GROUND WATER PROSPECTING IN FRACTURED SLATE USING DC RESISTIVITY AND THE VLF-BASED WADI SYSTEM - KERSHAW COUNTY, SOUTH CAROLINA

by

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South Carolina Water Resources Commission
Open-File Report 27
July 5, 1988

STATE
OF
SOUTH CAROLINA

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EXECUTIVE SUMMARY

1. The Bethune Rural Water Company requested the assistance of the South Carolina Water Resources Commission in helping them locate a favorable public-supply well site.

2. Surface geophysical techniques were employed at four potential sites in an effort to locate water in fractured slate.

3. Direct-current resistivity and the VLF-based WADI system were used at each site.

4. Resistivity data collected from the Wenner array did not sufficiently penetrate the slate to produce meaningful results.

5. Resistivity data collected from the Schlumberger array suggests the possibility of a fracture zone at one of the four sites.

6. WADI profiles indicate the presence of subsurface and surface conductors at each of the sites. However, it is unclear whether these conductors represent fracture zones.

7. Although no fractures are clearly discernible, there are sites which are more promising than others. These are listed from best to worst:

BEST.	Site 3 (the "cut-down" site)
	Site 1 ("Ned's Creek" site)
	Site 4 (the farmer's land)
WORST.	Site 2 (the "church" site)

INTRODUCTION

The South Carolina Water Resources Commission (SCWRC), at the request of the Bethune Rural Water Company and in cooperation with the University of South Carolina and the United States Geological Survey, conducted surface geophysical surveys on the outskirts of Bethune (Kershaw County) in an effort to locate a favorable well site (Figure 1). Currently, two wells supply the community; one pumps 300 gpm (gallons per minute), and the other, 125 gpm. To meet increased demands during the summer months and to provide a measure of security if one of the two wells should fail, a third well is required.

Potential sites for this new well must be located near existing transmission lines to meet economic constraints (Figure 2). Four such sites, chosen in part by the Hardwood Beebe engineering firm and by members of the Bethune Rural Water Company, were surveyed with surface geophysical instruments. Schlumberger and Wenner direct-current electrical soundings were made at sites 1 and 3 and at sites 1, 2, and 3, respectively; the VLF-based "WADI" system was employed at sites 1, 3, and 4 (Figure 2).

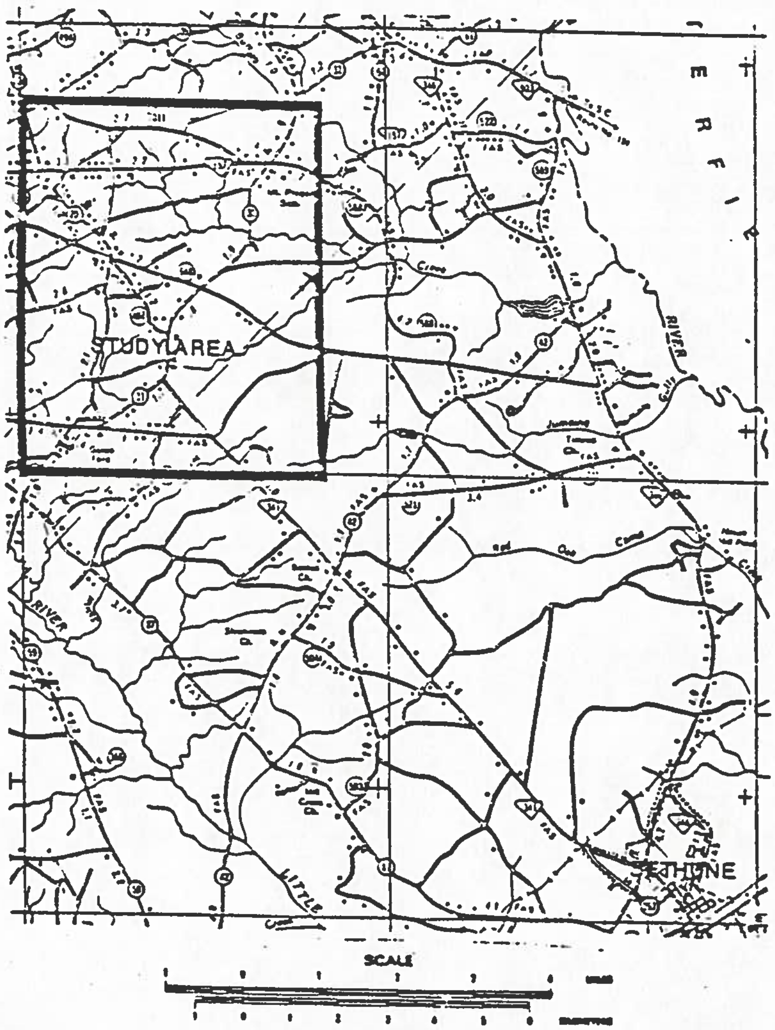

Figure 1. Location of the study area.

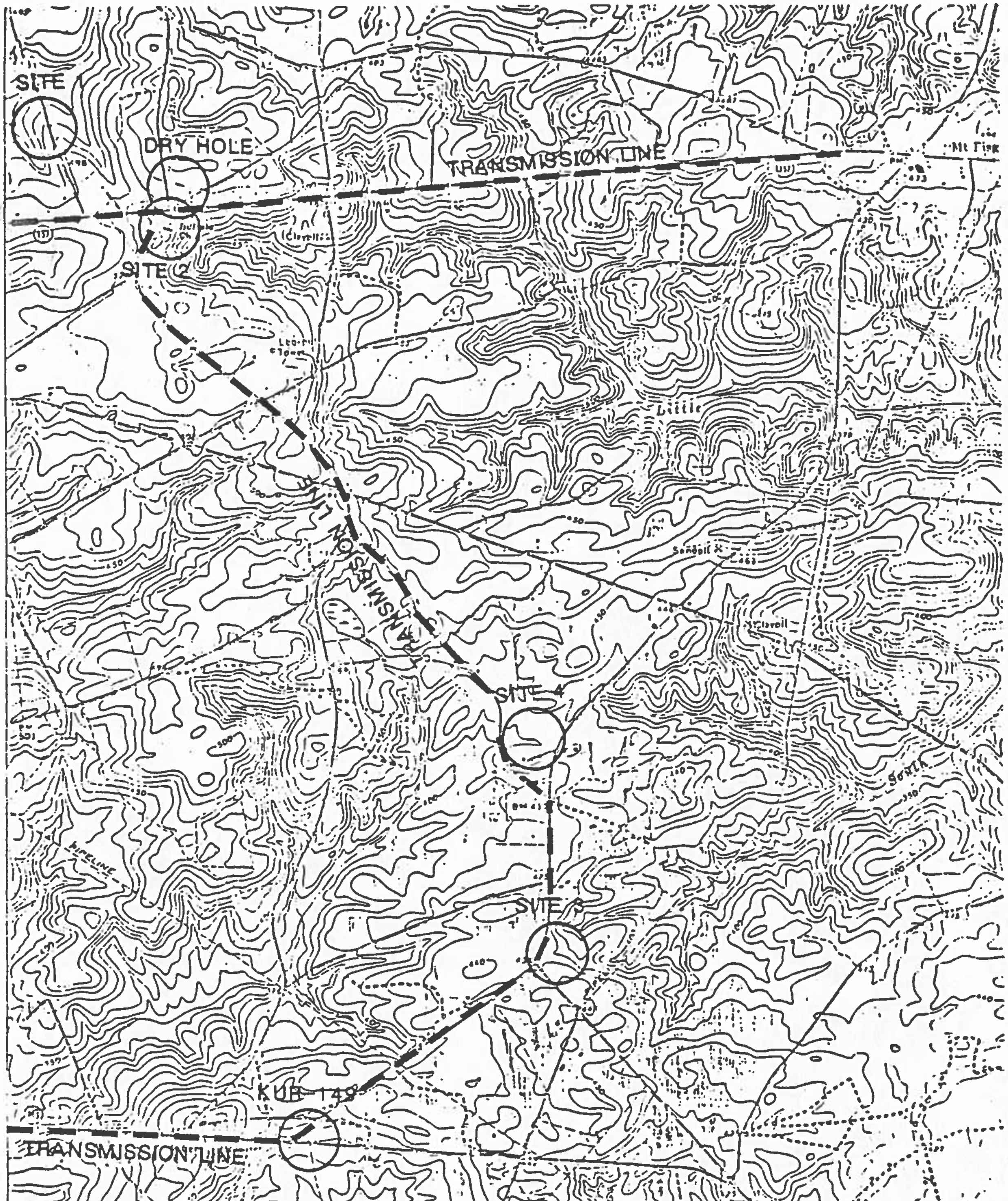

Figure 2. Location of surveyed sites and transmission lines.

GEOLOGY AND HYDROLOGY OF THE STUDY AREA

The study area is covered by a thin veneer of Middendorf Formation sediments overlying saprolite and slate. The Middendorf is an unconsolidated clayey sand but is too thin in the area to provide adequate amounts of water. Shallow wells tapping this water-table aquifer quickly go dry even at low pumping rates (personal communication with Donnie Horton, Bethune Rural Water Company).

Saprolite, which underlies the Middendorf, is a thick residual soil formed in response to the chemical decomposition of the basement complex. Its potential to supply water is generally unknown. However, a common practise among well drillers in the State is to set casing through the entire length of this unit and drill into the underlying basement rock for water. This widespread practise implies that little water is transmitted through this unit. An analysis of drillers logs and geophysical logs indicates an average combined thickness of 83 feet for the Middendorf and saprolite units in the area (range 21 ft - 130 ft).

Cuttings from a well (labeled "DRY HOLE", see Figure 2) in the study area indicate that the basement rock is a dark green slate (Carolina Slate). Slate is a highly compacted, fine-grained metamorphic rock typically derived from shale. Between the slate and clayey saprolite is a 30- to 40-foot zone composed of a light-green, friable rock much less compacted than the slate and texturally resembling argillite. This rock represents a transitional zone between the highly weathered saprolite and the unweathered slate. Beyond this zone, the slate occurs to the total depth of the well (500 feet below land surface).

Unfractured slate is impermeable (mean permeability less than 0.045 millidarcies; see Davis and DeWiest, 1966). Consequently it is not a good aquifer. Fractured slate, however, can be more than 1000 times as permeable. A well, therefore, must intersect these fractures to produce water.

METHODOLOGY

The objective was to locate fluid-filled fractures in the slate by using surface geophysical instruments. Two instruments were used: a DC resistivity device (courtesy of the Earth Sciences Resources Institute at the University of South Carolina) and a VLF-based "WADI" system (courtesy of the United States Geological Survey, Water Resources Division).

The DC Resistivity Technique

The principles of the direct-current resistivity technique are detailed by Zohdy and others, 1974. In general, a known and constant current is sent through the ground at two outside electrodes (labeled 'A' and 'B', Figure 3). The resulting electric potential is measured at two inside electrodes (labeled 'M' and 'N', Figure 3). Potential and current are then used to calculate electric resistance (by Ohm's Law). Resistance and electrode distance are used to estimate resistivity.

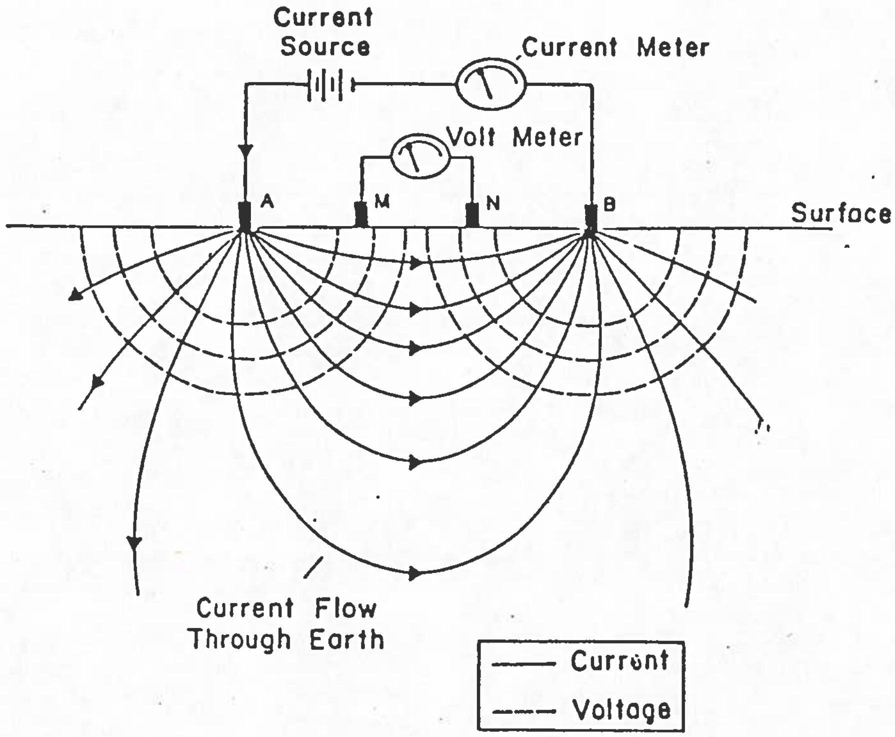

Figure 3. Principle of the resistivity technique (from Benson and others, 1982).

Resistivity is a fundamental property of all materials. It is a measure of the resistance that a material has to electricity per unit length and unit cross-sectional area of the material. It is conventionally expressed in units of ohm-meters or ohm-feet. (One ohm-meter is equivalent to 3.28 ohm-feet.) Resistivities of common rocks are listed in Figure 4. For example, a unit length and sectional area of clay is less resistant to electricity than sand with the same length and area. These differences constitute the usefulness of the technique to groundwater exploration. Fractured slate will have a lower resistivity than unfractured slate due to the conductive water in the fractures.

There is no absolute relationship between the electrode spacings and the penetration depth of the current (see Zohdy and others, 1974, p. 20). However, the positions of the four electrodes are, in a relative manner, related to the depth to which current will flow. As the distance between the outside electrodes (AB) is increased relative to the distance of the inside electrodes (MN), the resistivity of deeper layers is measured.

The procedure for collecting data is to hammer each of the electrodes, which are metal spikes, into the ground at predetermined intervals. Current is then sent through the ground through the outside electrodes. Potential is measured at the inside electrodes and internally converted to apparent resistivity which is recorded by the operator. Distances between the spikes are then increase in a systematic fashion and resistivity is

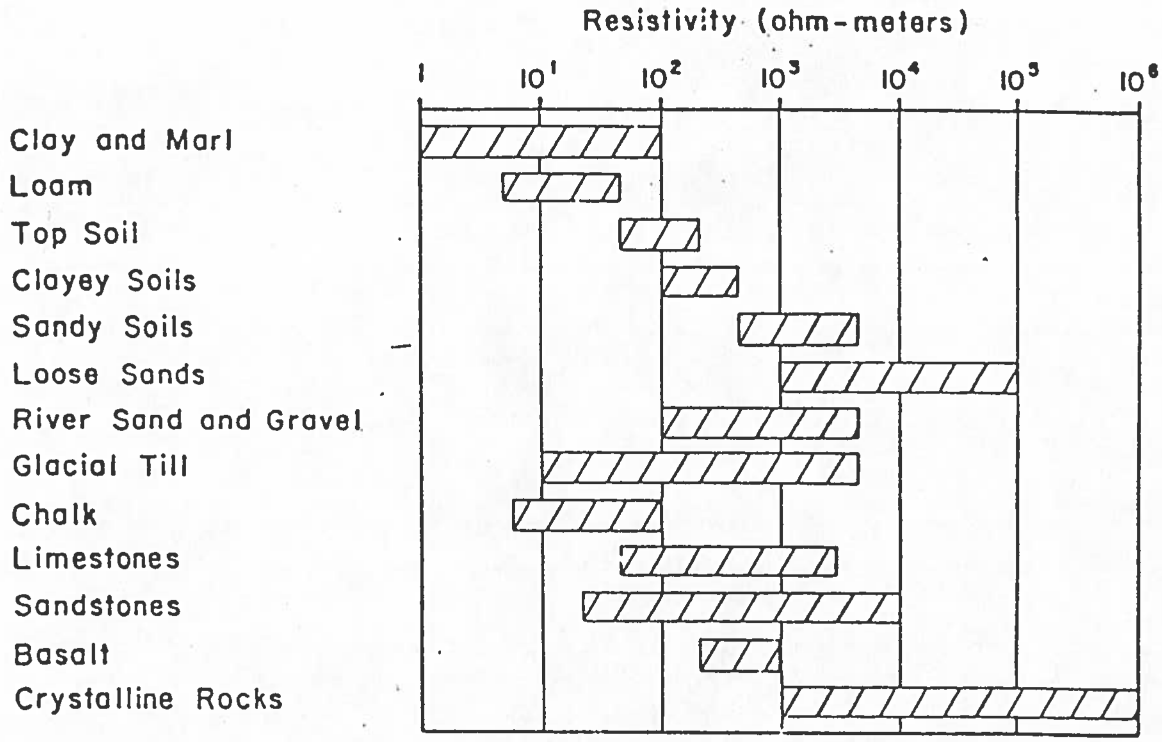

Figure 4. Resistivities of common rocks (from Benson et al., 1982).

measured at each station. As such, raw data are in the form of a measured resistivity as a function of electrode spacing. The length of cable available and the power of the current generator dictate the maximum distance to which the electrodes can be moved apart. In this case, the maximum distance between the outside electrodes was 600 feet.

Two such measurements (called "electrical soundings") were conducted at each site. One sounding was made by using the "Schlumberger" array, and the second was made with the "Wenner" array (Figure 5). With the Schlumberger array, the inside electrodes are kept at a distance that is less or equal to five times the distance between the outside electrodes (AB   5MN). With the Wenner array, the inside electrodes are kept at a distance equal to 1/3 the distance between the outside electrodes (AB = 3MN). The Schlumberger array has a "slightly greater probing depth and resolving power than Wenner sounding curves for equal AB electrode spacing" (Zohdy and others, 1974, p. 16).

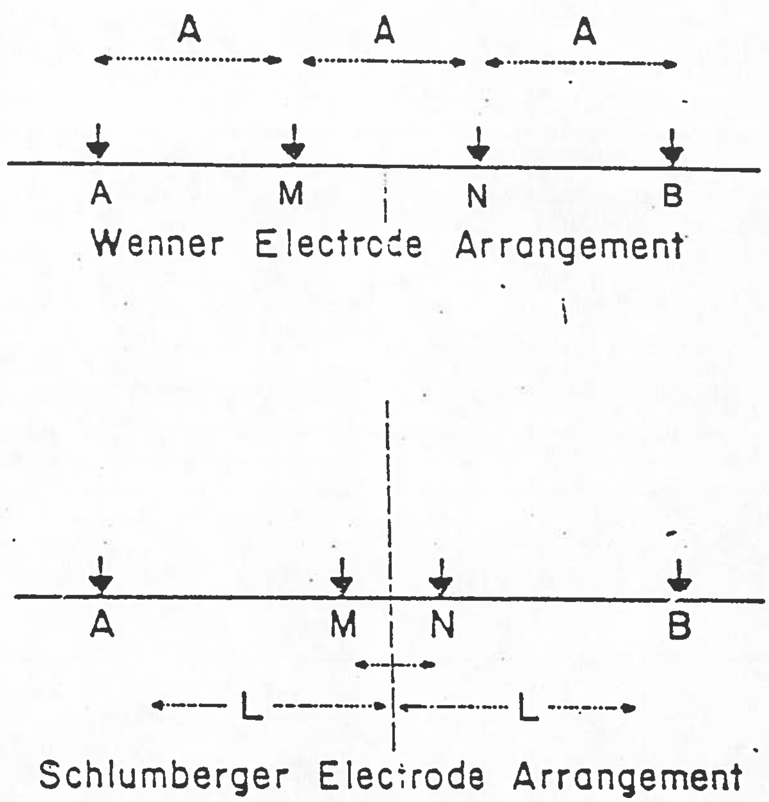

Figure 5. Schlumberger and Wenner arrays (modified from Benson and others, 1982).

The VLF-based "WADI" Technique

The second device used is called a "WADI". The WADI is an instrument that operates on the principle of very low frequency radio waves ("VLF", 15-30 kHz) generated by transmitters around the globe. These radio waves are tuned in by the WADI's receiving antenna (Figure 6). Both the strength and direction of the primary signal are affected by conductive structures located on the surface or in the subsurface. The result is a weak secondary field generated around these conductors (ABEM WADI Instruction Manual). The WADI measures the phase displacement and strength of this secondary field and records and displays it on a screen.

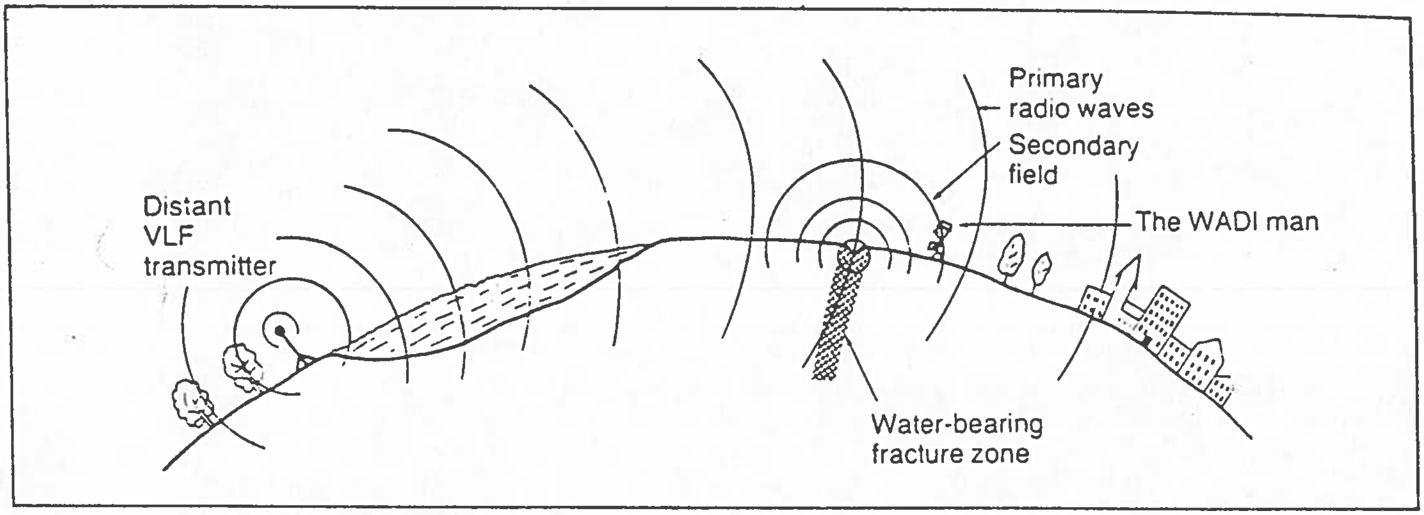

Figure 6. Principle of the WADI instrument.

The procedure for collecting the data is to run a pair of parallel traverses over the area of interest. Measurements are made at equal intervals along the traverse; in this case a measurement was taken every 15 feet and stored in the WADI. An interpolation technique then interpolates values between the stations and produces a continuous curve over the traverse. Peaks along the curve represent surface or subsurface conductors.

Table 1 cross-references the sites and the various techniques used.

Table 1. Sites surveyed in the study area.

SITE	ELEVATION (ft)	Wenner	Schlumberger	WADI
1 (Ned's Creek)	470	X	X	X
2 (near Church)	500	X		
3 (cut-down area)	430	X	X	X
4 (farmer's land)	420			X
DRY HOLE	500	X	X	X
KUR-149 (300 gpm)	420	X	X	X

RESULTS AND INTERPRETATIONS

Wenner Sounding Curves

On February 3, 1988, Wenner soundings were made at the three proposed sites mentioned above. In addition, two other soundings were made, one at a recently drilled dry well (labeled 'DRY HOLE') and the other at the well producing in excess of 300 gpm (labeled 'KUR-149'). These latter two sites were surveyed so their sounding curves could be compared with the curves made at the proposed sites.

Raw data for each sounding are in Appendix I-A. The curves for each individual site are in I-B. Figure 7 is an overlay of the five Wenner sounding curves.

On these curves, apparent resistivity is plotted along the vertical axis, and the 'a' spacing is plotted on the horizontal axis. Logarithmic coordinates are conventionally used for reasons stated by Zohdy and others, 1974 (pp. 20-22).

An examination of Figure 7 indicates that each site, with the exception of KUR-149, shows a monotonic decrease in resistivity with depth. This response reflects both changes in lithology and water saturation. The high resistivities at shallow depths correspond to the unsaturated zone of the Middendorf sand. In this zone, both air and water occupy the pore system. Air, with a resistivity approaching infinity, greatly increases the apparent resistivities of the sands. As the relative proportion of air decreases, water becomes the continuous fluid phase in the pore system. Water is more conductive than air. Consequently, saturated sand is more conductive, or less resistive, than unsaturated sand.

Superimposed on this saturation change is a change from sandy Middendorf sediments to clayey saprolite. Saturated clay is both electronically and electrolytically conductive. Furthermore, it typically has very high porosity. Both of these factors result in a greatly reduced resistivity in the saprolite.

Slate typically has very high resistivities, ranging from 1,500 to 6,000 ohm-ft (see Carmichael, 1982, and Parkhomenko, 1967, p. 294). It is resistive because the conductive pore water has been squeezed out of the rock during compaction. However, the introduction of water-filled fractures will greatly reduce the electrical resistance of slate. Therefore, a theoretical sounding curve over slate would show very high apparent resistivities over the unfractured slate with marked drops in resistance over fractures.

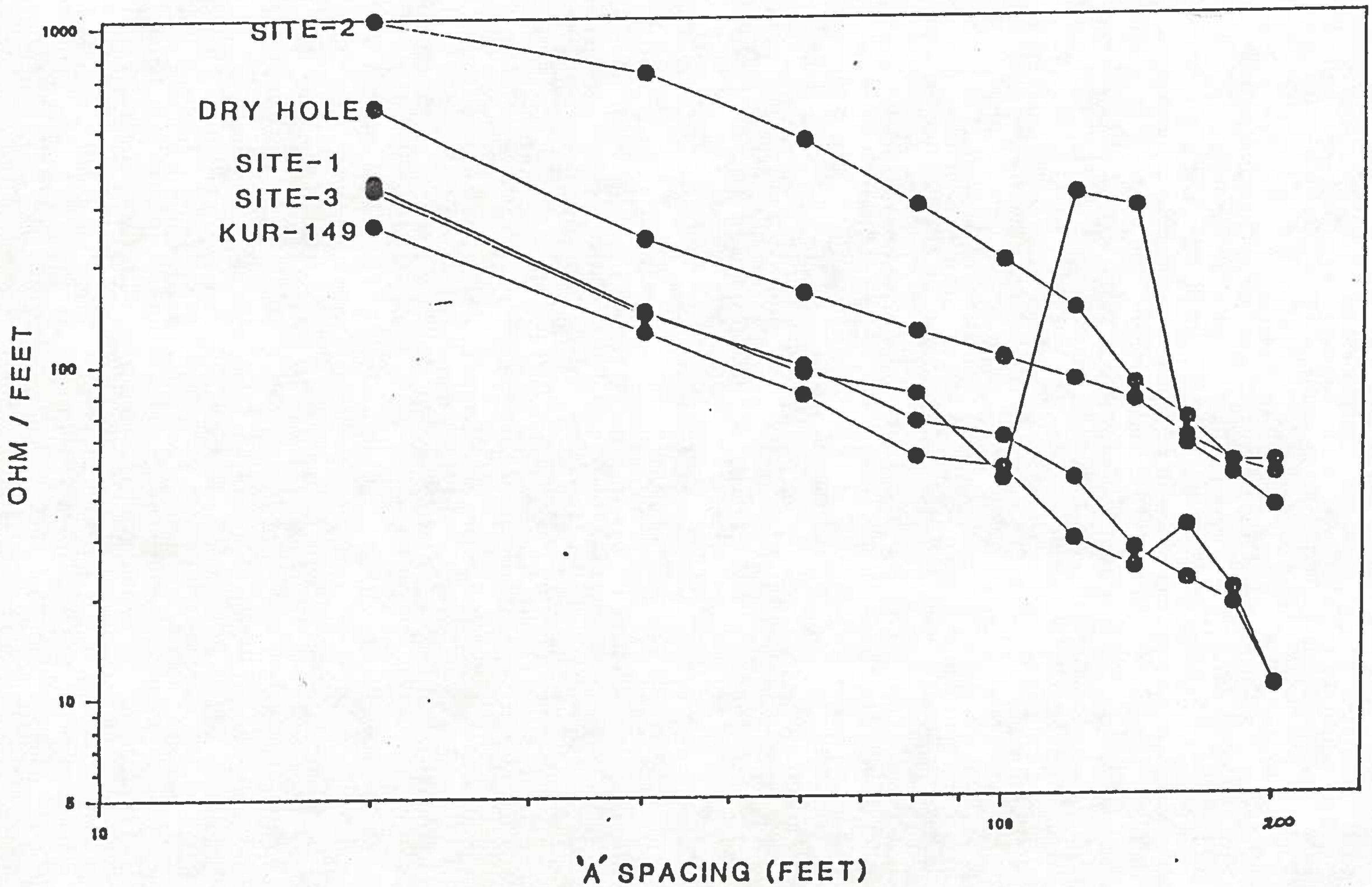

Figure 7. Overlay of the five Wenner sounding curves.

In the study area, the theoretical curve would show high resistivities at shallow depths (corresponding to the unsaturated, sandy zone), low resistivities at intermediate depths (corresponding to the saturated, clayey zone), and very high resistivities at deep depths (corresponding to the unfractured slate). This curve is conventionally described as an H-type curve (Zohdy and others, 1974, p. 27). However, the high resistivities of the slate are not observed at any of the sites. A possible explanation is that the current has not penetrated deeply enough into the subsurface to produce meaningful results. If probing depth was sufficient, then the longer electrode spacings would show gradual increases in apparent resistivity and eventually would asymptotically approach a horizontal line marking the true resistivity of the slate.

There are numerous opinions regarding the probing depth of the dc-resistivity measurement (see Roy and Elliot, 1981). However, no rules of thumb can safely be applied (Zohdy and others, 1974). In general, the probing depth is a complex function of electrode spacing, electrode configuration, and the thickness and resistivity of the layers. Zohdy, therefore, suggested that soundings be made over areas of known geology to get an idea of penetration depths.

At the "DRY HOLE" site, the basic geology is known. The thickness of the overburden (Middendorf plus saprolite) is only 60 ft (from the driller's log). However, even over this relatively thin overburden, the sounding curve shows no indication that current has significantly penetrated to the depth of slate; there is no increase in resistivity at the longer electrode spacings (Figure 8).

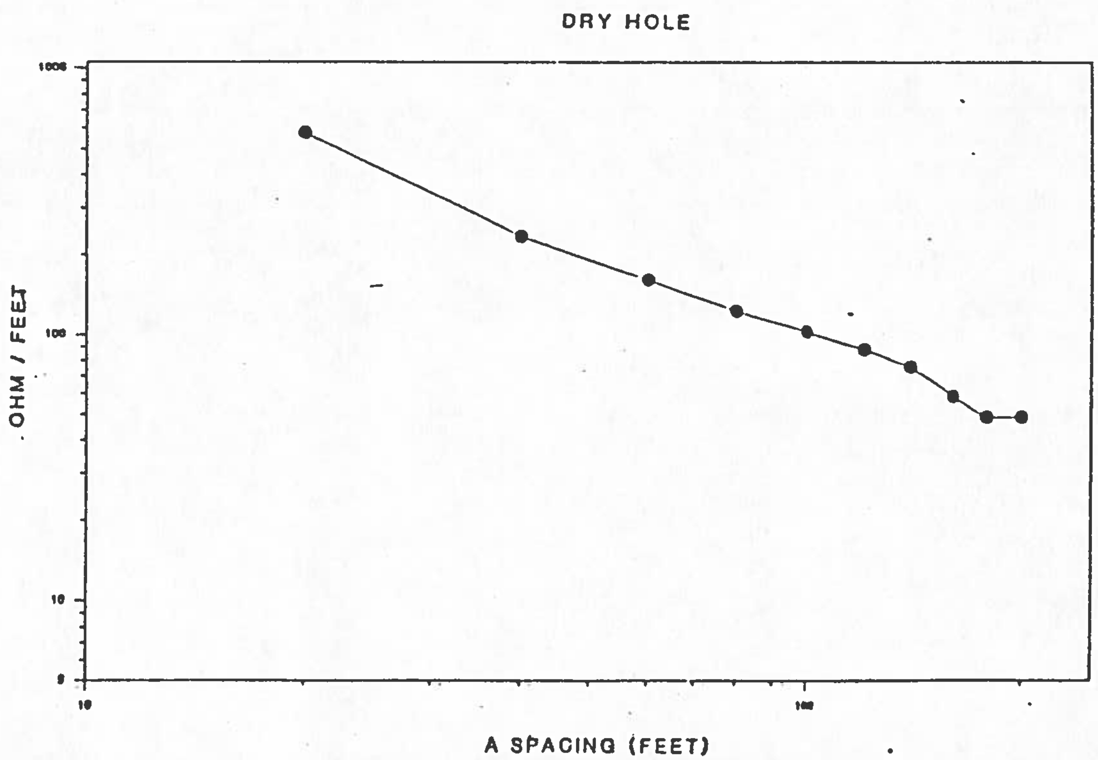

Figure 8. Wenner sounding curve over the DRY HOLE site showing no indication of highly resistive slate.

It was at this same site that bedrock samples were available. Approximately 35 ft of the slightly weathered, friable slate overlies the unweathered slate. This transition zone would theoretically be less resistive than the slate because of its higher porosity. This implies that current would have to penetrate not only the 60 ft of overburden, but also the low resistivity transitional zone before intersecting the slate.

In light of this, it is pertinent to quote Benson and others, 1982, who stated that "the maximum 'a' spacing should be at least 3 to 4 times the depth of interest in order to permit adequate characterization of deeper layers." The maximum 'a' spacing obtained in the report was 200 ft. This spacing would correspond to a measuring depth of 50-66 ft (according to Benson). As stated above, the average thickness of overburden alone is 83 ft. Therefore, it is improbable that we penetrated the slate deeply enough, if at all. Add to this the 35 ft of slightly weathered slate and the depth of penetration would have to be greater than 100 ft. This corresponds to an 'a' spacing of 300-400 ft.

Site 2 and the DRY HOLE site are located within 1/4 mile of each other. Both show higher overall resistivities than the remaining three sites. A possible explanation is that both these sites have a relatively thin, dry overburden which is more resistive than the other three sites.

Sites 1 and 3 and KUR-149 all have similar ranges of resistivities. It is known from a driller's log that KUR-149 has 110 ft of overburden. The similarity in the curves at these three sites therefore suggests that sites 1 and 3 also have thick overburdens. A general correlation between the thickness of the overburden and location of fracture zones has been observed (Nielsen and Kruger, 1985). The theory for such a correlation is that water can percolate deeper into the basement rock over fracture zones, thus accelerating the weathering process. The result is a thick weathering profile.

Such indirect correlations should be applied with caution. It is reasonable to suspect that a portion of the overburden in the low-lying areas was contributed by erosion of topographically higher areas. However, it is interesting to note that both the 300-gpm well and the dry well are located at local topographic highs. The producing well has more than 110 ft of overburden and shallow fractures starting at 125 ft; whereas the dry well has only 60 ft of overburden and no prominent fracture zones.

During the analysis, there was some question as to what the actual resistivity of the Carolina Slate was. Unfortunately, no borehole resistivity data in the area were available. Therefore, the above interpretation hedges on the use of standard resistivity values between 1,500-6,000 ohm-ft for slate. For example, what if the Carolina Slate is so mineralogically different and less compact than the standard, that fractured slate is more resistive than unfractured slate? The anomaly on Figure 7 at the producing well could then be interpreted as a fracture zone. It is known that there is extensive fracturing at this site because the well is yielding more than 300 gpm. The driller reported water at 125 ft, 145 ft, and 175 ft, which is relatively shallow. However, it is probable that this anomaly is due either to a lateral inhomogeneity in the subsurface or to a non-geologic factor such as poor electrical contact between the electrodes and the earth. First, it is doubtful that the standard and the Carolina Slate could be so different. The deepest measured apparent resistivity made at the producing site was 36 ohm-ft. This is roughly two orders of magnitude below the standard. Secondly, a repeat traverse across the site, using the Schlumberger array (less sensitive to lateral inhomogeneities), did not produce the same anomaly.

Schlumberger Sounding Curves

On March 12, 1988, Schlumberger soundings were made at four sites: sites 1 and 3, the DRY HOLE site, and the producing well KUR-149. The decision to return and make these soundings was based on the possibility that the Wenner soundings did not penetrate deeply enough into the subsurface. An additional reason was that the Schlumberger soundings, owing to their smaller MN distance, have a higher resolution and, therefore, are less affected by other subsurface conditions (stray currents) and lateral inhomogeneities.

Raw data for the Schlumberger curves are in Appendix II-A. The sounding curves for each site are in II-B. Figure 9 is a composite overlay of the four Schlumberger curves. The curves are conventionally expressed, with apparent resistivity plotted along the vertical axis and half the AB distance (AB/2) plotted on the horizontal axis.

There is some evidence that the Schlumberger array has penetrated deeper into the subsurface and into the slate. A gradual increase in resistivity at longer electrode spacings is observed at the dry hole (at AB/2 = 160), at site 1 (at AB/2 = 260), and at site 3 (at AB/2 = 220). Furthermore, this increase in resistivity begins at longer spacings for sites 1 and 3 than it does for the dry hole, again suggesting that the overburden is thicker at these two sites.

There is a sharp drop in resistivity at site 3 at the longest spacing (AB/2 = 200, Figure 10). It is possible that this drop represents a fracture zone in the slate. However, the resistivity is extremely low (only 0.155 ohm-ft) and the zone is defined by only a single data point. It is therefore suspect.

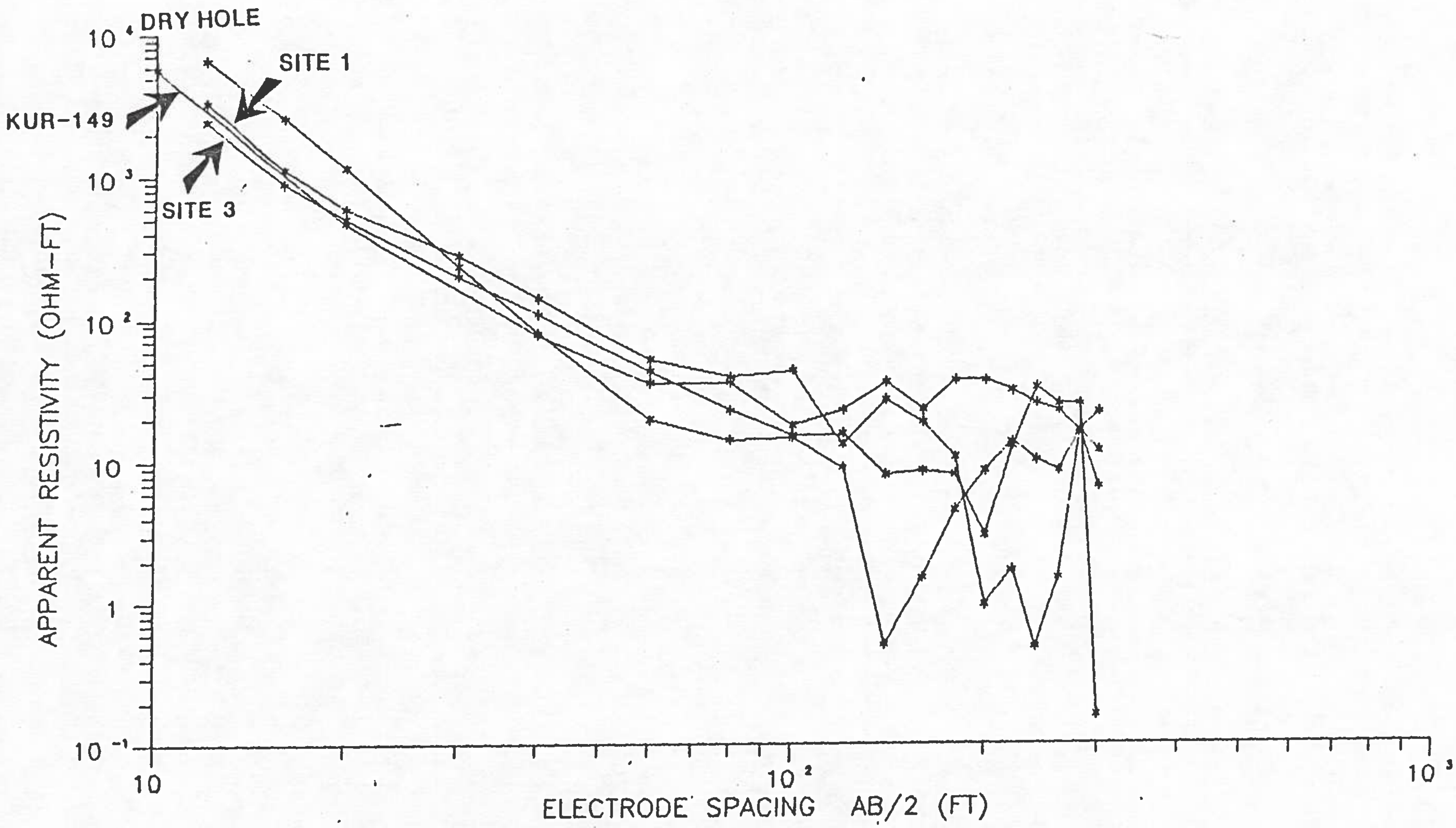

Figure 9. Overlay of the four Schlumberger sounding curves.

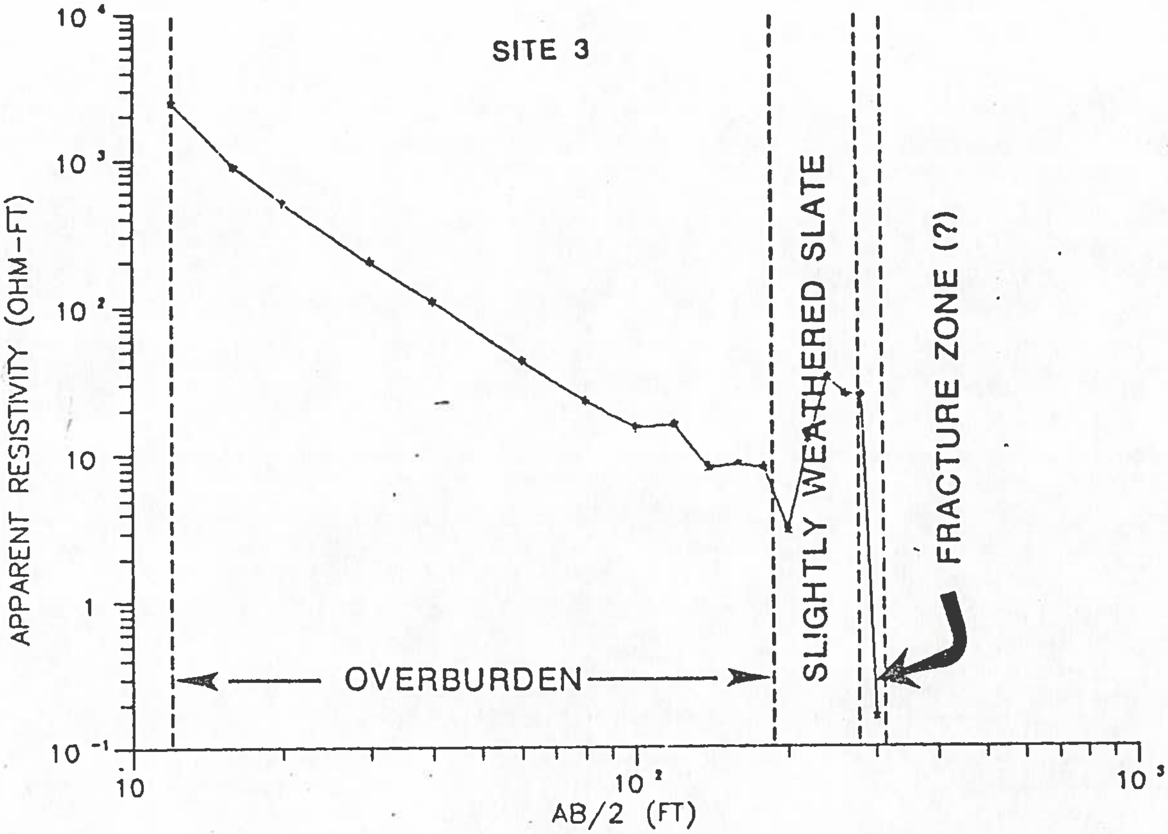

Figure 10. Schlumberger sounding curve over site 3 and the geological interpretation.

WADI curves

On April 29, 1988, the WADI device was employed at sites 1, 3, and 4, at the producing well (KUR-149) and at the dry well. Two parallel traverses were made at each site. An interpolated curve is generated for each traverse. These are overlaid and displayed in Figures 11-15. The solid curve in each figure represents a traverse made in one direction while the dashed curve represents the second traverse made in the opposite direction. The vertical axis is the filtered, in-phase tilt angle of the secondary field, and the horizontal axis is the distance marked off from the starting point of the traverse.

With exception to the dry well, each site shows indications of surface/subsurface conductors. At the dry well, the WADI profiles are flat, suggesting no conductors (Figure 11). At site 4 there are two very sharp and narrow peaks (Figure 15). One is a positive peak and occurs at the 280-foot mark. It occurs during the traverse in one direction (solid curve) but is missing on the traverse in the opposite direction (dashed curve). This anomaly represents a wire fence that crossed the traverse.

The second anomaly occurs at the 370-foot mark. It is a negative anomaly and repeats in both directions. It is unclear what this

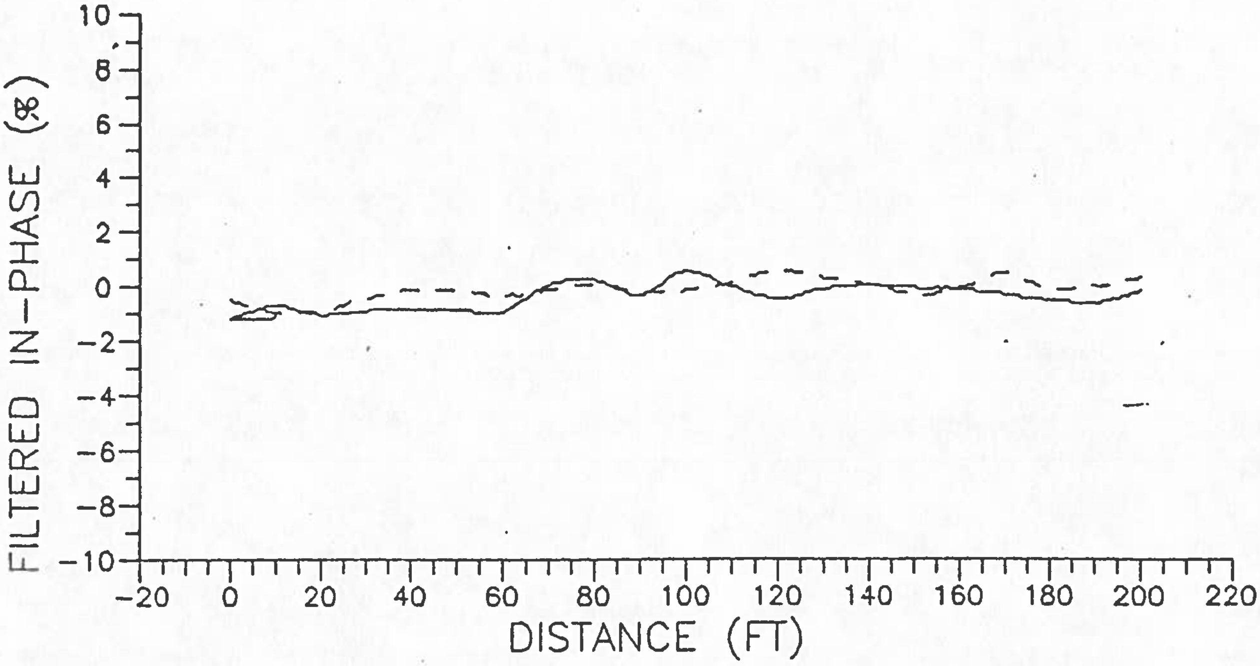

Figure 11. WADI profiles across the DRY HOLE site.

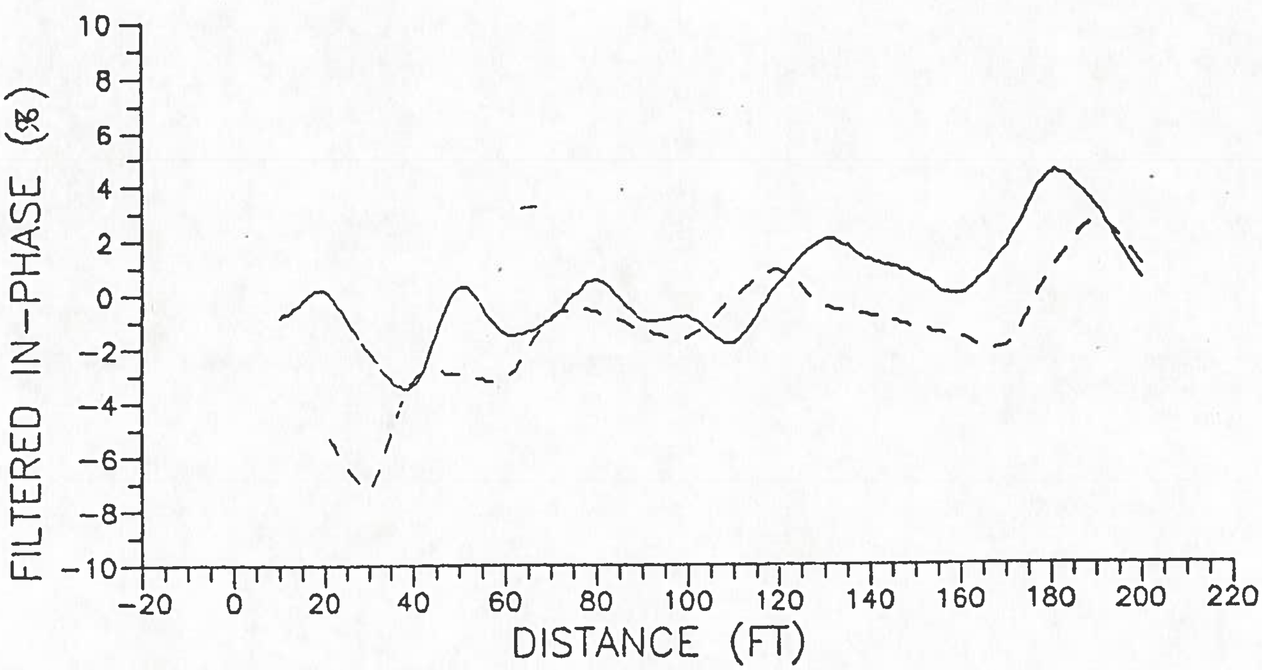

Figure 12. WADI profiles across site KUR-149.

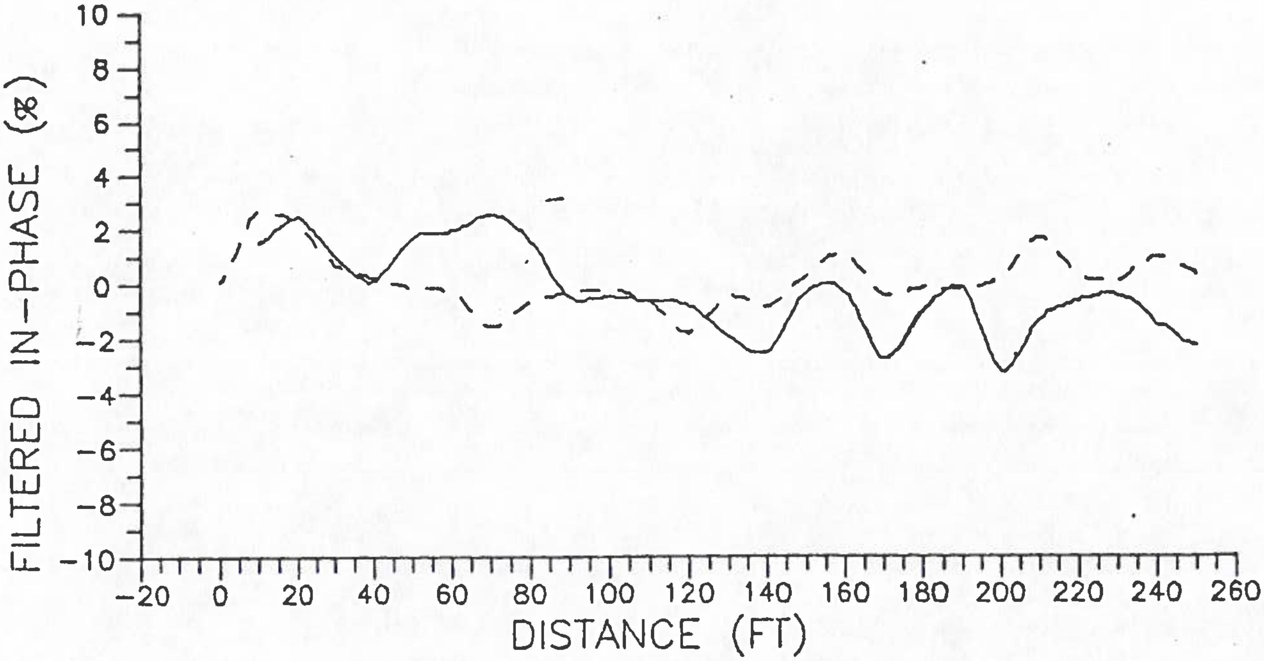

Figure 13. WADI profiles across site 1.

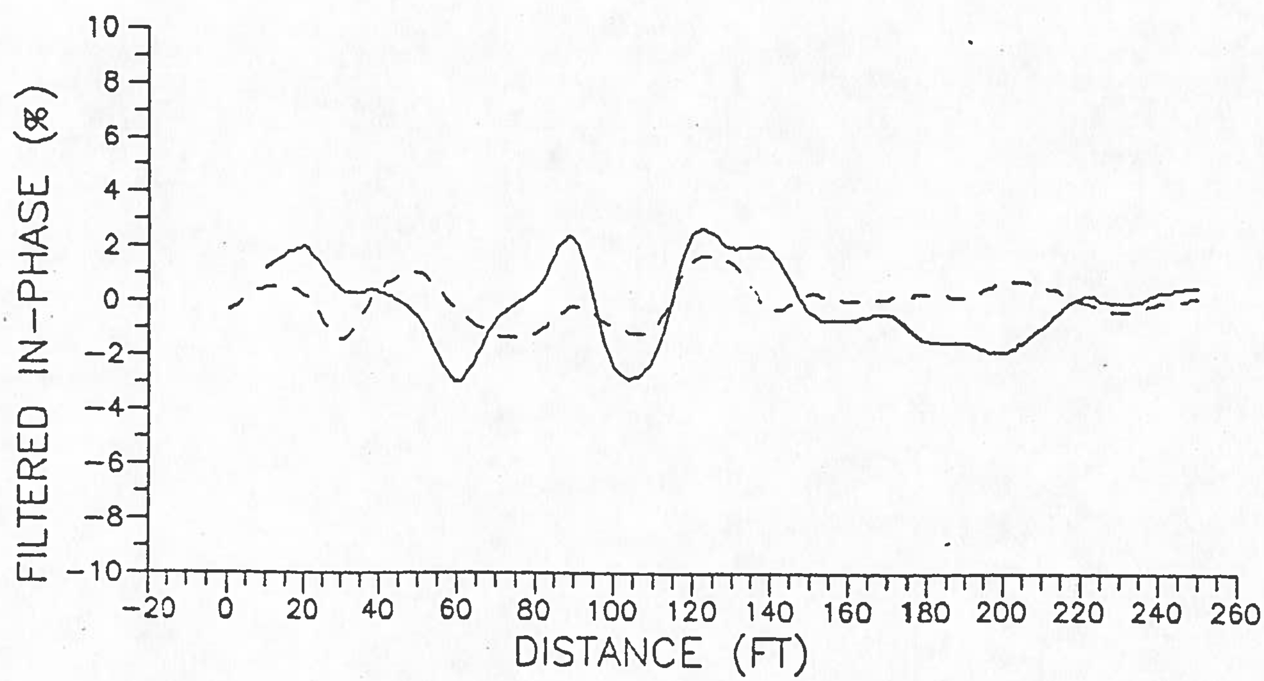

Figure 14. WADI profiles across site 3.

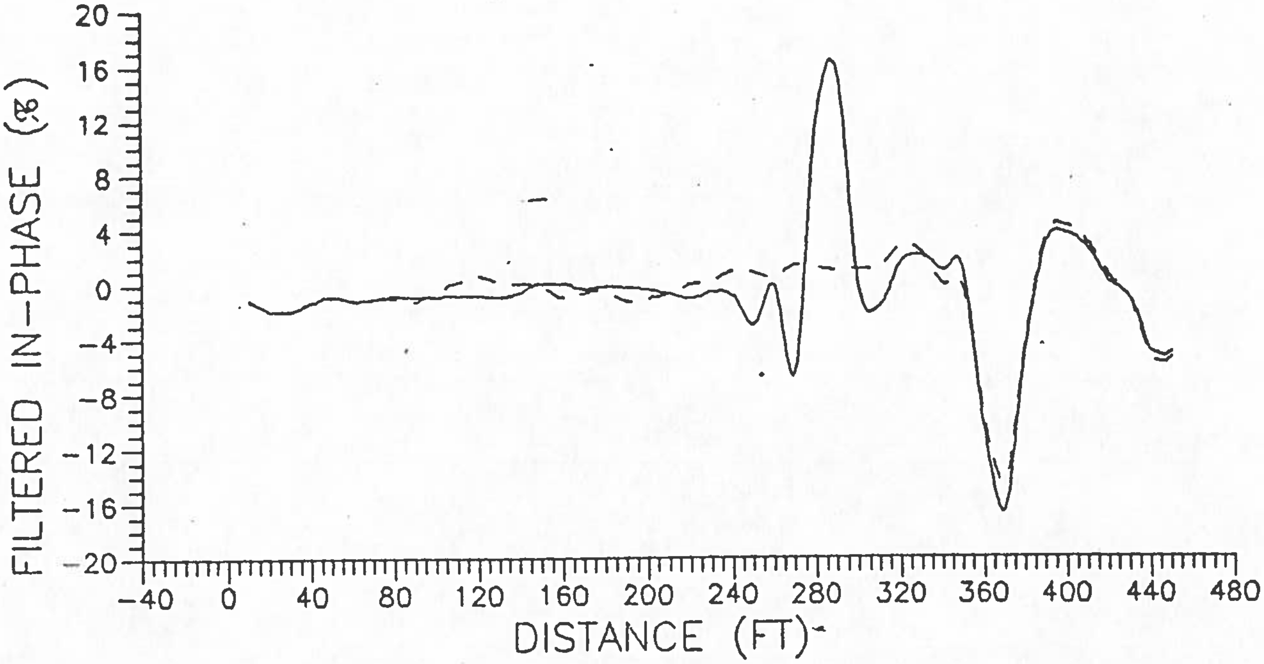

Figure 15. WADI profiles across site 4.

represents. However, the near-perfect correlation of the spike across both traverses suggests that it may be a buried pipe.

The producing well and sites 1 and 3 all show peaks along their curves (Figures 12-14). However, it is uncertain whether the amplitudes of these peaks are significant to suggest fracture zones. These curves were also generated in the field while measurements were being made. In the field, however, the anomalies were not as evident and therefore were not flagged. Only after plotting them at a different scale did the curves show any features. Consequently, it is unclear whether the peaks are significant and represent fracture zones or are due to the expanded scale which magnifies their amplitudes.

In general, however, the anomalies do repeat between traverses; that is, the curves are correlated at each site. This suggests that the signals are not noise but represent real subsurface features.

DISCUSSION AND RECOMMENDATIONS

Although no clear fracture zones can be discerned, some of the sites look more promising than others. The Wenner soundings at site 2 are similar to the Wenner soundings at the dry well, suggesting that site 2 is also dry. The WADI profiles at site 4 are generally flat, eliminating this site.

Sites 1 and 3 are the most promising. The anomaly on the Schlumberger curve, together with the anomalies on the WADI profiles, makes site 3 the most attractive. Therefore, it is suggested that more extensive WADI profiles be run at site 3. Anomalies in the field should then be flagged.

The advantages of the WADI system are that it requires only one man to operate, data are collected rapidly, and data can be analyzed in the field at the time they are collected. The additional profiles will require only one day to collect. The best-looking anomaly can be flagged and drilled.

In general, yields from crystalline rocks are greatest along valleys and broad ravines and lowest at or near crests of hill (see Davis and DeWiest, 1966, p. 327). The expense of adding an additional water line should be evaluated in light of this. Other sites in the area are topographically more promising than the sites analyzed in this report; however, those sites are several miles from the existing water lines.

The interpretations made herein are the author's opinions and are based upon inferences from the data acquired. The South Carolina Water Resources Commission cannot guarantee the accuracy of these interpretations and bears no responsibility for any costs incurred as a result of the them.

REFERENCES

Benson, R. C., Glaccum, R. A., and Noel, M. R., 1983, Geophysical Techniques for Sensing Buried Wastes and Waste Migration, National Water Well Association, 236 pp.

Carmichael, R. S. (ed.), 1982, Handbook of Physical Properties of Rocks, Volume I: Florida, CRC Press, Inc., 404 pp.

DeWiest, R. M., and Davis, S. N., 1966, Hydrogeology: New York, John Wiley and Sons, 463 pp.

Nielsen, K. A., and Kruger, I., 1985, Groundwater occurrences in weathered basement complex areas -- in Proceedings of the World Congress on Water Resources, Brussels, June 9-15, 1985, p. 189-198.

Parkhomenko, E. I., 1967, Electrical Properties of Rocks: New York, Plenum Press, 314 pp.

Roy, K. K., and Elliot, H. M., 1981, Some observations regarding depth of exploration in d.c. electrical methods: Geoexploration, v. 19, p. 1-13.

Zohdy, A. A., G. P. Eaton, and Mabey, D. R., 1974, Application of surface geophysics to ground-water investigations: Techniques of Water-Resources Investigations of the United States Geological Survey, Chapter D1, 116 pp.

APPENDIX I-A

Raw data for the Wenner sounding curves

W/DRY HOLE

ELECTRODE SPACING (ft.)		DIAL READING X SCALE MULT (Ohms) FULL	LEFT	RIGHT	MULT.	APPARENT RESISTIVITY (Ohm-ft.) FULL	LEFT	RIGHT	CUMULATIVE RESISTIVITY (Ohm-ft.)
10/30	20	572.5			1	572.5			
20/60	40	233.0			1	233.0			
30/90	60	160.0			1	160.0			
40/120	80	122.0			1	122.0			
50/150	100	102.0			1	102.0			
60/180	120	87.5			1	87.5			
70/210	140	75.5			1	75.5			
80/240	160	58.5			1	58.5			
90/270	180	49.0			1	49.0			
100/300	200	49.0			1	49.0			

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ELECTRODE SPACING (ft.)		DIAL READING X SCALE MULT (Ohms) FULL	LEFT	RIGHT	MULT.	APPARENT RESISTIVITY (Ohm-ft.) FULL	LEFT	RIGHT	CUMULATIVE RESISTIVITY (Ohm-ft.)
10/30	20	346.0			1	346.0			
20/60	40	142.0			1	142.0			
30/90	60	92.5			1	92.5			
40/120	80	79.5			1	79.5			
50/150	100	44.0			1	44.0			
60/180	120	315.0			1	315.0			
70/210	140	286.5			1	286.5			
80/240	160	55.5			1	55.5			
90/270	180	45.0			1	45.0			
100/300	200	36.0			1	36.0			

SITE 1

ELECTRODE SPACING (ft.)		DIAL READING X SCALE MULT (Ohms) FULL	LEFT	RIGHT	MULT.	APPARENT RESISTIVITY (Ohm-ft.) FULL	LEFT	RIGHT	CUMULATIVE RESISTIVITY (Ohm-ft.)
10/30	20	332			1	332			
20/60	40	138.5			1	138.5			
30/90	60	97.5			1	97.5			
40/120	80	66.0			1	66.0			
50/150	100	59.0			1	59.0			
60/180	120	44.0			1	44.0			
70/210	140	27.0			1	27.0			
80/240	160	22.0			1	22.0			
70/270	180	18.5			1	18.5			
100/300	200	10.5			1	10.5			

SITE 2 Near Church

ELECTRODE SPACING (ft.)	DIAL READING X SCALE MULT (Ohms)				APPARENT RESISTIVITY (Ohm-ft.)			CUMULATIVE RESISTIVITY (Ohm-ft.)
	FULL	LEFT	RIGHT	MULT.	FULL	LEFT	RIGHT	
10/30 20	104.0			10	104.0			
20/60 40	722.0			1	722.0			
30/90 60	456.0			1	456.0			
40/120 80	292.5			1	292.5			
50/150 100	198.5			1	198.5			
60/180 120	142.5			1	142.5			
70/210 140	85.0			1	85.0			
80/240 160	66.5			1	66.5			
90/270 180	49.0			1	49.0			
100/300 200	45.0			1	45.0			

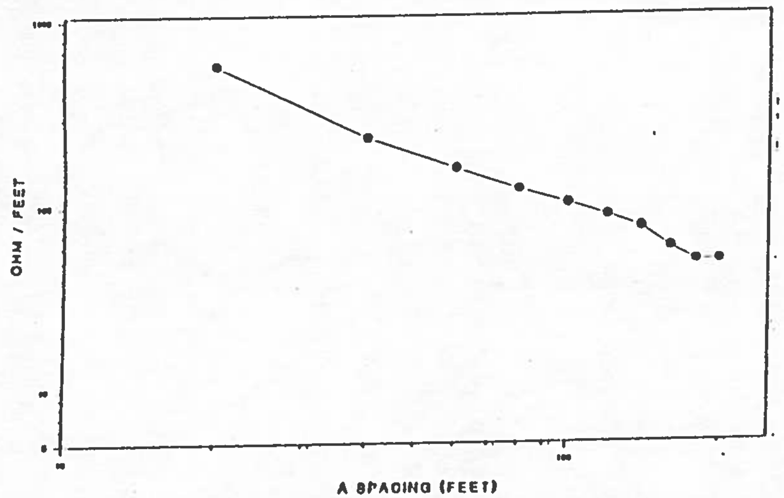
" CUT DOWN " SITE 3

ELECTRODE SPACING (ft.)		DIAL READING X SCALE MULT (Ohms) FULL	LEFT	RIGHT	MULT.	APPARENT RESISTIVITY (Ohm-ft.) FULL	LEFT	RIGHT	CUMULATIVE RESISTIVITY (Ohm-ft.)
10/30	20	258.0			1	258.0			
20/60	40	123.0			1	123.0			
30/90	60	79.5			1	79.5			
40/120	80	51.5			1	51.5			
50/150	100	47.5			1	47.5			
60/180	120	29.0			1	29.0			
70/210	140	24.0			1	24.0			
80/210	160	31.5			1	31.5			
90/270	180	20.5			1	20.5			
100/300	200	10.5			1	10.5			

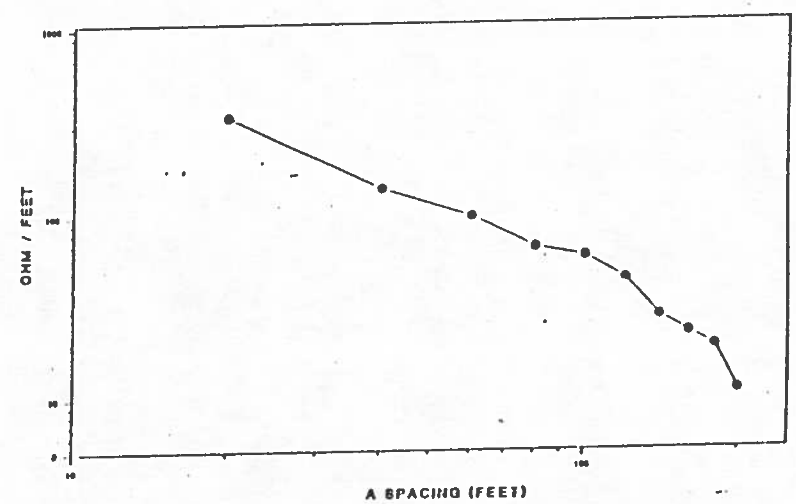
APPENDIX I-B

Wenner sounding curves

DRY HOLE



SITE-1



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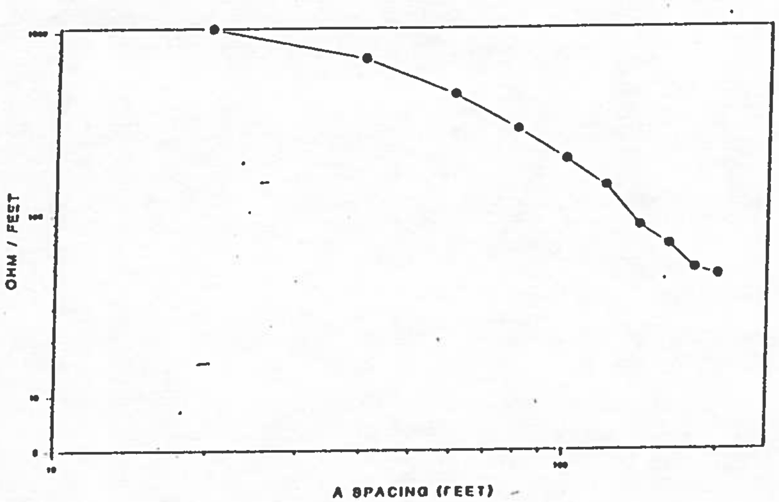

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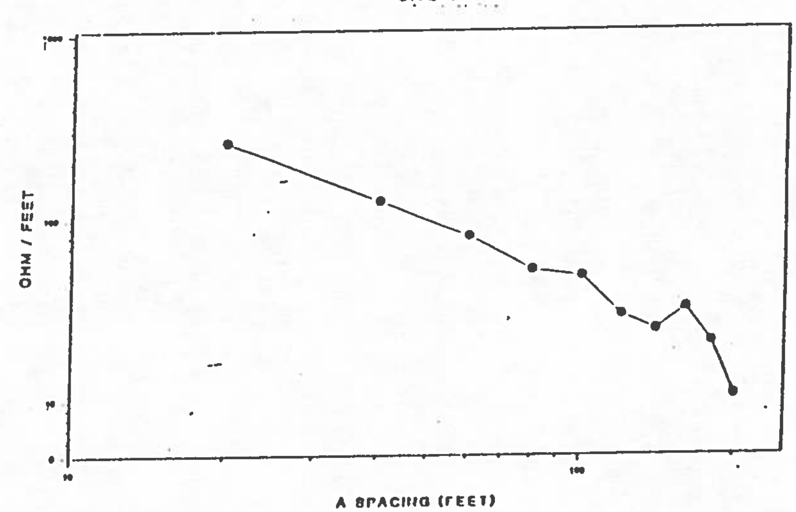


APPENDIX II-A

Raw data for the Schlumberger sounding curves

BETHUNE 03-12-88 DRY HOLE

ELECTRODE SPACING (ft.)	DIAL READING X SCALE MULT (Ohms) FULL	LEFT	RIGHT	MULT.	APPARENT RESISTIVITY (Ohm-ft.) FULL	LEFT	RIGHT	CUMULATIVE RESISTIVITY (Ohm-ft.)
12	656.5			10	6565.0			
16	257.0			10	2570.			
20	115.5			10	1155.0			
30	233.0			1	233.0			
40	79.5			1	79.5			
60	19.5			1	19.5			
80	14.0			1	14.0			
100	14.5			1	14.5			
120	9.0			1	9.0			
140	.5			1	.5			
160	1.5			1	1.5			
180	4.5			1	4.5			
200	8.5			1	8.5			
220	13.5			1	13.5			
240	10.0			1	10.0			
260	8.5			1	16.0			
300	6.5			1	6.5			

ELECTRODE SPACING (ft.)	DIAL READING X SCALE MULT (Ohms)				APPARENT RESISTIVITY (Ohm-ft.)			CUMULATIVE RESISTIVITY (Ohm-ft.)
	FULL	LEFT	RIGHT	MULT.	FULL	LEFT	RIGHT	
10	577.5			10	5775.0			
20	463.0			1	463.0			
40	77.0			1	77.0			
60	35.0			1	35.0			
80	35.0			1	35.0			
100	17.5			1	17.5			
120	22.5			1	22.5			
140	35.0			1	35.0			
160	22.5			1	22.5			
180	36.0			1	36.0			
200	36.0			1	36.0			
220	30.5			1	30.5			
240	25.0			1	25.0			
260	22.0			1	22.0			
280	16.0			1	16.0			
300	21.5			1	21.5			

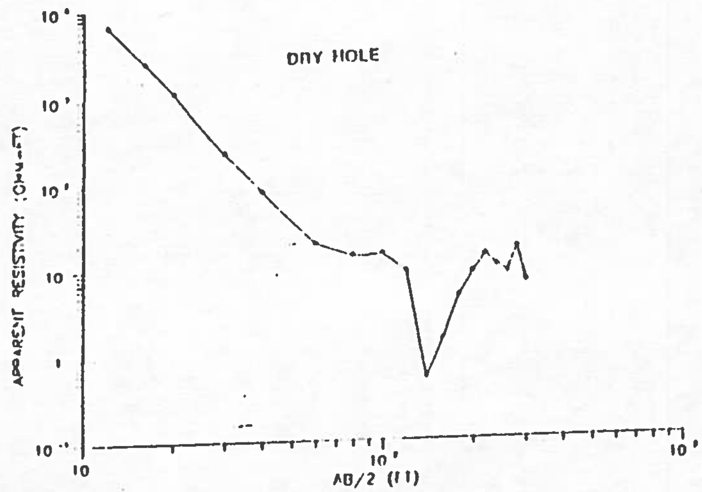
SITE 1

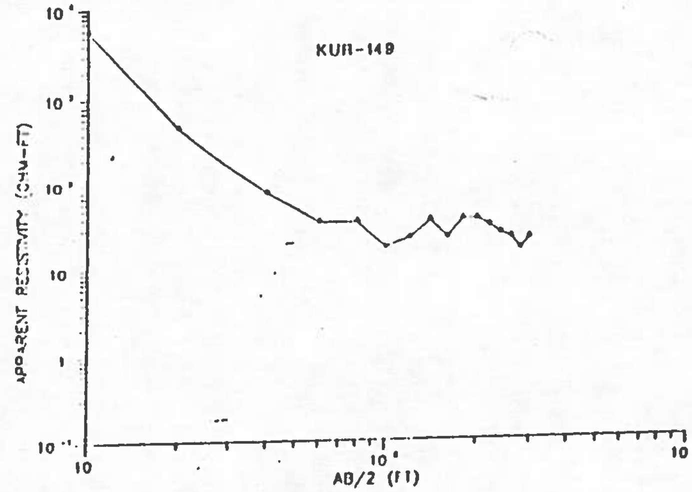
ELECTRODE SPACING (ft.)	DIAL READING X SCALE MULT (Ohms) FULL	LEFT	RIGHT	MULT.	APPARENT RESISTIVITY (Ohm-ft.) FULL	LEFT	RIGHT	CUMULATIVE RESISTIVITY (Ohm-ft.)
12	336.5			10	3365.0			
16	112.5			10	1125.0			
20	592.0			1	592.0			
30	275.0			1	275.0			
40	138.0			1	138.0			
60	51.0			1	51.0			
80	38.5			1	38.5			
100	42.5			1	42.5			
120	13.0			1	13.0			
140	26.5			1	26.5			
160	18.5			1	18.5			
180	10.5			1	10.5			
200	96.4			.01	.964			
220	17.0			.1	1.7			
240	479			.001	.479			
260	1.5			1	1.5			
280	16.0			1	16.0			
300	11.5			1	11.5			

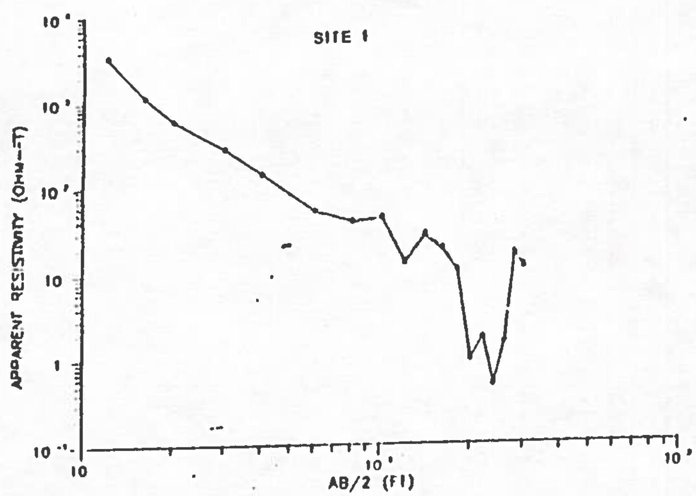
ELECTRODE SPACING (ft.)	DIAL READING X SCALE MULT (Ohms)				APPARENT RESISTIVITY (Ohm-ft.)			CUMULATIVE RESISTIVITY (Ohm-ft.)
	FULL	LEFT	RIGHT	MULT.	FULL	LEFT	RIGHT	
12	243.5			10	2435.0			
16	885.5			1	885.1			
20	500.5			1	500.5			
30	197.5			1	197.5			
40	107.0			1	107.0			
60	42.5			1	42.5			
80	22.5			1	22.5			
100	15.0			1	15.0			
120	15.5			1	15.5			
140	8.0			1	8.0			
160	8.5			1	8.5			
180	8.0			1	8.0			
200	3.0			1	3.0			
220	12.5			1	12.5			
240	32.0			1	32.0			
260	24.5			1	24.5			
280	24.5			1	24.5			
300	155.5			.001	.155			

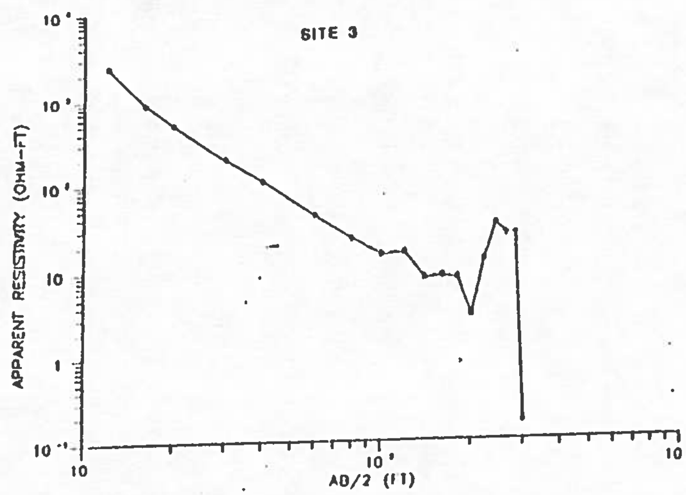
APPENDIX II-B

Schlumberger sounding curves


DRY HOLE
APPARENT RESISTIVITY (OHM-FT)
AB/2 (FT)


KUR-149
APPARENT RESISTIVITY (OHM-FT)
AB/2 (FT)


SITE 1
APPARENT RESISTIVITY (OHM-FT)
AB/2 (FT)


SITE 3
APPARENT RESISTIVITY (OHM-FT)
AB/2 (FT)