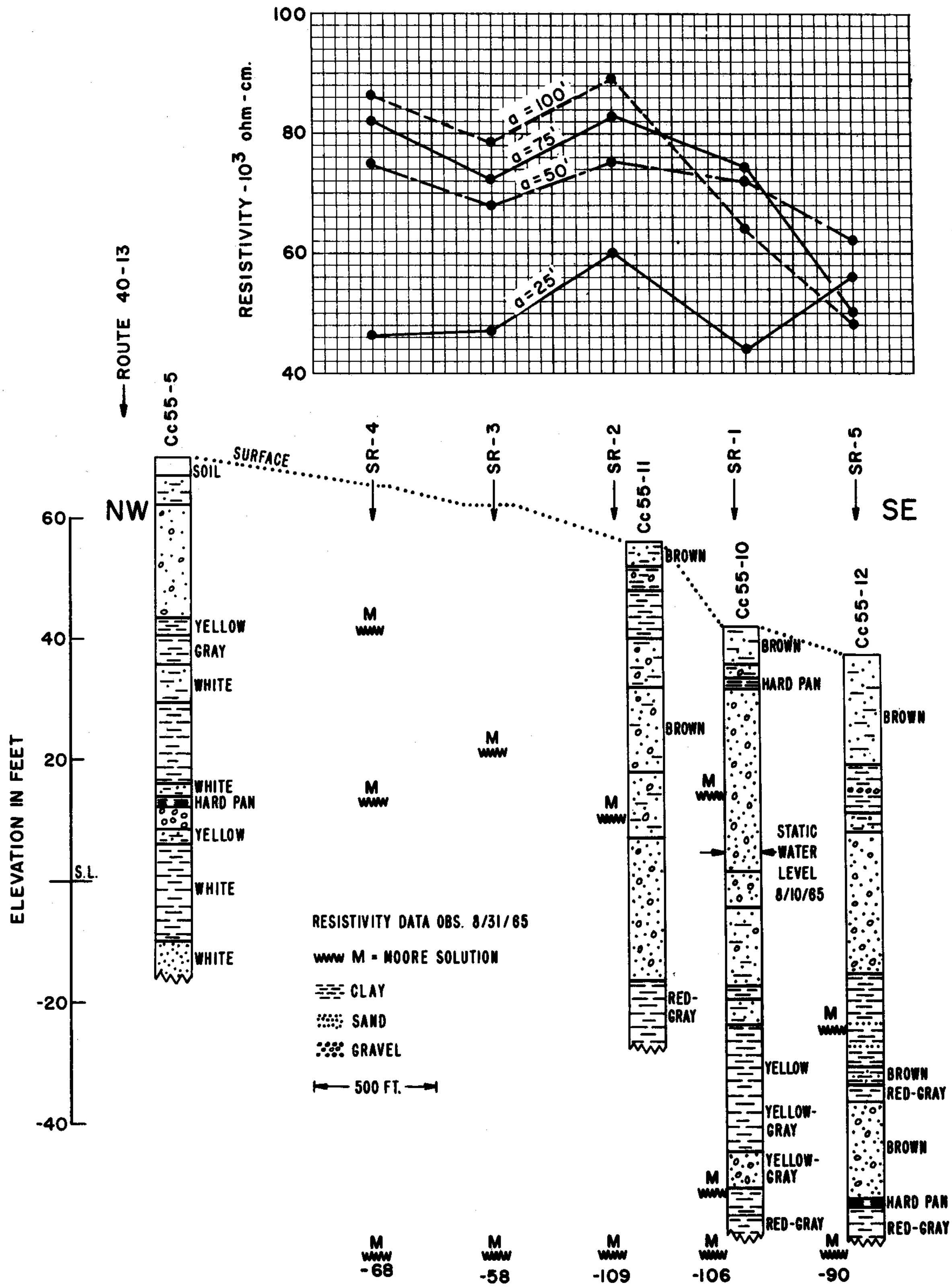


Figure 4. School Lane Area cross-section.

Moore cumulative solutions near wells (Figure 4) do not appear to be of lithologic significance. The solution at SR 1 is 10 feet above the static water level observed on August 10, 1965, three weeks prior to the resistivity survey. Possibly this could be a water table solution. Deeper Moore solutions are noted at the bottom of Figure 4, and these vary from an elevation of -58 to -109 feet below sea level. Crystalline rock elevations are expected to be below -200 feet elevation, so these cannot be correlated with bedrock.

## Horizontal Resistivity Traversing

Results of horizontal traversing are plotted on Figure 4 and in Table 3 with "a" spacings of 25, 50, 75, and 100 feet. Wells with thicknesses of predominantly sand and gravel from the southeast to the northwest are as follows: Cc55-12, 24 feet; Cc55-10, 49 feet; and Cc55-11, 56 feet. There is an apparent thickening of the sand and gravel section from the southeast to the northwest. This is a substantial increase in the horizontal traverse resistivities for "a" spacings of 50, 75, and 100 feet in the same direction. This suggests that there is some reasonable empirical correlation between both the thickness and depth of the predominantly sand and gravel section. To follow this interpretation further to the northwest one might expect some thinning at SR 3 and thickening at SR 4. No data is available at well Cc55-5, but the sand-gravel bed is 19 feet thick and is shallow. On this basis one could predict that the greatest thickness of sand and gravel is between SR 1 and SR 4.

Table 3

School Lane Horizontal Traverse Data

(Resistivity values in ohm-cm x $10^3$ versus "a" spacing)

| Profile No. | "a" spacing in feet 25 | 50 | 75 | 100 |
|---|---|---|---|---|
| SR 1 | 44.0 | <u>70.0</u> | <u>71.0</u> | 64.0 |
| SR 2 | 60.6 | <u>75.0</u> | <u>83.0</u> | <u>89.0</u> |
| SR 3 | 47.0 | 68.0 | <u>72.0</u> | <u>78.0</u> |
| SR 4 | 46.0 | <u>75.0</u> | <u>82.0</u> | <u>86.0</u> |
| SR 5 | 56.0 | 61.7 | 50.0 | 48.0 |

## Summary for the School Lane (New Castle) Area

Curve-matching and the Moore cumulative technique do not give solutions, or solutions do not correlate with the well data. The horizontal traversing data suggest a correlation between high resistivity values and thickness of sand and gravel section.

# BEAR AREA RESULTS

## Well Data Available

Three wells are on or near the line of traverse (Figure 5). Dc32-2 is 1000 feet east of resistivity spread BR 1; and the Artesian Water Company wells, here designated wells A and B, are located 40 feet southeast of BR 2 and 600 feet north of BR 3, respectively. Dc32-2 is not indicated as a water producer, but the wells A and B are reputed to be high producers for the Artesian Water Company, and are presumed to be in a Pleistocene channel.

## Resistivity Data

### Curve-Matching Technique

For the most part the field curves are poor matches with the Mooney and Wetzel curves. The matches that were made are indicated on the Bear cross-section (Figure 6). The water table range for 1951-1960 (Boggess and Adams, 1963) are plotted against locations where such data is available. At least one of the Mooney and Wetzel depths agrees with the water table range. The solution at BR 1 seems to reflect lithology at well Dc32-2; at well A the lowest BR 2 solution appears to agree with the top of the sand and gravel zone; and at well B the BR 3 solutions do not agree with any lithologic change reported. There is no consistent relationship from well to well with water table or lithologic changes, and it is not felt that these are good solutions to the resistivity problem.

### Moore Cumulative Technique

Similarly, the Moore cumulative solutions appear to be unrelated with lithology or the Mooney and Wetzel solutions. However, they all do give deeper solutions from elevations of 30 to 90 feet below sea level, as was the case in the School Lane area. The real significance of these solutions is unknown at the present. Precambrian bedrock from well

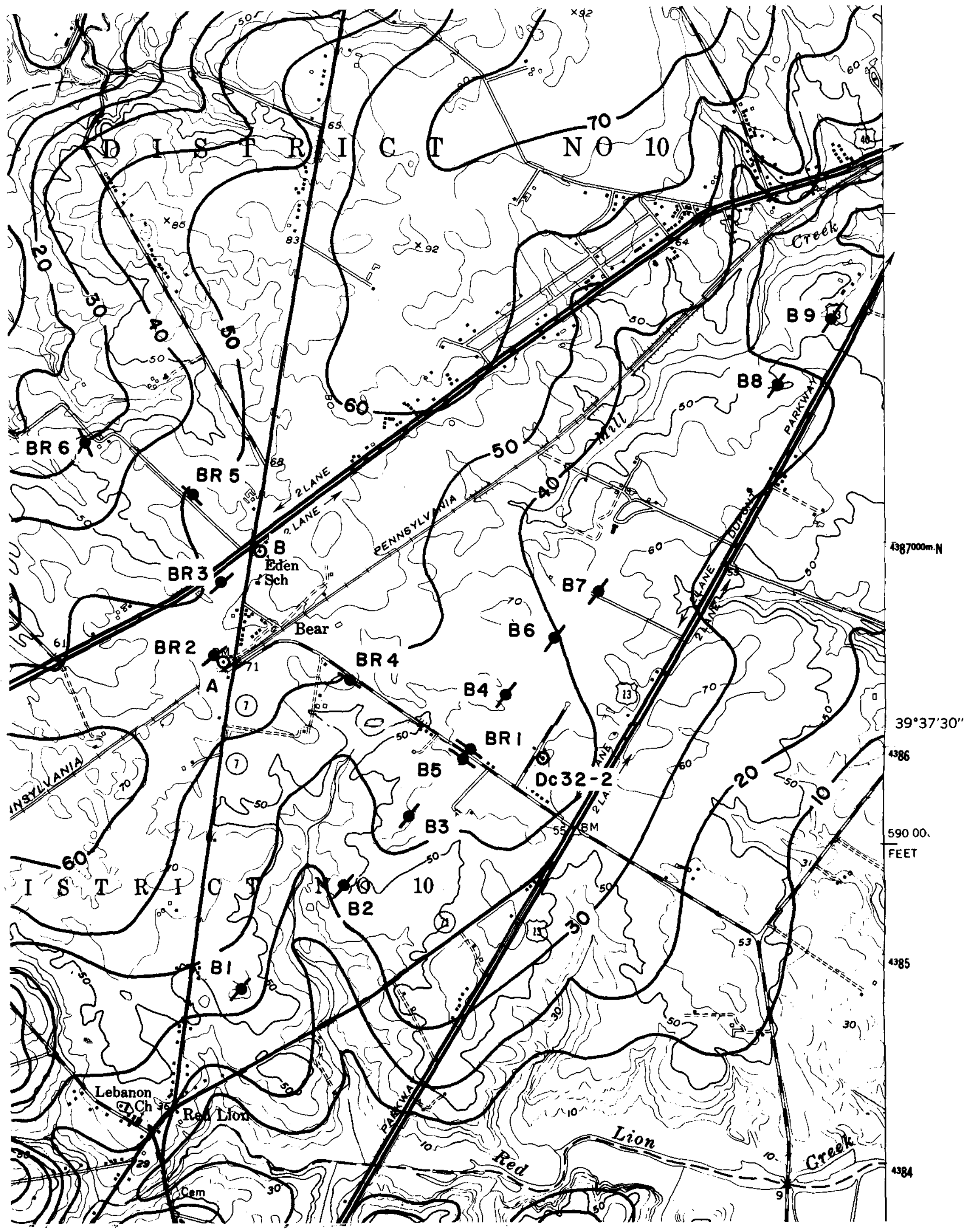


Figure 5. Location of resistivity stations, Bear Area with 10-foot water-table contours (9/1958); after Boggess et al. (1963).

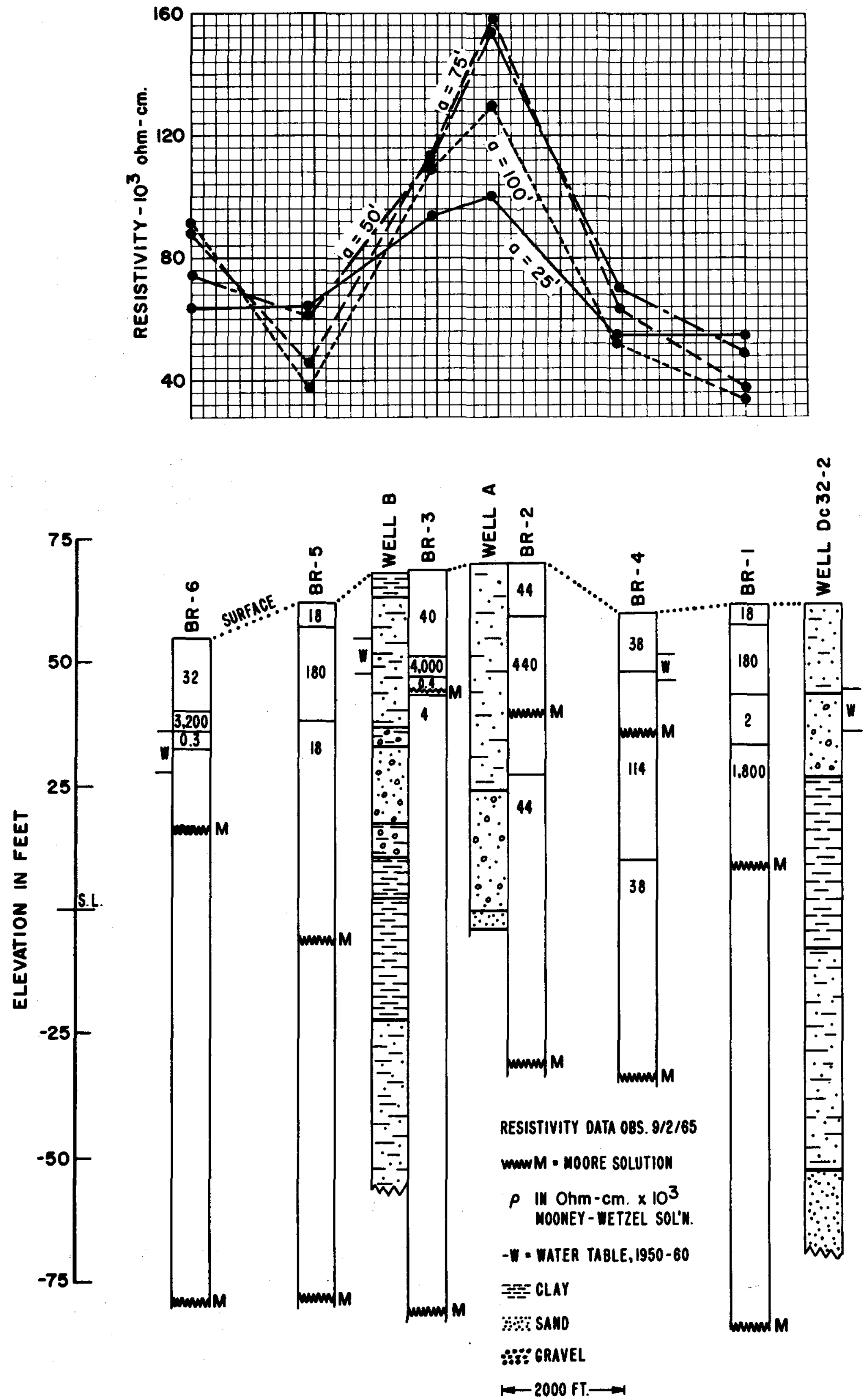


Figure 6. Bear Area cross-section.

Dc42-1, about one and one-half mile south of the Bear cross-section, gives the elevation at -340 feet, so this is not related to that interface.

## Horizontal Resistivity Traversing

On the upper part of the Bear cross-section (Figure 6) and in Table 4 is given the data with "a" spacing of 25, 50, 75, and 100 feet. It is quite apparent that BR 2 and BR 3, next to the high-production wells A and B, have anomalously high resistivities, and are in excess of 100,000 ohm-cm. The sand and gravel zones are in the 35 to 60-foot depth range at well B, and 45-75 depth range for well A. Peak resistivity values occur at 50 and 75 foot "a" spacings in each case. At BR 1, 1000 feet from well Dc32-2, a peak value for that spread is reached at "a" spacing of 25 feet, and steadily decreases as the "a" spacing is increased. This is good agreement with the shallow depth of 17-30 feet for the 13-foot sand and gravel bed at the well.

Table 4

Bear Area Horizontal Traverse Data

(Resistivity values in ohm-cm x $10^3$ versus "a" spacing)

| Profile No. | "a" spacing in feet 25 | 50 | 75 | 100 |
|---|---|---|---|---|
| BR 1 | 54.0 | 48.0 | 37.0 | 33.0 |
| BR 2 | <u>100.0</u> | <u>153.0</u> | <u>158.0</u> | <u>130.0</u> |
| BR 3 | 94.0 | <u>112.0</u> | <u>115.0</u> | <u>111.0</u> |
| BR 4 | 54.0 | 70.0 | 63.0 | 52.0 |
| BR 5 | 64.0 | 61.0 | 46.0 | 36.0 |
| BR 6 | 64.0 | 74.0 | 88.0 | 90.0 |

## Summary for the Bear Area

There is excellent agreement between anomalously high resistivity values and high-producing wells using the horizontal traversing technique. Other techniques of interpretation are not very good. This channel could probably be traced by the horizontal resistivity traversing technique.

## COMMENTS ON THE INTERPRETATION OF THE U. S. GEOLOGICAL SURVEY RESISTIVITY SURVEY*

It is suggested herein that the greatest value of resistivity in the location of Pleistocene channels is qualitative, and is related to the location of high resistivity zones by horizontal resistivity traversing. It therefore seems appropriate to look at the U. S. Geological Survey data (Spicer et al., 1955) from this point of view. Table 5 is the horizontal resistivity traverse data taken from the U. S. Geological Survey report for all stations for an "a" spacing of 25, 50, 75, and 100 feet. Values greater than 75,000 ohm-cm are underlined.

Spread A-19 is about 300 feet from the Tidewater Oil Company deep test hole 8 (see Figure 6 of Spicer et al., 1955). It reports 57 feet of sand with some grit and silt near the lower part. Resistivity values are high for an "a" spacing of 50, 75, and 100 feet, suggesting that the qualitative value of the horizontal resistivity traverse interpretation is shown. The Moore cumulative plot of A-19 is included herein as Figure 7, and there are two solutions at 25 and 50 feet, corresponding to an elevation of +38 feet and +13 feet, respectively. The lower depth compares well with the +12 feet elevation of the top of clay in test hole 8. Thus, at this hole, the curve-matching data of the U. S. Geological Survey, the Moore cumulative empirical technique, and the horizontal resistivity traverse evaluation all compare well with the lithologic data.

There are several other areas with resistivity anomalies of interest. A-24, B-11, and B-7 show very high resistivity values at "a" spacings of 50, 75, and 100 feet. In fact, these are similar to the Bear channel values. High values are found for A-26 and a lesser high is at B-3. B-11 is 1300 feet southwest of well Dc23-2, and A-26 is 1200 feet north of Kings College well (Dc52-24). These wells are rated "wells of large capacity, more than 300 gpm." A-13 gives extremely high values, but this is probably an error by a factor of 10 and the U. S. Geological Survey discounts it.

Both A-24 and B-7 look promising, but are not located near wells. B-7 might be on trend with the Artesian Water Company wells in the Bear area, where resistivity values are high at BR 2 and BR 3.

*See Appendix C for the U. S. Geological Survey Location Map (from Spicer et al., 1955).

Table 5

U. S. Geological Survey Horizontal Traverse Data

(Resistivity values in ohm-cm x $10^3$ versus "a" spacing)

| Profile No. | "a" spacing in feet 25 | 50 | 75 | 100 |
|---|---|---|---|---|
| A 1 | 30 | 28 | 26 | 26 |
| A 2a | 55 | 48 | 41 | 33 |
| A 2 | 47 | 49 | 35 | 21 |
| A 31 | 47 | 35 | 22 | |
| A 3 | 54 | 51 | 56 | 56 |
| A 4 | 39 | 30 | 44 | 41 |
| A 5 | 21 | 32 | 38 | 42 |
| A 29 | 42 | 33 | 21 | 14 |
| A 30 | 82 | 76 | 64 | 48 |
| A 32 | 29 | 44 | 50 | 45 |
| A 6 | 70 | 72 | 64 | 57 |
| A 7 | 47 | 55 | 48 | 41 |
| A 8 | 47 | 39 | 26 | 18 |
| A 9 | 39 | 10 | | |
| A 10 | 18 | 8 | 5 | 4 |
| A 11 | 8 | 4 | 4 | 5 |
| A 12 | 16 | 7 | 5 | 5 |
| A 13 | 200 ? | 150 ? | 125 ? | 100 ? error? |
| A 14 | 43 | 11 | 5 | 4 |
| A 15 | 24 | 11 | 5 | 5 |
| A 16 | 31 | 19 | 11 | 7 |
| A 17 | 39 | 23 | 14 | 8 |
| A 18 | 64 | 38 | 22 | 15 |
| A 19 | 48 | 76 | 95 | 95 |
| A 20 | 49 | 67 | 68 | 63 |
| A 21 | 30 | 46 | 57 | 60 |
| A 22 | 56 | 69 | 76 | 64 |
| A 23 | 54 | 64 | 60 | 48 |
| A 24 | 67 | 100 | 105 | 97 |
| A 25 | 25 | 43 | 56 | 65 |
| A 26 | 43 | 62 | 78 | 87 |
| A 27 | 35 | 39 | 38 | 27 |
| A 28 | 4 | 3 | 3 | 3 |
| A 33 | 50 | 30 | 16 | 10 |
| B 1 | 45 | 32 | 28 | 29 |
| B 2 | 65 | 54 | 45 | 32 |
| B 3 | 68 | 84 | 70 | 54 |
| B 4 | 32 | 32 | 27 | 25 |
| B 5 | 58 | 48 | 36 | 24 |
| B 6 | 63 | 49 | 32 | 23 |
| B 7 | 78 | 110 | 130 | 128 |
| B 8 | 58 | 57 | 43 | 33 |
| B 9 | 54 | 19 | 17 | 17 |
| B 10 | 62 | 46 | 28 | 25 |
| B 11 | 59 | 79 | 86 | 85 |
| B 12 | 36 | 39 | 40 | 34 |
| B 13 | 2 | 3 | 4 | 6 |

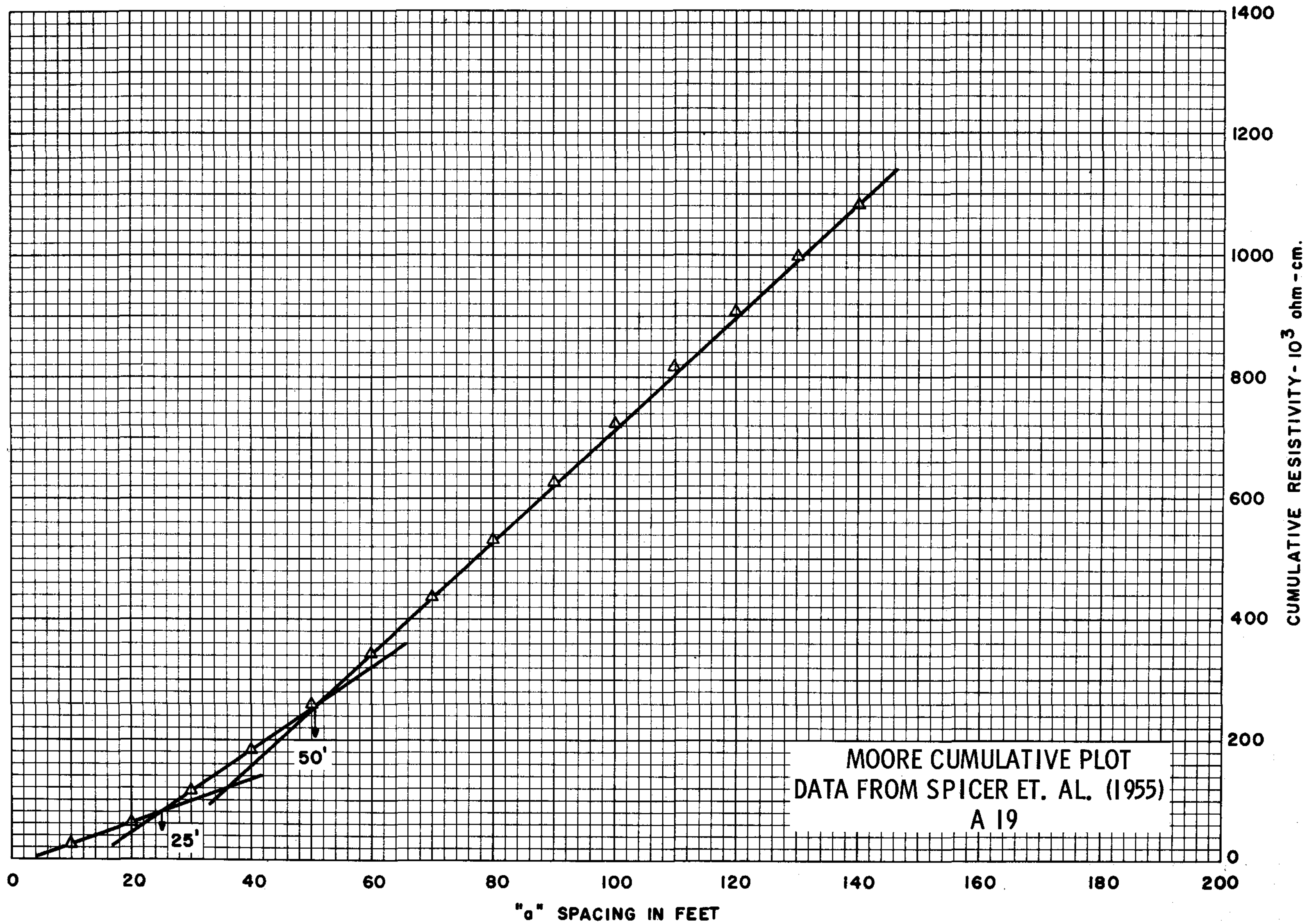


Figure 7. Spread A-19 Moore Cumulative Plot.

## CONCLUSIONS AND RECOMMENDATIONS

Most resistivity methods assume homogeneous and horizontal layers, and usually not more than three to four discrete units. The Pleistocene and pre-Pleistocene sediments in Delaware are a highly variable mixture of sand, clay, gravel, and pebbles. Considering this, there is little wonder that it is difficult to find an interpretative resistivity layering that can be correlated with the lithology.

The method which gives the best results, i.e., the closest correlation between anomalous resistivity data and the presence of known or potential aquifers, is the horizontal resistivity traversing technique. This method of analysis is empirical, but it has met with some success as indicated in this report. The correlation is between high resistivity values, usually 75,000 ohm-cm at "a" spacings of 50, 75, and 100 feet, and either thick sections of sand and gravel, or near highly productive water wells.

There is no conclusive evidence of a difference in the seismic velocity between the Pleistocene and the pre-Pleistocene sediments to depths of about 200 feet. Thus, the seismic-refraction technique produced negative or questionable results.

It is my recommendation that further use of the resistivity technique is a useful method under conditions of close well control. Efforts in the search for the Pleistocene channels underlain by Tertiary or Cretaceous sediments should be directed toward the refinement of the horizontal resistivity traverse technique.

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# APPENDIX A

## Well Logs

All logs have been supplied by the Delaware Geological Survey, except wells A and B in the Bear area supplied by the Artesian Water Company. Depth intervals in feet.

**Hc34-1**

| | |
|---|---|
| 0-3 | top soil |
| 3-60 | coarse sand |

**Hc34-5**

| | |
|---|---|
| 0-3 | top soil |
| 3-18 | coarse sand and gravel |
| 18-51 | sand and clay |
| 51-53 | fine sand |
| 53-54 | clay |
| 54-56 | coarse sand |

**Hc34-25**, Welfare Home

| | |
|---|---|
| Pleistocene | |
| 0-2 | top soil |
| 2-8 | medium sand, few peb. |
| 8-13 | med sand, peb., clay |
| 13-34 | med sand, some clay |
| 34-61 | med sand |
| 61-78 | med sand, some clay |
| 78-85 | fine-med sand, peb. |
| 85-93 | med-coarse sand |
| 93-98 | coarse sand, qtz peb. |
| 98-103 | coarse sand, sm peb. |
| Miocene ? | |
| 103-114 | blue clay |

**Cc55-10**

| | |
|---|---|
| 0-6 | sandy clay |
| 6-8 | sand, gravel, clay |
| 8-10 | hard pan |
| 10-40 | sand, gravel, clay |
| 40-46 | sand, coarse gravel, some clay |
| 46-59 | fine sand, clay, gravel |
| 59-61 | clay |
| 61-65 | fine sand, clay |
| 65-74 | clay |
| 74-86 | clay |
| 86-92 | sand and gravel |
| 92-96 | clay |
| 96-100 | clay |

Static water level 37 feet on August 10, 1965

**Hc44-1**

| | |
|---|---|
| 0-14 | clay |
| 14-20 | sand, clay, gravel |
| 20-26 | sand, med clay |
| 26-38 | sand |
| 38-50 | sand |
| 50-51 | fine sand, clay |
| 51-54 | sand, clay |
| 54-60 | med sand |
| 60-68 | sand, clay |
| 68-108 | coarse sand, pea gravel |
| 108-112 | coarse sand, iron ore |
| 112-137 | coarse sand, pea gravel |

**Cc55-5**

| | |
|---|---|
| 0-3 | top soil |
| 3-8 | clay, sand |
| 8-27 | sand, gravel, iron ore |
| 27-29 | clay |
| 29-34 | clay |
| 34-40 | clay, sand |
| 40-41 | sand |
| 41-54 | clay |
| 54-56 | clay, fine sand |
| 56-57 | hard pan |
| 57-62 | gravel, iron ore |
| 62-64 | sand, clay |
| 64-80 | clay, little sand |
| 80-86 | coarse sand |

**Cc55-11**

| | |
|---|---|
| 0-4 | sandy clay |
| 4-8 | clay and stones |
| 8-16 | clay |
| 16-24 | sandy clay, gravel |
| 24-38 | coarse sand, gravel, some clay |
| 38-49 | clay, sand, gravel |
| 49-72 | sand, gravel |
| 72-83 | clay |

<u>Cc55-12</u>

| | |
|---|---|
| 0-18 | sandy clay |
| 18-26 | clay with gravel beds |
| 26-29 | sand, clay, stones |
| 29-53 | sand and gravel |
| 53-68 | clay, streaks of sand |
| 68-71 | sandy clay |
| 71-74 | clay |
| 74-90 | coarse sand and gravel |
| 90-91 | hard pan |
| 91-97 | clay |

<u>Dc32-2</u>

| | |
|---|---|
| 0-2 | top soil |
| 2-18 | sand and clay |
| 18-35 | sand and gravel |
| 35-70 | clay |
| 70-74 | fine sand |
| 74-115 | clay, fine sand |
| 115-123 | fine sand |
| 123-132 | medium sand |

<u>Well A</u> (Rt. 7 and Penna. RR)
Bear

| | |
|---|---|
| 0-2 | top soil |
| 2-46 | sandy clay |
| 46-55 | dirty sand, gravel and stones |
| 55-70 | sand, gravel and stones |
| 70-73 | fine sand |
| 73- | hard red clay |

<u>Well B</u> (Adj. Red Fox Rest. Rt. 40, Bear area)

| | |
|---|---|
| 0-2 | top soil |
| 2-5 | clay |
| 5-31 | sandy clay |
| 31-34 | sand, fine gravel mixed with clay |
| 34-47<br>47-50 | sand, fine gravel, excellent quality, clean and sharp fine sand and gravel |
| 50-53 | fine gravel, some clay |
| 53-57 | fine gravel, clay and some stones |
| 57-65 | red clay |
| 65-90 | clay |
| 90-125 | sandy clay |

# APPENDIX B

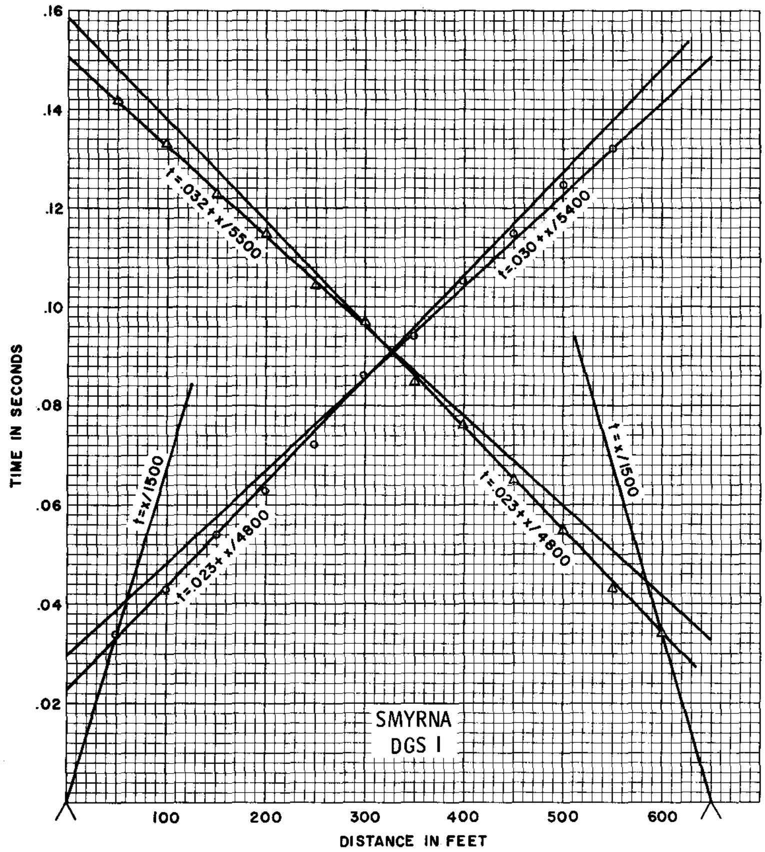
## Geophysical Graphs

Smyrna Area seismic travel time plots

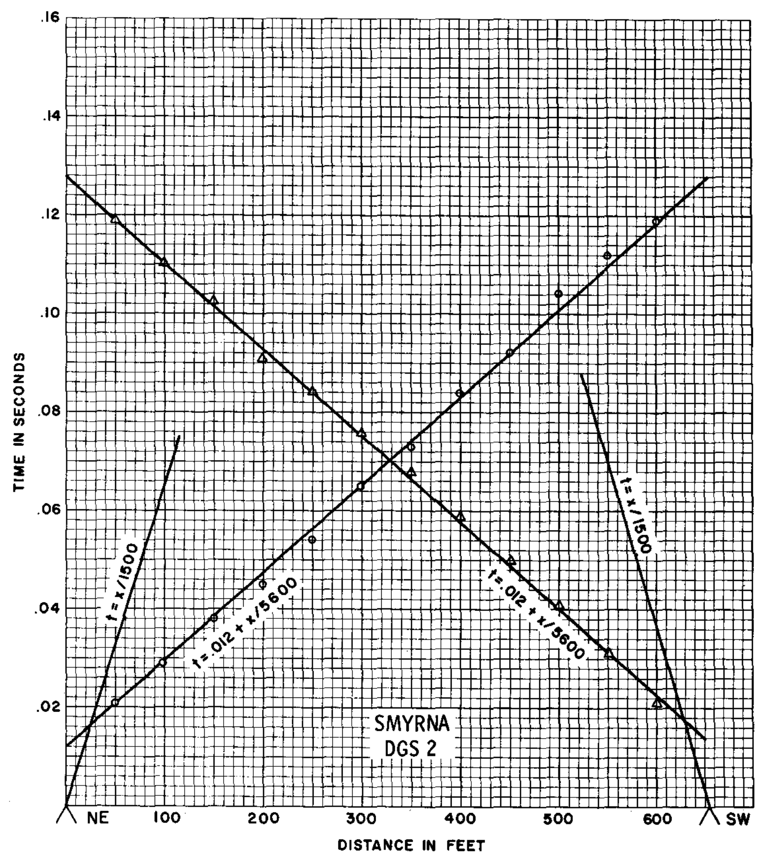
Smyrna Area resistivity graphs

School Lane (New Castle) Area resistivity graphs

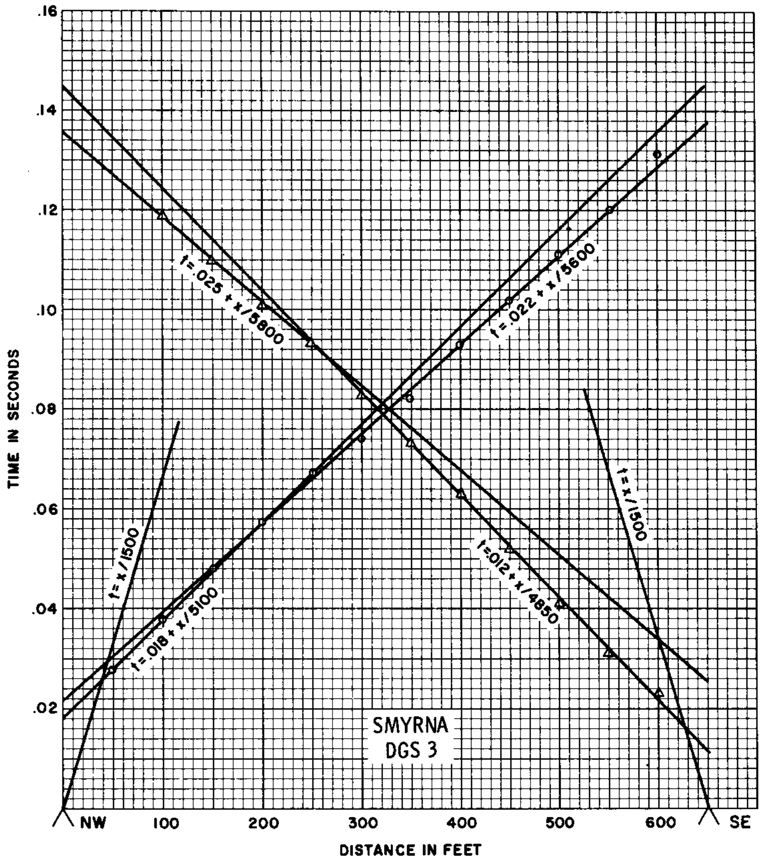
Bear Area resistivity graphs



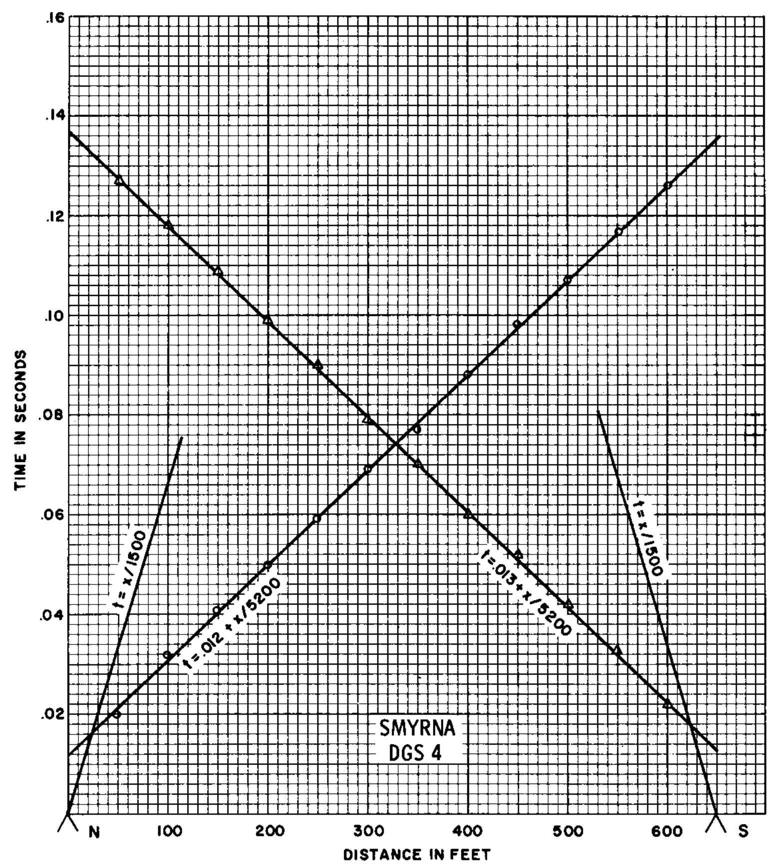
SMYRNA
DGS 1
t=.032+x/5500
t=.030+x/5400
t=.023+x/4800
t=.023+x/4800
t=x/1500
t=x/1500
TIME IN SECONDS
DISTANCE IN FEET

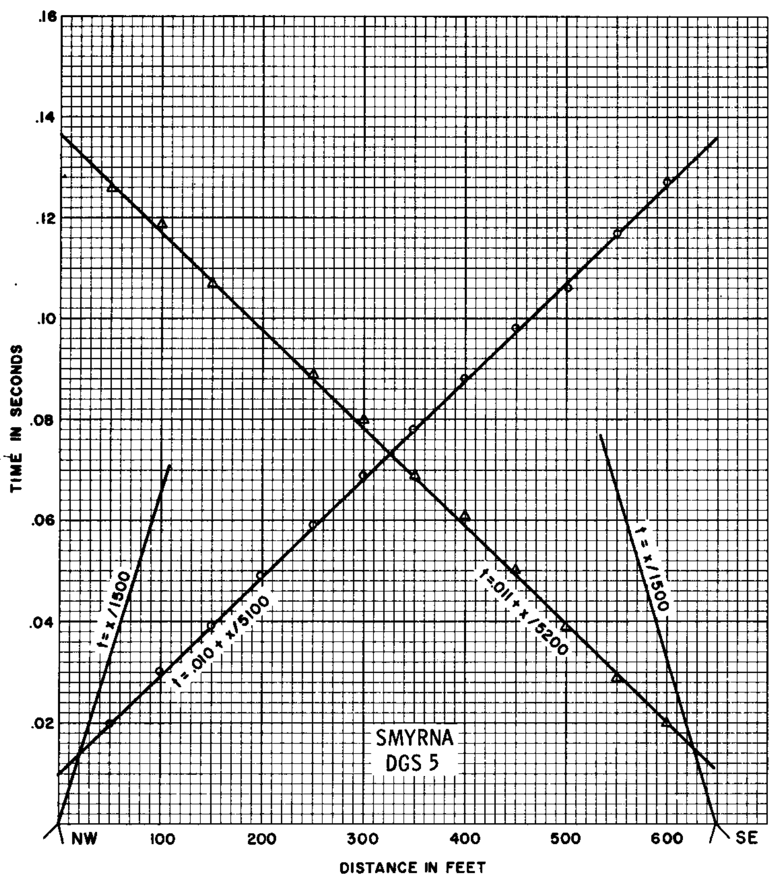
SMYRNA
DGS 2
t=.012+x/5600
t=.012+x/5600
t=x/1500
t=x/1500
NE
SW
TIME IN SECONDS
DISTANCE IN FEET

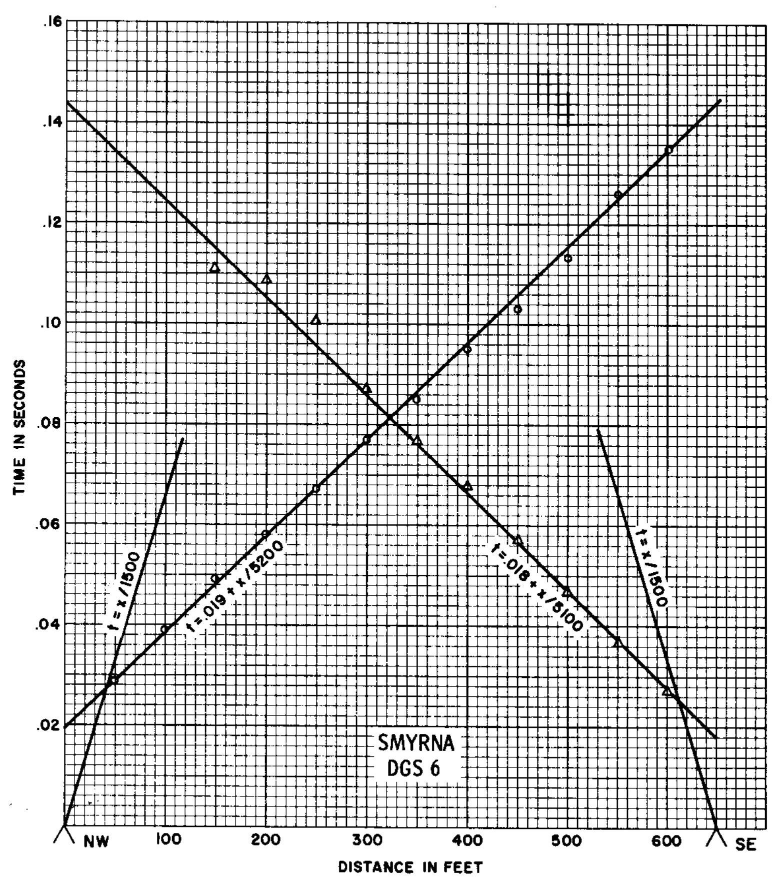


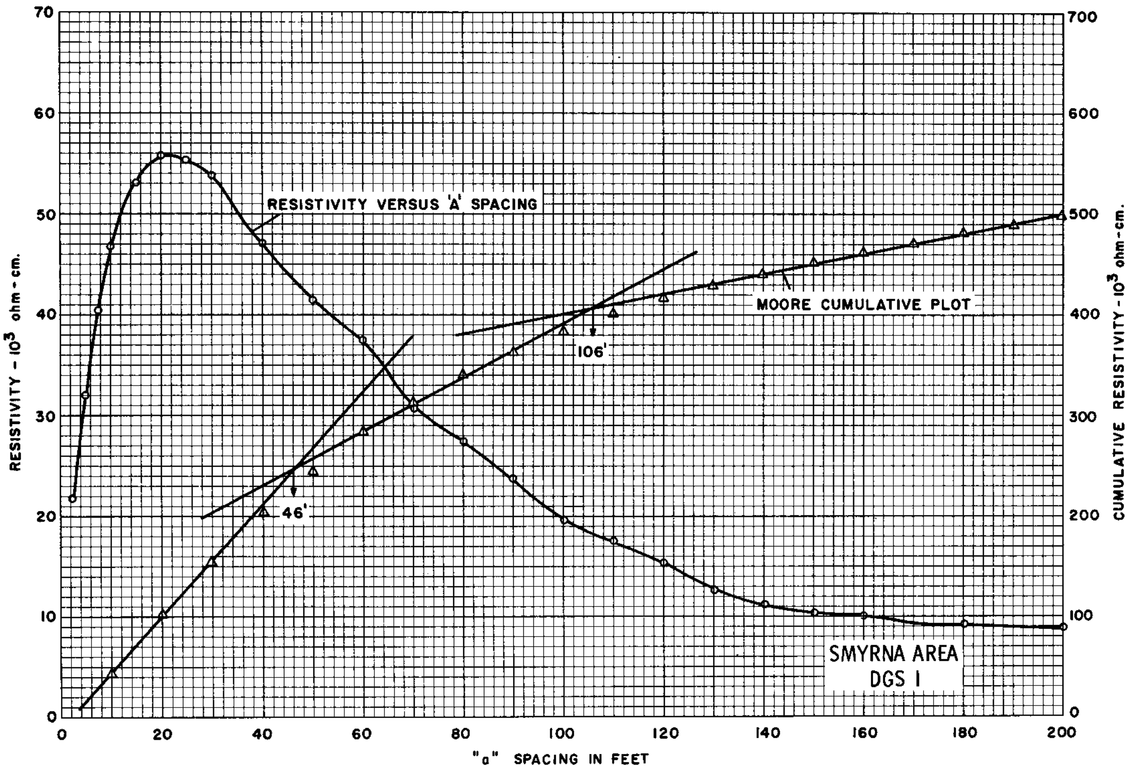
.16
.14
.12
.10
.08
.06
.04
.02
TIME IN SECONDS
NW
100
200
300
400
500
600
SE
DISTANCE IN FEET
t = .025 + x/5800
t = .022 + x/5600
t = x/1500
t = x/1500
t = .012 + x/4850
t = .018 + x/5100
SMYRNA
DGS 3

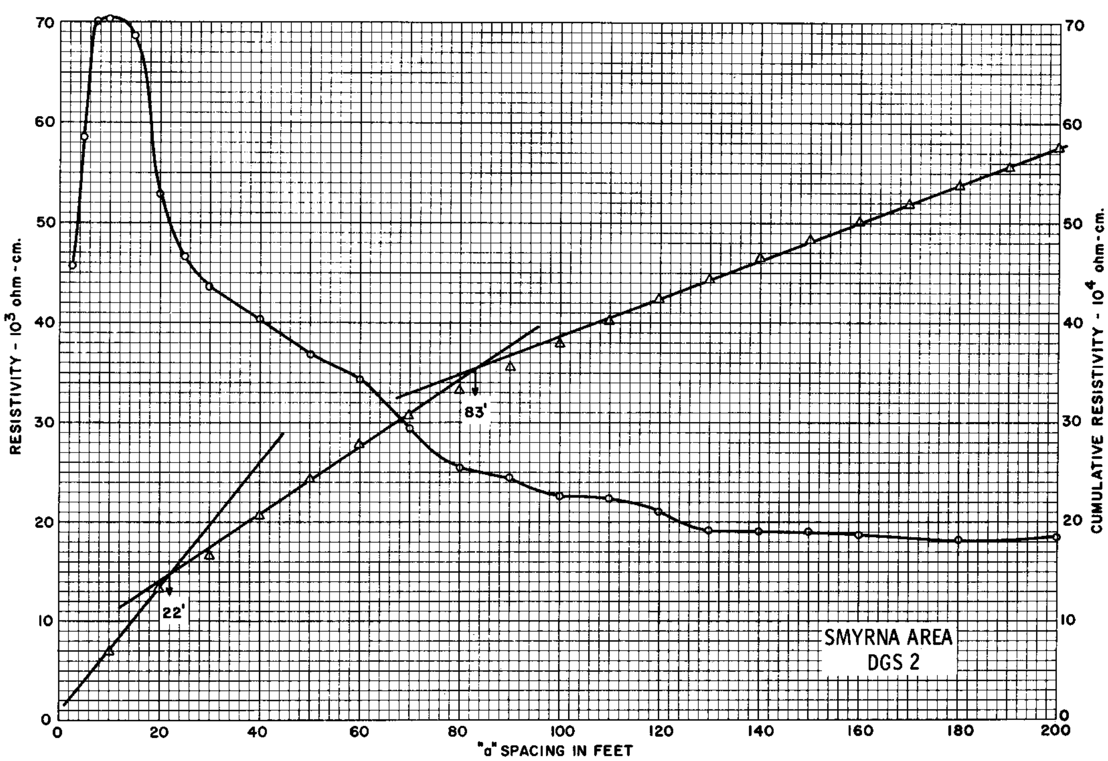



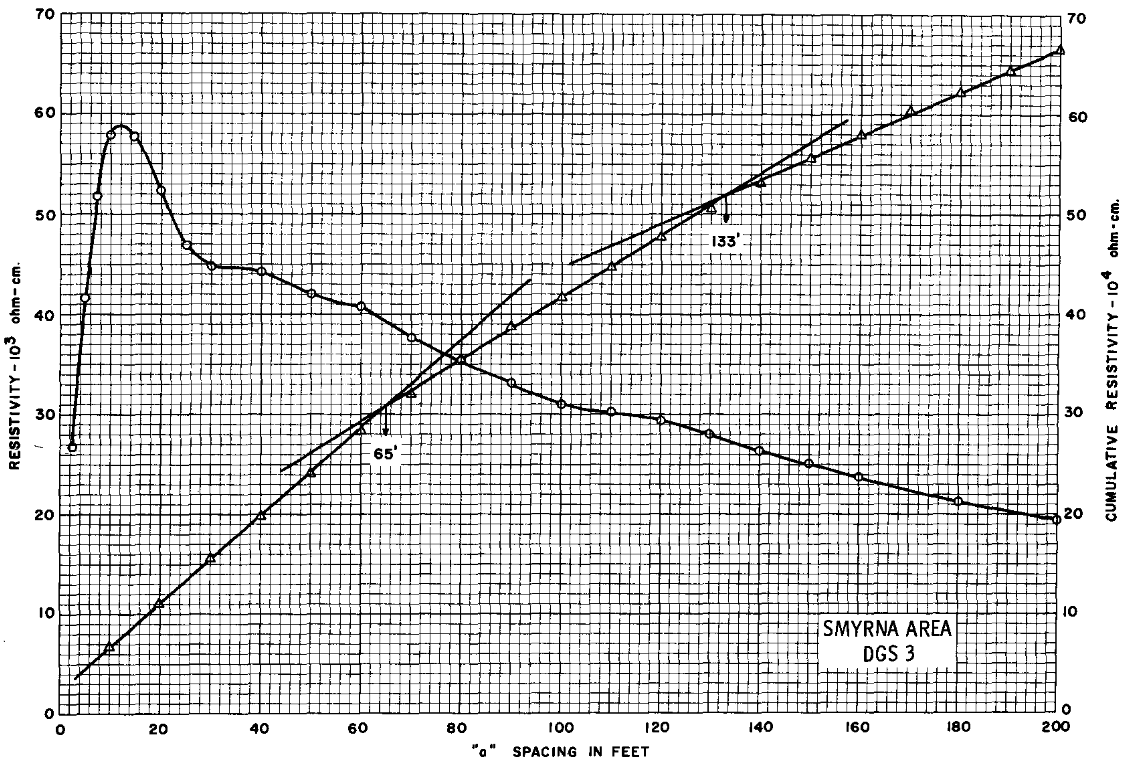
.16
.14
.12
.10
.08
.06
.04
.02
TIME IN SECONDS
N
100
200
300
400
500
600
S
DISTANCE IN FEET
t = x/1500
t = x/1500
t = .012 + x/5200
t = .013 + x/5200
SMYRNA
DGS 4


.16
.14
.12
.10
.08
.06
.04
.02
TIME IN SECONDS
t = x/1500
t = .010 + x/5100
t = .011 + x/5200
t = x/1500
SMYRNA
DGS 5
NW
100
200
300
400
500
600
SE
DISTANCE IN FEET

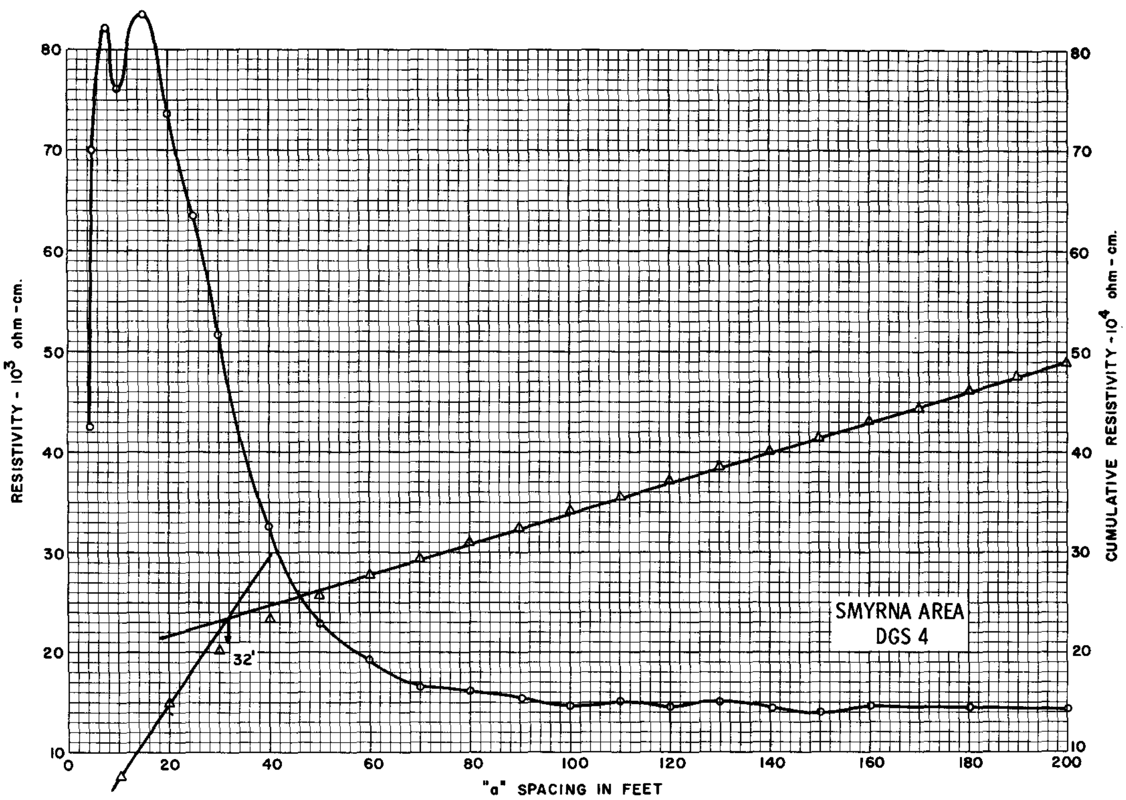

.16
.14
.12
.10
.08
.06
.04
.02
TIME IN SECONDS
t = x/1500
t = .019 + x/5200
t = .018 + x/5100
t = x/1500
SMYRNA
DGS 6
NW
100
200
300
400
500
600
SE
DISTANCE IN FEET


RESISTIVITY VERSUS 'A' SPACING
MOORE CUMULATIVE PLOT
46'
106'
SMYRNA AREA
DGS 1
RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^3$ ohm-cm.
"a" SPACING IN FEET

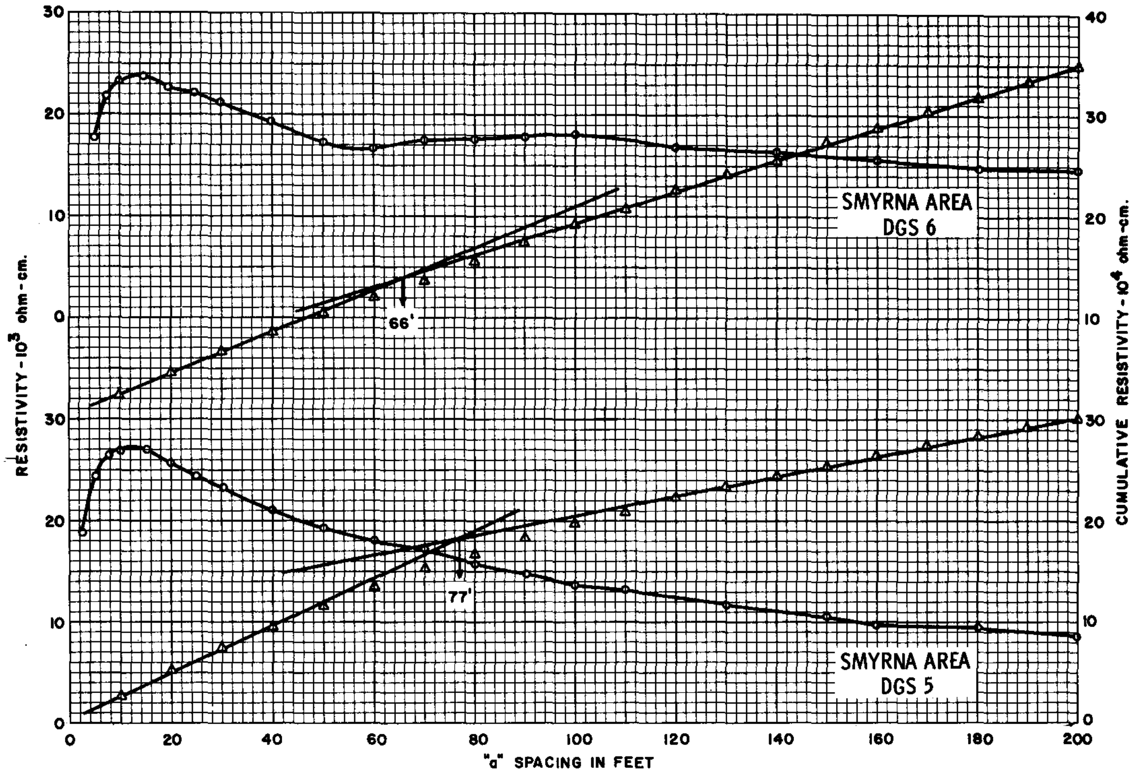

22'
83'
SMYRNA AREA
DGS 2
RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^4$ ohm-cm.
"a" SPACING IN FEET

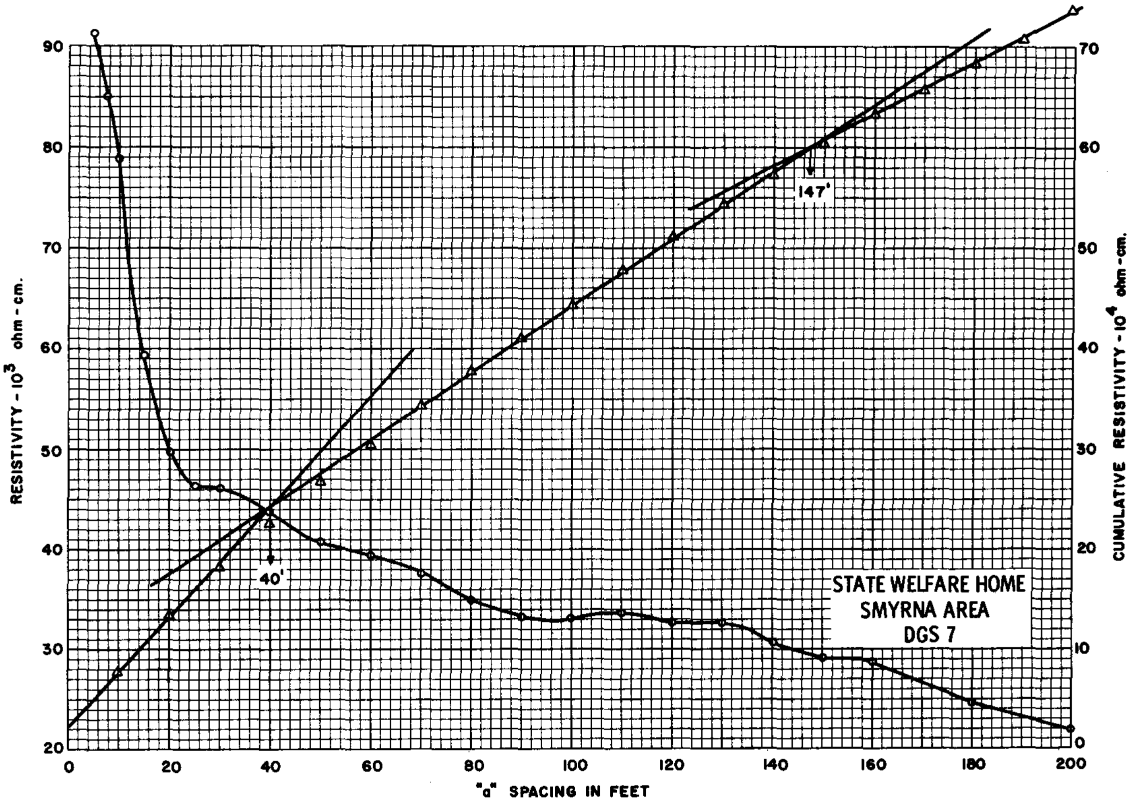


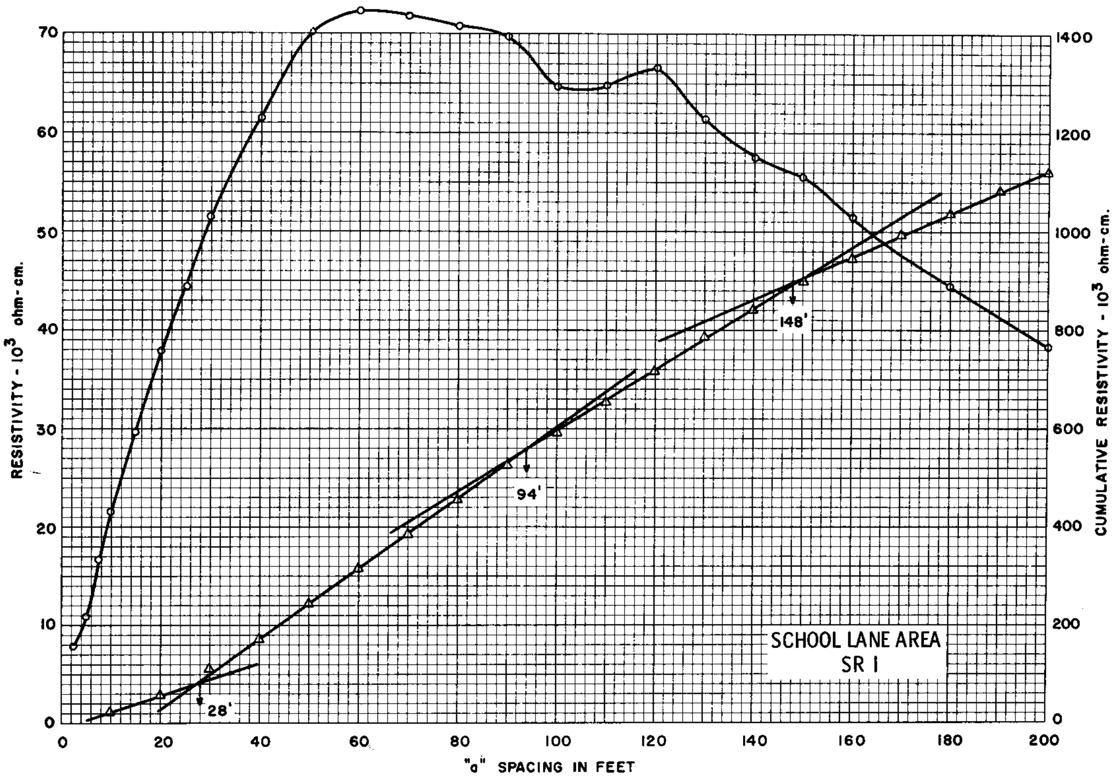
RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^4$ ohm-cm.
"a" SPACING IN FEET
65'
133'
SMYRNA AREA
DGS 3

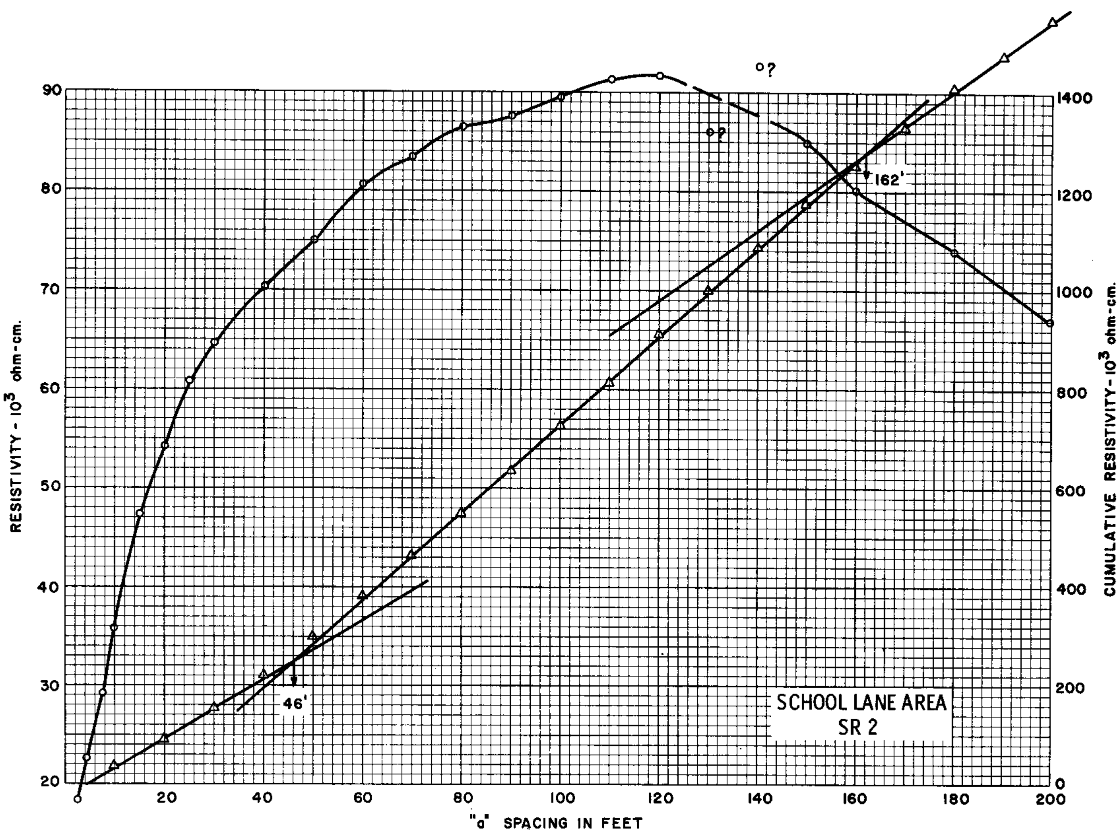
RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^4$ ohm-cm.
"a" SPACING IN FEET
32'
SMYRNA AREA
DGS 4


SMYRNA AREA
DGS 6
66'
SMYRNA AREA
DGS 5
77'
RESISTIVITY - 10³ ohm-cm.
CUMULATIVE RESISTIVITY - 10⁴ ohm-cm.
"a" SPACING IN FEET

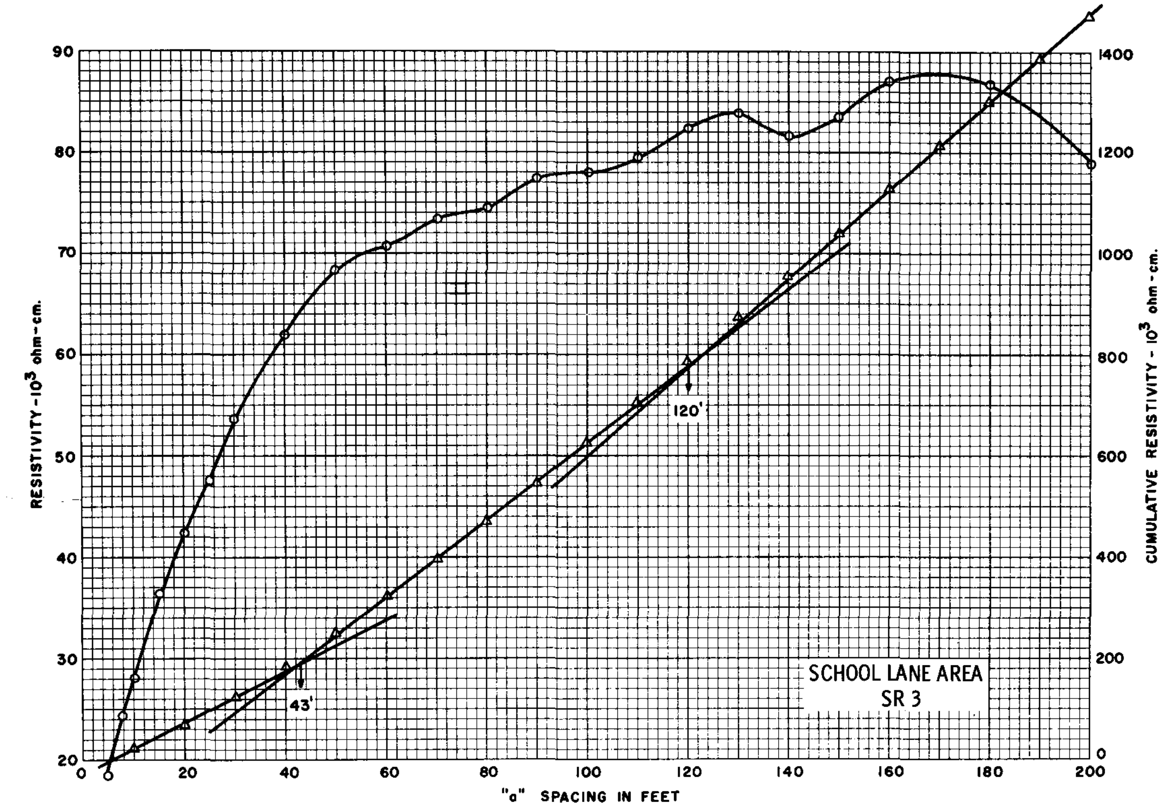

STATE WELFARE HOME
SMYRNA AREA
DGS 7
40'
147'
RESISTIVITY - 10³ ohm-cm.
CUMULATIVE RESISTIVITY - 10⁴ ohm-cm.
"a" SPACING IN FEET

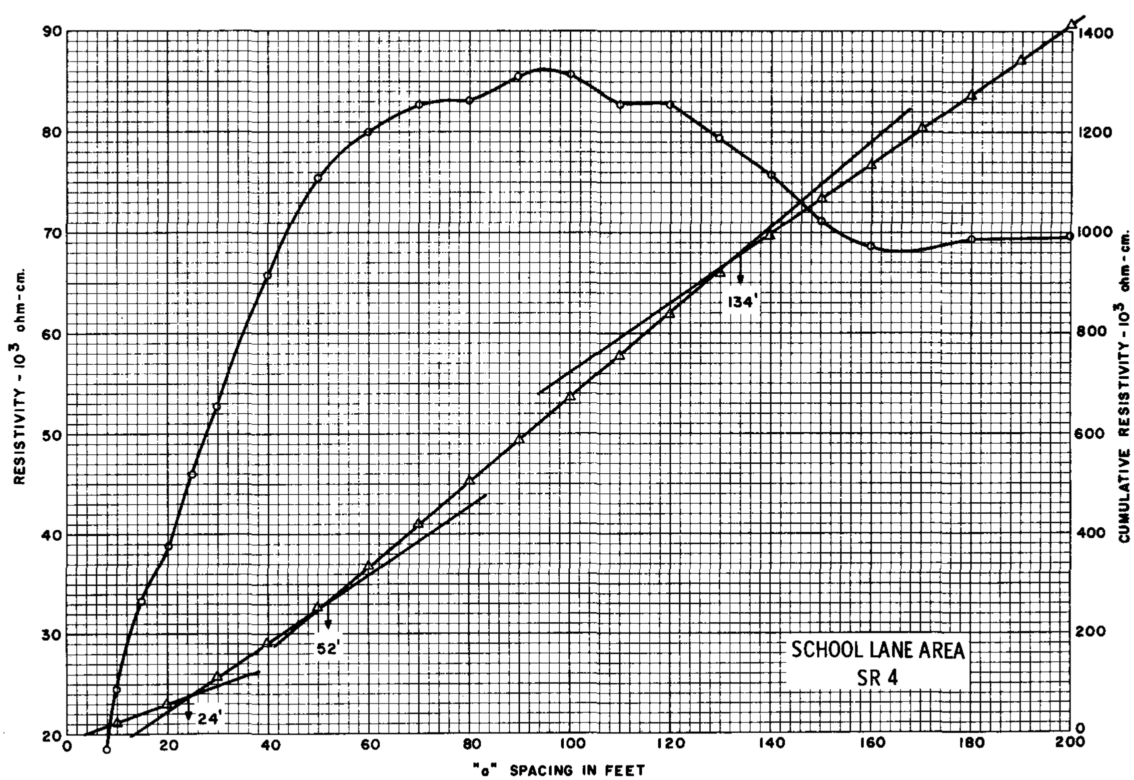


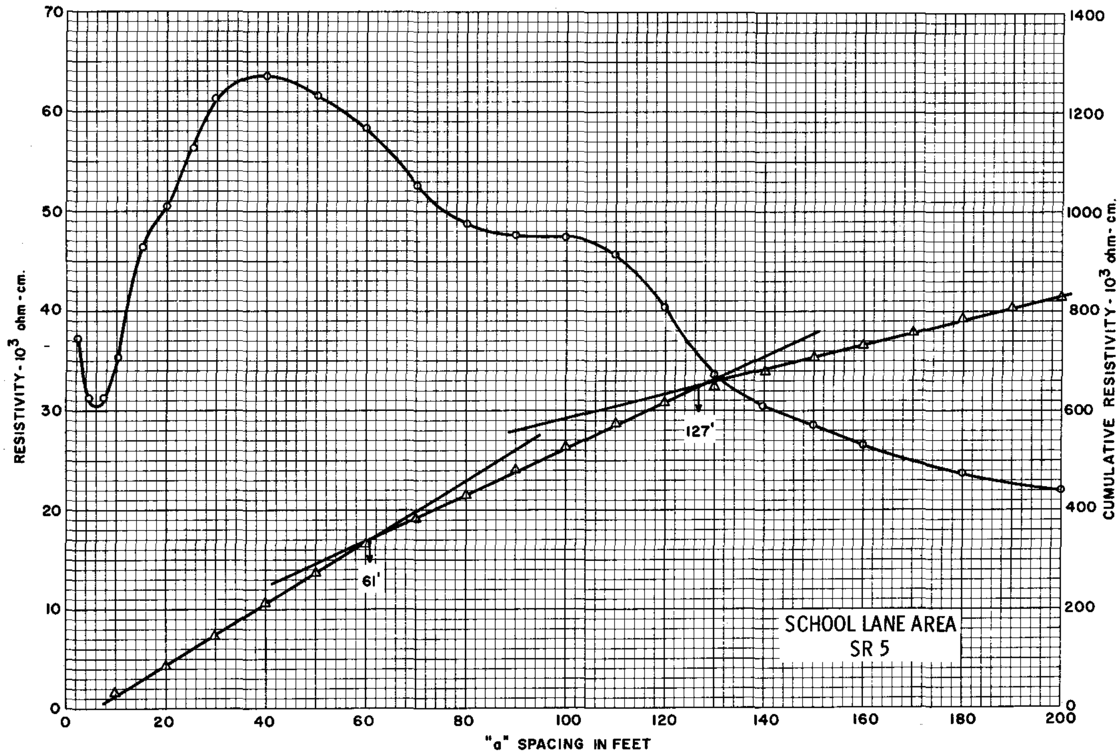
RESISTIVITY - 10³ ohm-cm.
CUMULATIVE RESISTIVITY - 10³ ohm-cm.
"a" SPACING IN FEET
28'
94'
148'
SCHOOL LANE AREA
SR I

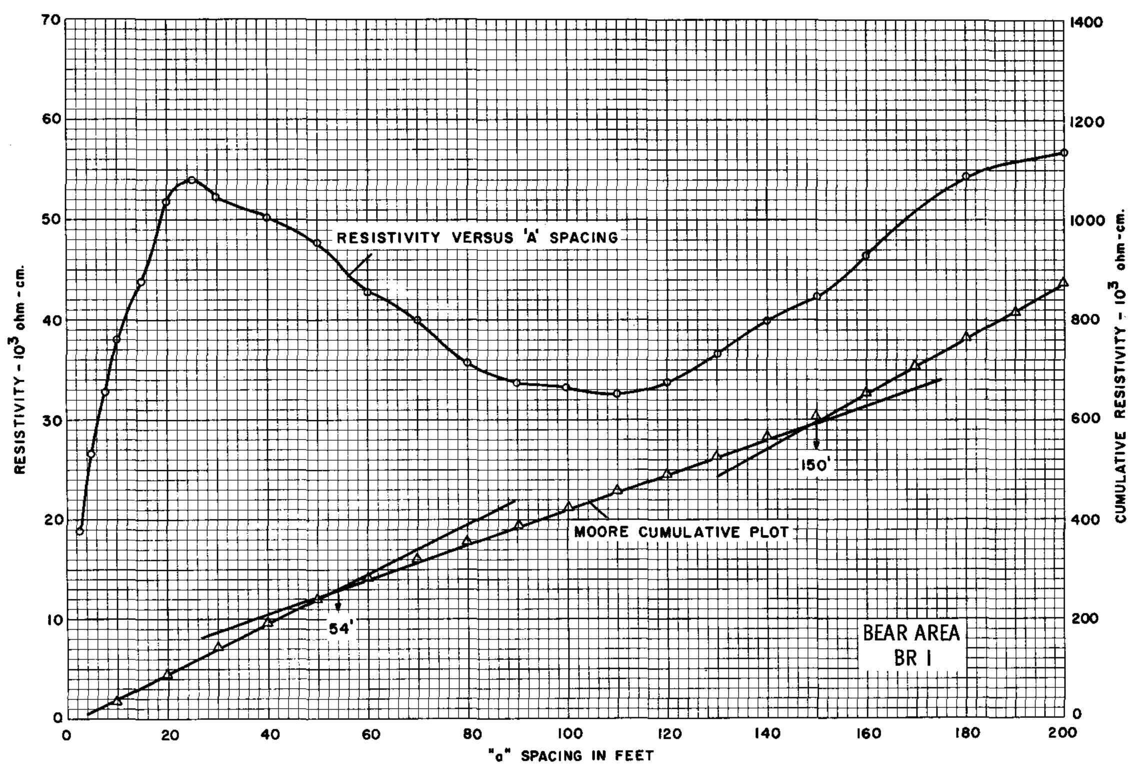



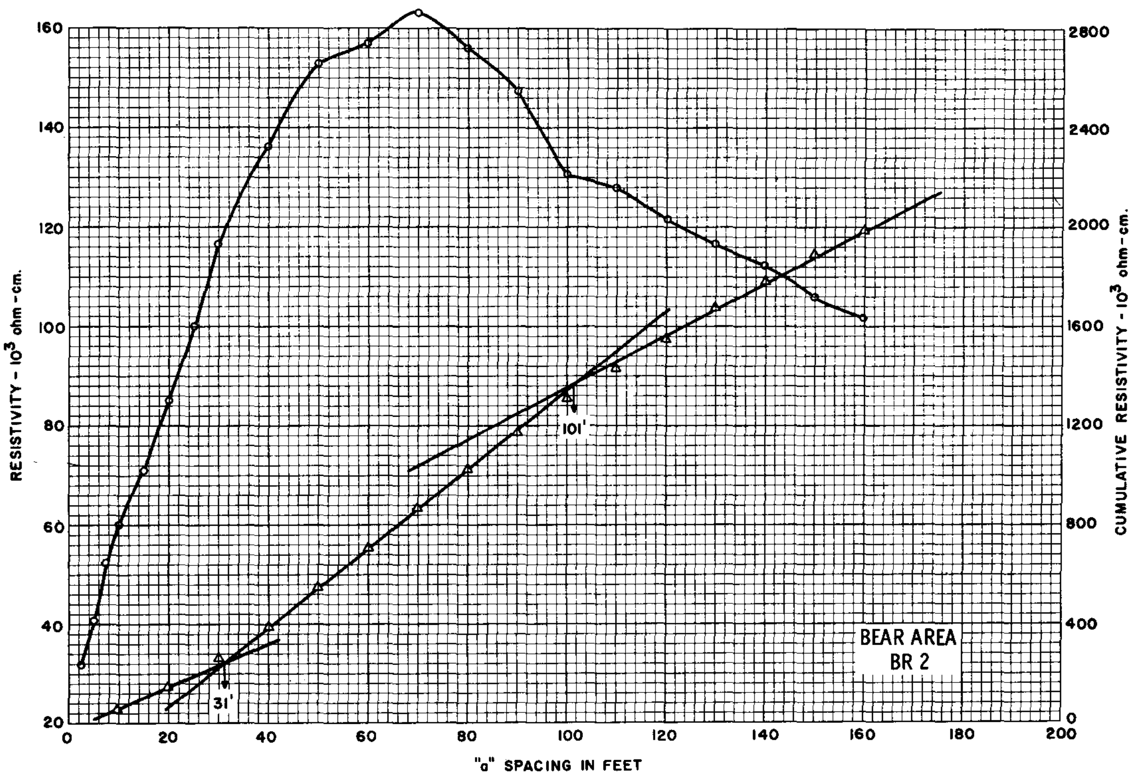
RESISTIVITY - 10³ ohm-cm.
CUMULATIVE RESISTIVITY-10³ ohm-cm.
"a" SPACING IN FEET
46'
162'
SCHOOL LANE AREA
SR 2


SCHOOL LANE AREA
SR 3
RESISTIVITY - 10^3 ohm-cm.
CUMULATIVE RESISTIVITY - 10^3 ohm-cm.
"a" SPACING IN FEET
43'
120'

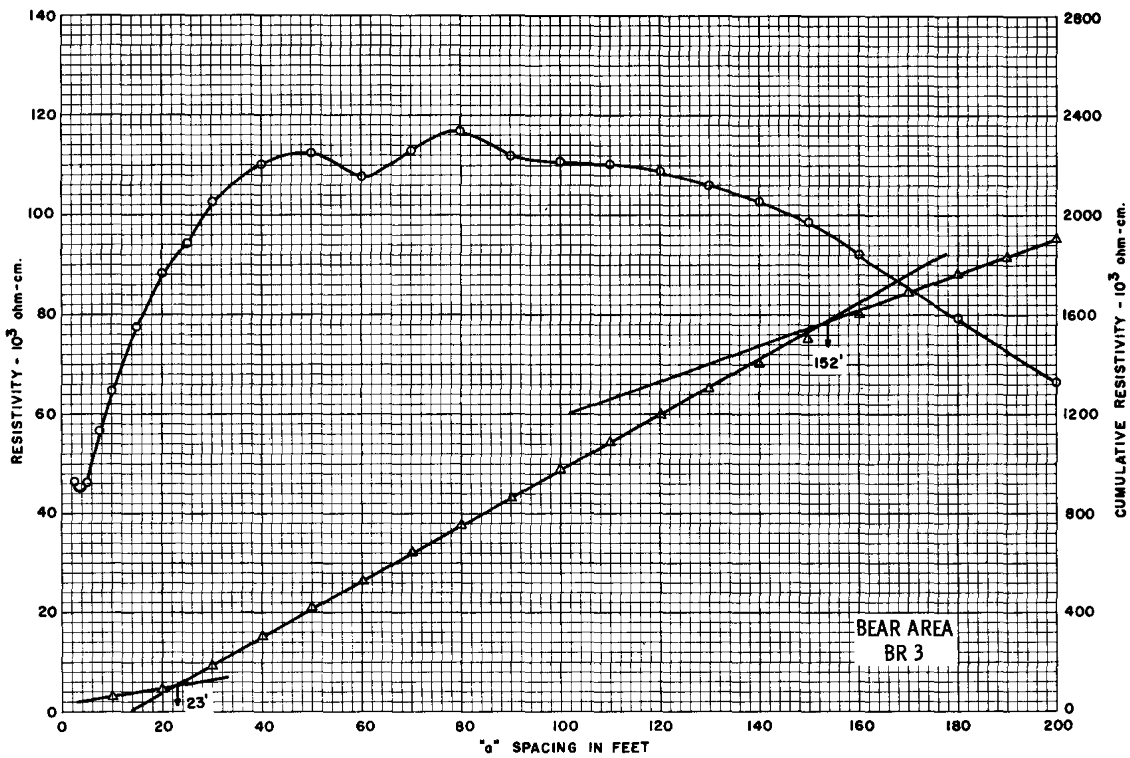

SCHOOL LANE AREA
SR 4
RESISTIVITY - 10^3 ohm-cm.
CUMULATIVE RESISTIVITY - 10^3 ohm-cm.
"a" SPACING IN FEET
24'
52'
134'


SCHOOL LANE AREA
SR 5
127'
61'
RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^3$ ohm-cm.
"a" SPACING IN FEET

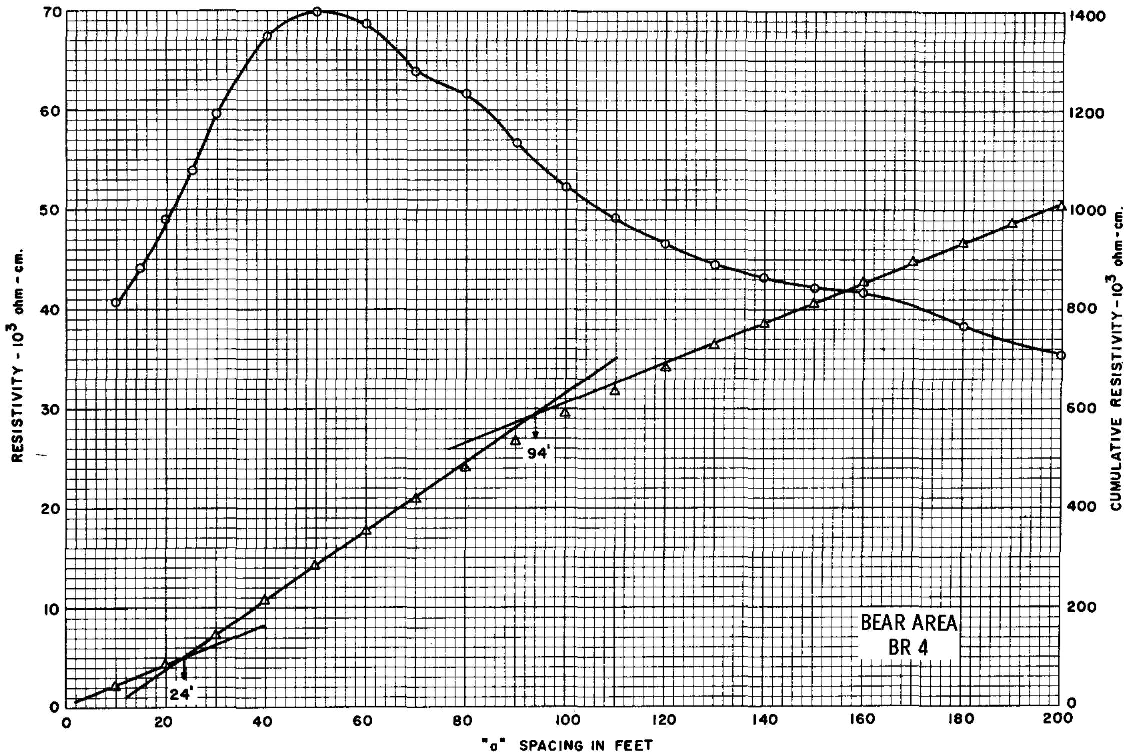

RESISTIVITY VERSUS 'A' SPACING
MOORE CUMULATIVE PLOT
150'
54'
BEAR AREA
BR 1
RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^3$ ohm-cm.
"a" SPACING IN FEET

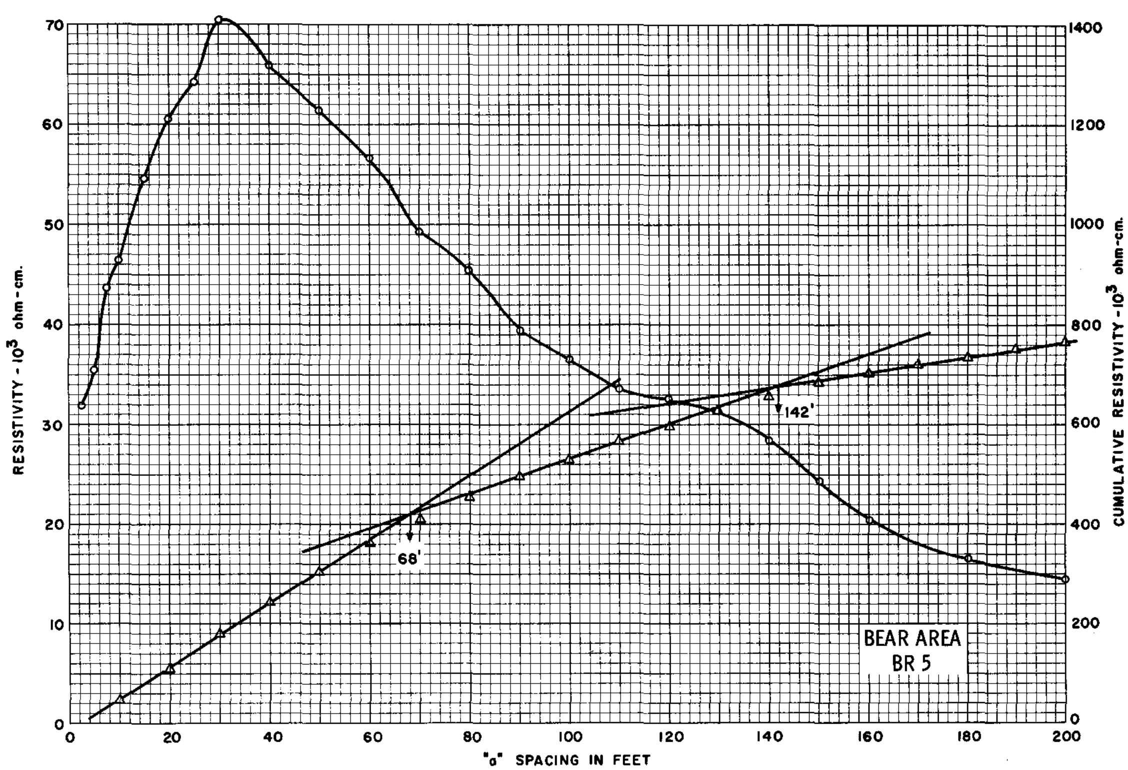


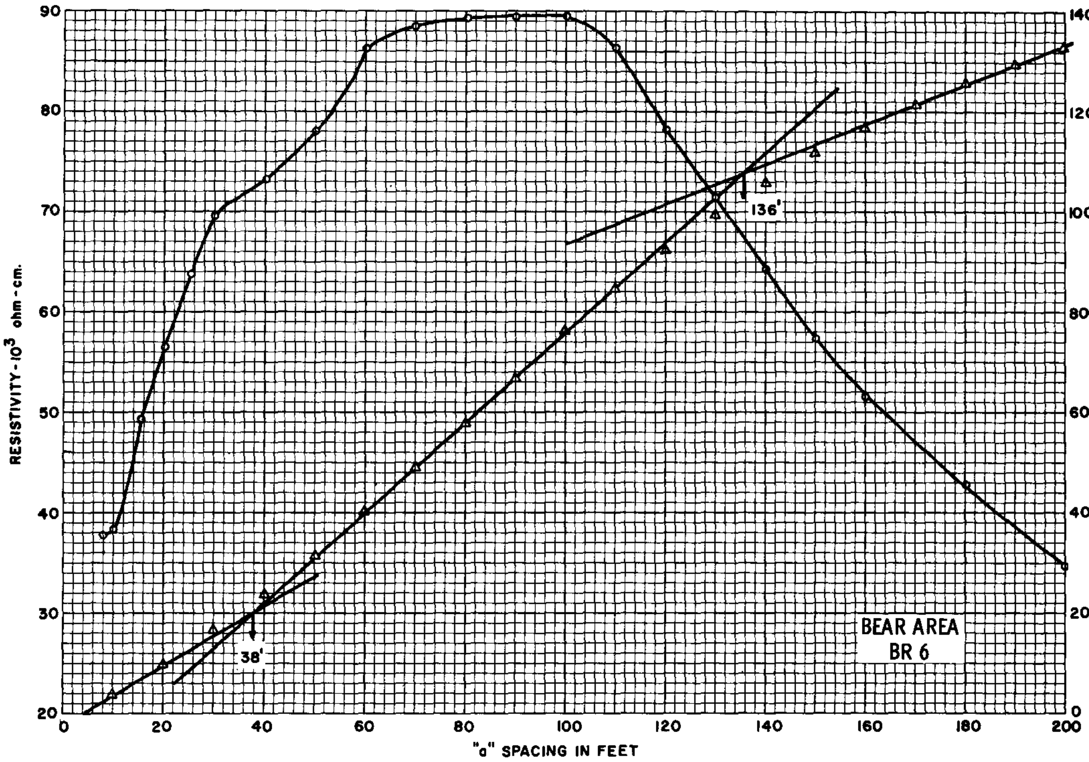
RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^3$ ohm-cm.
"a" SPACING IN FEET
31'
101'
BEAR AREA
BR 2

RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^3$ ohm-cm.
"a" SPACING IN FEET
23'
152'
BEAR AREA
BR 3


BEAR AREA
BR 4
RESISTIVITY - 10$^3$ ohm-cm.
CUMULATIVE RESISTIVITY - 10$^3$ ohm-cm.
"a" SPACING IN FEET
24'
94'


BEAR AREA
BR 5
RESISTIVITY - 10$^3$ ohm-cm.
CUMULATIVE RESISTIVITY - 10$^3$ ohm-cm.
"a" SPACING IN FEET
68'
142'



RESISTIVITY - $10^3$ ohm-cm.
CUMULATIVE RESISTIVITY - $10^3$ ohm-cm.
"a" SPACING IN FEET
38'
136'
BEAR AREA
BR 6

APPENDIX C

U. S. GEOLOGICAL SURVEY LOCATION MAP
(from Spicer et al., 1955)